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Maria José Juan Jordá for the degree of Master of Science in Marine Resource Management presented on March 15, 2006
Title: Integration of Oceanographic Information off the Washington and Oregon Coasts into West Coast Groundfish Ecology and Fisheries Management

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John A. Barth

To date, the use of oceanographic data in fisheries management has been limited by the scarcity and the difficulty of accessing complete oceanographic datasets. Consequently, fish stocks are managed with limited knowledge about the habitat where fish live and incomplete understanding of what oceanographic conditions affect their populations. With the long-term goal to improve science for ecosystem-based management of the West Coast groundfish fishery, this study had three objectives. First, the assembling and merging of disperse oceanographic datasets for temperature, salinity, chlorophyll-a and current velocity from the 1930s to the year 2004 off the Washington and Oregon coasts. Second, the generation of oceanographic data products relevant for fisheries research, consisting of the computation and the plotting of climatological monthly means, standard deviations and coefficients of variation for a variety of ocean variables at several depths. Third, the development of an exploratory example of how oceanographic information collected in this study can be of use to improve the science and management of groundfish. Thus, a study was developed to investigate if groundfish distribution and abundances are associated with any ocean habitat or individual oceanographic variables, using a combination of univariate, classification and ordination techniques. The fish data were derived from a routine

bottom trawl survey conducted by the National Oceanic and Atmospheric Administration Northwest Fisheries Science Center (NOAA-NWFSC).

Five ocean habitats with distinct physical and biological characteristics were identified off the Washington and Oregon coast: Offshore Habitat, Upwelling Habitat, Highly Variable Upwelling Habitat, River Plume Habitat, and Highly Variable Habitat. These ocean habitats were characteristic of cold-regime summer upwelling conditions. Overall, the analyses suggested that the species composition differ among the five ocean habitats. Some species were highly indicative of some habitats; however, overall the associations were weak due to the high degree of overlap of ocean habitats in terms of species composition. All the analyses were consistent in associating shallower species with the shallowest habitats (the Highly Variable, River Plume and Upwelling habitats) and the deeper species with the deeper habitats (the Offshore and the Highly Variable Upwelling habitats), suggesting that groundfish are adapted to wide environmental ranges. In addition, the overall abundance and diversity of groundfish was higher in the shallower habitats. In contrast, groundfish species showed strong associations with individual environmental factors, primarily depth, surface chlorophyll-a, and salinity and temperature at the bottom of the seafloor, indicating that groundfish distributions are mainly organized along depth gradients. Latitudinal variations in upwelling intensity, river discharge and productivity along the coast were also important factors influencing shallow species distributions and abundances. For example, three regions with high chlorophyll-a concentrations were associated with large abundances of specific groundfish species. These regions were found over Heceta Bank, over the Juan de Fuca canyon and in the Columbia River Plume.

This study began with the assembly of several ocean variables and the development of some preliminary ocean data products relevant to fisheries studies. However, the addition of other ocean variables, such as dissolved oxygen, and the computation of new ocean products, such as mixed-layer depth, and thermocline depth and strength, would be valuable. Future work should involve more interdisplinary studies between fisheries and oceanography, the integration of oceanographic information off the west coast of the U.S., and the collection of concurrent ocean data at each fish trawl location.

Integration of Oceanographic Information off the Washington and Oregon Coasts into West Coast Groundfish Ecology and Fisheries Management

by

Maria José Juan Jordá

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Maria José Juan Jordá, Author

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INTEGRATION OF OCEANOGRAPHIC INFORMATION OFF THE WASHINGTON AND OREGON COASTS INTO WEST COAST GROUNDFISH ECOLOGY AND FISHERIES MANAGEMENT

1 INTRODUCTION

This study's aim is to integrate the oceanographic knowledge obtained from the Washington and Oregon coasts into fisheries research and management of the West Coast groundfish fishery. To date, the use of oceanographic data in fisheries science and management has been minimal due to the difficulty of obtaining relevant oceanographic datasets commensurate with fisheries data. In fact, even determining which oceanographic factors are appropriate for fisheries research has been seen as a challenge (Quinn and Niebauer, 1995). Consequently, groundfish stocks are managed with limited knowledge about their ocean habitats and limited understanding of which and how oceanographic conditions affect their populations.

In order to integrate oceanographic information into fisheries research and management, this study is divided into three sections: first, the assembling and merging of disperse and disparate oceanographic datasets; second, the generation of relevant oceanographic data products for fisheries research; and last, an exploratory example of how oceanographic information can be used to investigate if there are any distinct ocean habitats associated with the distributions and abundances of West Coast groundfish species.

This work was initiated because of a combination of events happening all over the world and, specifically, on the west coast of the United States. The first reason for this study was the increasing concerns about the global status of fisheries and the realization of the widespread decline and collapse of major fish stocks around the world. The decline of New England fisheries and the commercial extinction of Atlantic halibut

(POC, 2003) are two classic examples. Off the west coast of the U.S., fisheries management failures, and consequently fisheries collapses can also be tracked. The collapse of the West Coast groundfish fishery is also a classic example, as many others, of over-exploitation, overcapitalization, lack of scientific understanding of the stocks and inadequate resources for research. In the long-term, this study attempts to improve the scientific understanding of the ecology of the West Coast groundfish and their management by making oceanographic data available in a geographic information system (GIS) format to fisheries scientists and managers, and by providing an exploratory analysis of how oceanographic data can be used to enhance the understanding of groundfish distributions.

The second reason for this study was the 1996 amendment to the Magnuson-Stevens Fisheries Conservation and Management Act (MSFCMA), which addresses the ecological impacts of fisheries. This act is the legal basis for fisheries management in the U.S. One of the major components of the act is the essential fish habitat (EFH) requirement. It demands identifying habitats that are essential for fish species managed under the Pacific Coast Groundfish Fisheries Management Plan. The act also requires measures "to minimize to the extent practicable the adverse effects of fishing on fish habitats" and encourages the conservation and enhancement of the habitats (Hildreth et al., 2002). The EFH provision has created an enormous effort to study the habitats of the groundfish species along the west coast of the U.S. To date, there have been successful attempts identifying, classifying and mapping seafloor habitats based on lithologic substrates (Romsos, 2004), which are being used to investigate the associations between fish and substrate. This has proved to be an important step towards the identification of

EFH. These attempts to identify EFH for groundfish species using benthic habitat information have been a remarkable step towards the objective of conserving and enhancing fish habitats. However, it has been acknowledged that other elements, such as water temperatures and salinities, dynamic current structures and climate, are also essential factors for identifying which habitats are necessary for fish during their life history.

The final motivation for this study was the recognition of a worldwide need for an ecosystem-based approach to manage fisheries resources (Browman and Stergiou, 2004). This is a new direction in fisheries management, where ecosystem components and interactions are given more priority than the management of single species (Pikitch et al., 2004). The Pew Oceans Commission (2003) and the U.S. Commission on Ocean Policy (2004), two major U.S. efforts, have proposed new strategies to manage our oceans and have highly recommended the use of ecosystem-based management (EBM). The usual approach to manage fisheries resources has been to manage fish stocks as single units, while ignoring species interactions and the dynamic ocean environment where fish live. According to these commissions, there is an urgent need to shift from single-species management and take a more holistic approach, as EBM offers, to manage human activities and the living resources of our planet. EBM is a holistic approach in the sense that it integrates ecological, social, economic and institutional perspectives into the decision-making process. In addition, this approach emphasizes the protection of ecosystem functions and key processes and accounts for the interconnectedness within and among systems, as well as the effects of fishing on the ecosystem (POC, 2003). The EBM approach creates a desirable framework where the knowledge of oceanographic processes are seen as an essential part of understanding fish populations and managing them.

In the last 50 years, a large number of oceanographic investigations have been undertaken off the Oregon and Washington coasts. These oceanographic investigations are the result of many years of academic and government efforts to conduct research for a wide variety of purposes. For example, the last two major interdisciplinary projects off Oregon have been the Global Ocean Ecosystem Dynamics Northeast Pacific Program (GLOBEC-NEP) and the Coastal Ocean Advances in Shelf Transport (COAST). Consequently, the result of all the oceanographic investigations is a dispersed and incomplete collection of valuable oceanographic datasets, which makes them less accessible and difficult to use in the field of fisheries oceanography. To date, the most readily available spatially explicit oceanographic data set for the Washington and Oregon coasts is the National Oceanographic Data Center (Levitus) World Ocean Atlas 1998 data. This data set offers products such as annual, seasonal or monthly long-term means for temperature and salinity at multiple depths (Ocean Climate Laboratory, 1999). The Levitus data products are limited to a spatial resolution of either 1 or 5 degrees grid resolution (~ 80-110 km or ~ 400-550 km) and its temporal coverage covers only the period from 1900 to 1997. The Levitus data set is very valuable in terms of coverage and spatial and temporal resolution when used for global or basin-scale ocean studies. When used in local or regional scale studies, it misses many of the oceanographic details, such as the defined boundaries of the upwelling region, fronts, the upwelling jet and many other mesoscale oceanographic features. Therefore, this limitation in the data, at relevant scales for regional fisheries studies, makes it more difficult for marine researchers or fisheries scientists to form productive questions and test hypotheses concerning fish population associations with marine habitats. Thus, the assembling of datasets in this study creates an opportunity to improve fisheries research and consequently, to improve scientific input to fisheries management decisions.

The oceanographic parameters selected for this study were temperature, salinity, chlorophyll-a concentrations and ocean current velocity. These oceanographic variables were selected for their relevance to groundfish ecology, their potential as descriptors of ocean habitats for fish, and their potential use in fisheries science and management. The main sources of data used in this study were remotely sensed from satellites and high-frequency (HF) land-based coastal radars, and from in situ instruments, such as conductivity-temperature-depth (CTD), bottle samples, and data from an acoustic Doppler current profiler (ADCP). The satellite sensors provide sea-surface temperature and chlorophyll-a. The CTDs measure subsurface temperature and salinity. Fluorometers and discrete bottle samples provide subsurface chlorophyll-a concentrations. HF radars measure surface ocean current velocity and, finally, ADCPs measure subsurface current velocities.

The second objective in this study was to compute ocean data products relevant for regional fisheries studies in a useful format for scientists and managers. More research is needed in order to determine what combinations of oceanographic data are most useful for fisheries research (Quinn and Niebauer, 1995). Averages, medians, running averages, extremes, standard deviations, and robust smoothers are suggestions of how oceanographic data could be organized and compressed for comparisons with fisheries data (Quinn and Niebauer, 1995). Based on the spatial and temporal resolution and coverage of the oceanographic data assembled in this study, climatological monthly means, standard deviations and coefficients of variation were developed for each of the oceanographic variables. A coefficient of variation is computed by dividing the standard deviation by the mean. These ocean data products were computed at depths of 0, 50, 100, 500, 1000 m and near the bottom. The climatologies are formed from the earliest time available (depending on the variable and time of the year) to the year 2004. All the ocean data products have been gridded and organized in a GIS, so data are easily visualized and accessible to scientists, fisheries managers, policy makers, and others.

The last objective of this study was to develop an exploratory analysis to investigate if there are any distinct ocean habitats, using the ocean variables assembled in this study, associated with the distribution and abundances of groundfish species off the Washington and Oregon coasts. For the purpose of this study, ocean habitat refers to the water-column component of habitat, as in contrast to the seafloor component of habitat. To date, the use of seafloor habitat information based on lithologic substrates have been widely used to understand groundfish abundances and distributions (Nasby, 2000; Whitmire, 2003). However, there is a still a lack in the fundamental understanding of how water-column factors such as water temperatures and salinities, dynamic current structures and climate, affect fish abundances and distributions. The understanding of the factors regulating the abundance and distributions of groundfish populations is required to improve our ability to forecast fish population trends and fish distributions in changing ocean conditions (McFarlane et al., 2000).

Basic ecology states that the abundance of plants and organisms in a given place are regulated by the availability of their habitat. So, what is a habitat? What factors create habitat? Habitat is the place or the type of environment where a specific organism or a group of organisms lives. Habitats are the results of biotic and abiotic factors interacting with each other. Abiotic factors in the marine environment refer mainly to temperature, salinity, depth, tides, currents, light and substrate. Biotic factors refer mainly to competition and predation. Certainly, the specific combinations of each of these factors create and continuously influence places or habitats where a particular community of organisms lives. In addition, marine habitats are exposed to a dynamic ocean system, with variability on multiple temporal and spatial scales. This can have implications for the habitat and on the organisms that inhabit it. The fact that the ocean is a very dynamic system and that fish themselves move through the ocean and utilize different habitats through their life cycle makes defining of habitat for fish difficult.

Despite the complexity of defining and identifying fish habitats, there has been a major effort to identify fish habitats at all stages of their life cycle since the 1996 amendments to the Magnuson-Stevens Act were passed. Many studies undertaken on the west coast have shown clear associations between groundfish abundances and distributions and seafloor habitat characteristics (Hixon et al., 1991; Stein et al., 1992; Yoklavich et al., 2000). In addition, other studies have shown how groundfish species distributions are associated with depth and latitude gradients (Weinberg 1994; Williams and Ralston 2002; Tolimieri and Levin 2006). However, there have been minimal attempts to investigate if there are any significant associations between the oceanographic water-column processes and fish abundances and distributions. For example, there have been some attempts to incorporate environmental information in stock assessments.

Schirripa and Colbert (2006) investigate how changes in ocean conditions affect sablefish recruitment within the California Current System.

There are several reasons why there have been few attempts to investigate how water-column processes affect the ecology of groundfish. First, there has been limited availability of highly accurate physical data about the system at appropriate temporal and spatial scales off Oregon and Washington coasts. Consequently, most of the studies rely on the few and discontinuous sets of environmental data that are available, leading to very limited success (Sharp, 2000). Second, if the data exist, it is hard get access to it because it is usually stored by different institutions and sometimes its existence is not widely known. Thirdly, even the fisheries-independent data itself on relative abundances and life history characteristics for many species have also been limited to the summer months and has been collected discontinuously over time. Finally, scientists over time have been faced with the difficulties of working with a dynamic, complex system such as is the ocean and understanding how fish populations respond to its variability. This has made such studies extremely complex since the ocean environment is highly variable across a range of spatio-temporal scales. The scales of the physical processes relevant to fishes ranges from turbulence conditions, which can affect interactions between individual larvae and their prey (occurs over centimeters and seconds), to physical processes that affect basin-scale ocean productivity (occur over 1000 km over 10s of years) (Sharp, 2000).

Regardless of the knowledge that the ocean is a very dynamic system, most of the fisheries science field has necessarily evolved under the assumption that marine ecosystems are in a steady state (Harrison and Parsons, 2000). This basic assumption implies that fish populations are not affected by climatic-oceanic changes. However, over the past several decades, there has been a clear recognition of the need to incorporate knowledge of the ocean as a dynamic system. Marine ecosystems have experienced major fluctuations in productivity in response to periodic perturbation in the oceanic-atmospheric system, and therefore it is not possible to keep ignoring that ocean dynamics are an essential component to understanding and managing fish populations.

In the Pacific Ocean, a decadal time-scale forcing in the ocean-atmospheric system has been identified, known as the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997). The PDO index reflects how the North Pacific ocean has been experiencing large scale changes in wind patterns and ocean temperatures, which are persistent over 10-30 year periods. Each multi-decadal period has been called a regime and the shift from one period to the other, a regime shift. The regimes identified with the PDO index are the 1927-1946, 1947-1976 and 1977-1998 (Minobe, 1997; Mantua et al., 1997; Francis and Hare, 1994; and Beamish et al., 1999). However, in 1998-1999 there was an apparent shift into a new atmospheric-oceanic state which has not been captured by the PDO index. This new oceanic-atmospheric pattern has been identified as the Victorian Pattern, named after the place where its significance was first identified (Bond et al., 2003). On a basin-wide scale, the North Pacific ocean from 1999-2002, in terms of sea level pressure and sea surface temperature, did not resemble either the period before or after the 1976/77 regime shift (Bond et al., 2003). Locally, the 1998/1999 shift has had a strong effect in the California Current System producing wind patterns and consequently oceanographic conditions similar to those observed before the 1976/1977 regime shift (Bond et al., 2003). Therefore, the Victoria pattern has generated a locally “cold” regime in the California Current System, which is thought to have been created by a pulse of subarctic water into the California current, creating cooler conditions in 2002 (Rodionov et al., 2004).

There are many studies documenting how the physical and biological dynamics of the Eastern Pacific are sensitive to decadal scale climate variability from local to basin-wide scales (Baumgartner et al., 1992; Francis and Sibley, 1991; Kawasaki and Omori 1988; Hollowed and Wooster, 1995). One of the most remarkable examples of basin-wide scale responses in marine ecosystems is revealed by Kawasaki and Omori (1988), who shows synchronization in the abundance patterns in the three separate sardine stocks off Japan, Chile and California. Sardine populations at each of these locations increased and decreased about the same time. These synchronous changes all over the Pacific suggest that sardine populations are subject to a commonality, the ocean environment. At the present time, Pacific sardines stock assessments on the west coast use an environmental index (i.e., a time series of sea-surface temperature recorded at Scripps Pier, La Jolla, California) to set harvest levels (Pacific Fishery Management Council, 2005). The sardine example and many other examples described in Hollowed and Wooster (1992) and McFarlane et al., (2000), show that the environment or the ocean habitat where fish live is a dynamic system and that it can influence marine fish by altering physical processes such as advection, upwelling and turbulence and biological processes such as food production, predations and rates of starvations.

As detailed in the example above, most examples in the literature focus more on pelagic organisms such as plankton and, in the case of fish, sardines and anchovies. However, it is important to explore how the ocean environment affects groundfish species which can be either strictly benthic or bentho-pelagic. Groundfish are long-lived species (some species can live over 100 years old) that probably have evolved to survive low production ocean regimes and to take advantage of high-production ocean regimes (McFarlane et al., 2000). McFarlane et al., (2000) showed how both short-lived and long-lived species respond to natural variability in the North Pacific. A recent study by Schirripa and Colbert (2006) demonstrated that physical oceanographic variables such as Ekman transport and sea level during key times and at key locations within the sablefish habitat have significant effects on juvenile sablefish recruitment. McFarlane et al., (2000) also suggested that the link between climatic-regime variation and fish is "coded" in the responses of the biology and dynamics of individual species and concluded that in order to improve our prediction of fish population trends and fish distributions in a dynamic ocean; it is crucial to improve our understanding of habitat preferences and needs for each species of fish. In addition, human fishing activities are adding more stress to the fish populations, reducing their ability to cope with a dynamic ocean-climate system. For these reasons, it is important to understand the natural ocean-climate variability in addition to the effects of fishing on fish populations and how they interact together.

As shown in the above examples, it is a big challenge to construct a proper study to understand how the ocean dynamics affect fish distributions at multiple spatial-temporal scales. However, the need to understand the linkage between specific ocean habitats and individual fish species distributions in a dynamic environment are still critical. Therefore, the last objective of this study proposes an exploratory analysis to (1) examine spatial distributions and abundances of groundfish distribution for the year 2004; (2)

identify ocean habitats using the ocean data collected in this study; and (3) investigate if any of the ocean habitats are associated with a specific groundfish species or group of groundfish species and distributions. Once we understand the needs and ocean habitat preferences of individual species, then we can focus more on how changing ocean conditions affect fish populations over space and time, eventually leading to more clarity in fish population trends.

Future studies should seek to link individual fish species distribution with ocean habitats in a dynamic environment as data become available. Therefore, this last objective will concentrate on our ability to define ocean habitats with the ocean data products collected and computed in this study and to measure what oceanographic variables are important and necessary to define and delineate ocean habitats. Furthermore, this last objective will attempt to identify specific groundfish species or species assemblages associated with particular ocean habitats.

The development of the exploratory analysis uses a combination of classification and ordination statistical techniques. The first part of the analysis consisted of a clustering analysis and a principal components analysis on the oceanographic data to define ocean habitats along the Washington and Oregon coasts. This analysis used climatological seasonal means and coefficients of variations of temperature, salinity and chlorophyll-a at different depths. Current velocity and subsurface chlorophyll-a concentrations were not included in the analysis because they lacked sufficient spatial coverage along the Washington and Oregon coasts. The second part of the analysis consisted of several statistical analyses of the combined ocean and fish data. First, a multi-response permutation procedure (MRPP) was used to test if the ocean habitats differ in species composition. Second, a univariate method called indicator species analysis (ISA) was used to determine indicator species for each ocean habitat. Finally, two different ordination methods were used to explore in more detail if groundfish distributions were associated with any of the ocean habitats. The first ordination method used in the analysis was an unconstrained ordination method called non-metric multidimensional scaling (NMDS). The second ordination method used was a constrained ordination method called canonical analysis of principal coordinates (CAP).

2 GENERAL BACKGROUND OF OCEANOGRAPHIC PROCESSES OFF THE WASHINGTON AND OREGON COAST

In the last 50 years, the circulation of the coastal waters off Oregon and Washington has been studied extensively. Nonetheless, most of the studies have concentrated on the summer upwelling season off the Oregon coast. The investigations reveal how the physical-biological system in the coastal waters off Oregon and Washington is driven by a variety of mechanisms acting on several temporal and spatial scales. Its physical variability can vary on time scales of day, weeks, seasons, years and decades (Huyer, 1983; Huyer *et al.,* 2002; Smith *et al.,* 2001). The spatial variability is mainly influenced on a local basis by topography such as submarine canyons and banks, headlands and capes, local wind forcing and local river inputs. This summary is a broad overview of the characteristic oceanographic processes acting on multiple spatial and temporal scales off the Oregon and Washington coasts, starting with day to weekly processes to multi-decadal scale processes and ranging from a few km to basin-wide processes.

The coastal circulation off Oregon and Washington coasts is part of the California Current System (CCS). The CCS forms the eastern section of the clockwise North Pacific Gyre, extending along the west coast of North America from British Columbia, Canada to Baja California, Mexico, and extending 1000 km offshore. The CCS is one of the major coastal upwelling regions in the world. Major upwelling regions occur at the eastern boundaries of the oceans supporting a major portion of the world's fisheries (Pauly and Christensen, 1995).

The study region covers the northern CCS from the Strait of Juan de Fuca in northern Washington (49^{o}N) to northern California (41^{o}N) and extends from the coastline to 127^{o}

west (Figure 2.1). The coastline runs from north-to south roughly as a straight line with the exception of Cape Blanco (42.8^{o}N), which protrudes offshore. The Washington coast is characterized by a wide continental shelf and the isobaths generally follow the coastline except for major submarine canyons, the most important being the Juan de Fuca canyon, 48.7^{o}N and the Astoria canyon, 46.2^{o}N. The Oregon coast has a narrower continental shelf. The isobaths follow also the coastline with the exception of some submarine banks off central Oregon (Heceta Bank, 43.75 - 44.75^{o}) and near Cape Blanco (Coquille Bank, 43^{o}N).

Local topographic features are an important factor influencing the coastal circulation. Heceta Bank, together with Cape Blanco are the major geological structures influencing the circulation in the northern CCS (Barth *et al.,* 2000a; Castelao and Barth, 2005). In addition, local winds and runoff are also major drivers of the surface circulation over the continental shelf off Oregon and Washington (Smith, *et al.,* 2001). The most important sources of freshwater runoff are the Strait of Juan de Fuca between Canada and the U.S. border (48.5^{o}N) and the Columbia River (46^{o}N), which is located at the border between Washington and Oregon.

The Columbia River creates a year-round river plume that produces the lowest salinities along the coast. In winter, the Columbia River plume is located off the Washington coast because winter currents are predominantly northward and move towards the shore due to the downwelling conditions. Therefore, in winter the Columbia River has more influence near the coast. In summer, the currents mainly flow southward and there is an offshore surface transport due to upwelling conditions. Therefore, the Columbia River plume lies southward and offshore of the Oregon coast.

Other interesting spatial structures found in the coastal waters of Oregon and Washington are fronts. Fronts are areas in the ocean where horizontal gradients of various measurable parameters change very rapidly, sometimes over only a few kilometers. Fronts define boundaries between different ocean water masses which have different ocean properties such us temperature and salinity, among others. They are important geographically because they are regions with high biological activity. In summer, there are two main fronts present along the coast. One is the boundary of the upwelling region front, which is associated with a southward surface flow; and the other is located on the boundary of the Columbia River plume (Castelao *et al.,* 2005).

Finally, the last spatial structure within the coastal waters is the seasonal stratification of the water-column. During winter, the general structure of the vertical stratification off Oregon and Washington is a surface mixed layer, caused mainly by wind mixing overlying a stratified lower water-column, except when winter storms occasionally mix the entire water-column to midshelf depths (~100 m). In contrast, in summer, the mixed layer depth is very shallow; the pycnocline starts at 10 or 20 m and the stratification is very strong. In addition, the summer is characterized by isopycnals sloping upwards towards shore, making water over the inner shelf denser due to cold and saltier water upwelled from the deep. In contrast, the winter is characterized by isopycnals sloping downward towards shore.

The next section includes a general overview of the oceanographic processes occurring off Oregon and Washington under different temporal scales. Starting on time scales from days to weeks, the physical processes are mainly driven by wind processes. Every 2-10 days a new weather system arrives at the Washington and Oregon coasts.

This has been called the "weather band." The weather band can interrupt upwelling favorable winds (equatoward winds) and consequently create relaxation periods within the summer upwelling season. During the relaxation period, the offshore surface Ekman transport is interrupted and can be reversed to onshore transport by downwelling favorable winds. In addition, during relaxation periods, the alongshore flow near the bottom and close to the shore can change direction and flow northward (Barth *et al.,* 2005b). Recently, Bane et al. (2005) showed the importance of 20-day intraseasonal oscillation to temporal variability of temperature over the central Oregon shelf.

Seasonal variability is the next important temporal scale of the CCS and has been extensively studied. There are seasonal cycles in the surface heating and cooling, precipitation and evaporation, winds and large-scale processes in the north Pacific (Huyer and Smith, 1978). However, the principal process causing the seasonal changes in ocean circulation in the CCS is wind stress (Huyer, 1983; Barth *et al.,* 2000). The wind stress along the coast is predominantly equatorward in summer and poleward in winter. This seasonal variability in the wind stress is controlled by the North Pacific high-pressure system and the low-pressure system over the North America continent, which change position and vary in strength seasonally.

In spring and summer, persistent equatorward winds establish strong upwelling along the coast. Generally, the upwelling season is set by the spring transition, which occurs generally around April-May (Huyer, 1983). The upwelling is the response of the ocean to the wind stress. Equatorward winds lead to surface offshore Ekman transport (Huyer and Smith, 1978) due to the Coriolis effect. Consequently, an onshore flow compensating the offshore flow results in upwelling of cold, saline and nutrient-rich waters near the coast. The upwelled waters originate from depths of 100-200 m (Barber and Smith, 1981; Barth *et al.,* 2000). At the same time, an upwelling front is created separating the colder, saline, nutrient rich upwelled waters nearshore from the warm, less saline, nutrient-poor waters offshore. The pressure gradients created across the front are balanced by the Coriolis force resulting in the formation of a strong alongshore equatoward coastal jet over the continental shelf (Huyer, 1983), which is reported to be in geostrophic balance. The coastal jet extends from the surface down to 50-75 m, with speeds up to 0.5 m s^{-1} near the surface and decreases with depth (Barth *et al.,* 2000).

Early in the upwelling season, wind-driven upwelling is confined to inshore of the continental shelf and the coastal jet flows along the shelf break near the coast (about 20-30 km offshore, over the shelf), especially in areas of simple bathymetry (north of cape Blanco) (Huyer et. 1974; Huyer *et al.,* 1983; Castelao and Barth, 2005; Huyer *et al.,* in press).

At the end of summer, the upwelling season is fully developed and the jet reaches strong velocities causing it to meander offshore bordering the Heceta Bank region and Cape Blanco. At the time when the jet crosses the steep topography, it becomes an oceanic jet (Barth *et al.,* 2000) and develops high mesoscale activity, forming meanders and eddies which can protrude up to 100 km offshore and can last over 2.5 months (Barth *et al.,* 2000; Strub and James 2002; Barth *et al.,* 2005b). The development of the high mesoscale activity around the Heceta Bank and Cape Blanco regions is likely the result of the interaction between the jet and the local topography (Barth *et al.,* 2005a; Castelao and Barth, 2005; Barth *et al.,* 2005b). The deflection of the coastal jet near the Heceta Bank and around Cape Blanco has been identified as a key mechanism by which materials and organisms are transported far from the coast (Barth *et al.,* 2005a; Castelao and Barth, 2005). In contrast, the inshore area of the Heceta Bank becomes a "lee" area as the upwelling jet flows around the bank. The lee area is characterized with low velocities and a cyclonic circulation or retentive circulation (Castelao and Barth, 2005; Barth *et al.,* 2005b; Kosro, 2005).

In addition, during the summer upwelling season, the introduction of nutrients into the surface waters by coastal upwelling and the increase in solar radiation makes the CCS a very productive system. The complex circulation with its inherent mesoscale activity found near particular topographic features creates heterogeneous distributions of chlorophyll-a and plankton. For example, the complex circulation found around Heceta Bank has profound effect on the biology, making this region one of the most productive area off the Oregon coast (Pearcy *et al.,* 1989). The Heceta Bank region has been identified as a biological hotspot that persists in space and time with the peculiarity that its habitat characteristics (its biological and physical features) and the nekton community vary over time (Reese and Brodeur, in press). In addition, the region off the Strait of Juan de Fuca has been identified as a highly productive area, a highly productive foraging ground for birds, fish and whales, and an important commercially fishing ground (Healy *et al.,* 1990). Interestingly, during the summer months a large anti-clockwise (cyclonic) eddy develops over the Juan de Fuca Canyon at the mouth of the Strait. The eddy is responsible for upwelling of deep, nutrient-rich water into the surface (Freeland and Denman, 1982).

Lastly, during the summer upwelling season, a poleward undercurrent also develops near the bottom of the seafloor (Huyer and Smith 1978; Burt and Wyatt 1964). This is the result of the main equatorward surface flow piling up water at the equator, and creating a pressure gradient. This pressure gradient results in a poleward flow, located just beneath the California Current. This undercurrent is characterized by warm, high-salinity and low-oxygen waters, and it has an overall mean speed of 0.10 m s^{-1}, a core depth rage of 100-300 m and is found 20-25 km off the shelf break (Pierce *et al.,* 2000).

In late fall and winter seasons, winter downwelling conditions are established in the northern CCS, another characteristic of eastern boundary currents. The fall transition occurs generally in October-November. During this time of year, winds over the northern CCS become northward on average and the equatoward flow over the shelf ceases. This occurs when the Pacific High pressure system, weakens and migrates westward and the Aleution Low pressure system gains strength over the Gulf of Alaska. The response of the ocean to poleward winds consists of a onshore surface Ekman transport, resulting in convergence and downwelling of warmer, fresher and nutrient-depleted waters near the coast (Huyer, 1977). Consequently, sea-surface temperatures and sea level along the coast rises. In addition, the California Undercurrent appears as a surface current. This poleward nearshore surface current is called the Davidson Current. During downwelling conditions, the winds become more variable than during the summer upwelling conditions, since storms are periodically transiting the CCS, reversing the wind direction continuously.

The following section summarizes the larger-scale climatic phenomena influencing the CCS. The first one is the El Niño Southern Oscillation (ENSO) cycle and the second is the Pacific Decadal Oscillation (PDO) (Mantua *et al.,* 1997). These large-scale fluctuations dominate basin-wide inter-annual and inter-decadal variability in the ocean-atmospheric system and are superimposed on top of the seasonal cycles in the CCS. Both of these phenomena influence the circulation off the Washington and Oregon coasts. The time scale of ENSO variability is 2-7 years. Its primary signatures are more visible at the equator and it has well-known global impacts. In contrast, the time scale of the PDO is 10-20 years. Its signal is strongest in the North Pacific and decreases towards the equator and its physical impact is concentrated in the North Pacific basin. Global impacts are, as yet, less certain.

The ENSO cycle, being the most important source of inter-annual variability in the CCS (Strub and James, 2002), has been extensively documented and its widespread ecological effects on ocean ecosystem have been widely recognized. Recently, progress has been made on predicting the occurrence and intensity of Los Niños with several months lead time (Cane, 2004). However, since each ENSO cycle is different, it is hard to foresee accurately its effects on the atmospheric and oceanic system and consequently its effect on the ecosystem.

The ENSO cycle originates in the equatorward Pacific and has two phases: a warm (El Niño) phase and a cool (La Niña) phase. These phases persist all the time in the ocean-atmospheric system, increasing and decreasing their intensity continuously. Therefore, there are not persistent neutral conditions observed in the ocean (Smith *et al.,* 2001). Ocean conditions are continuously altered either by El Niño or La Niña.

El Niño can transmit its effects to the CCS in two ways, and these distinct mechanisms likely have different biological impacts. The first mechanism is via coastal-trapped waves as they propagate northward along the west coast of North America. Coastal-trapped waves, one form of which are Kelvin waves, originate in the tropical

Pacific, and as they propagate, they displace the thermocline reducing the strength of coastal upwelling on the eastern side of the Pacific. They also are associated with an increased poleward flow. The second mechanism is via atmospheric teleconnections, which produce strong surface signals and anomalous metereological conditions in the north Pacific (Huyer *et al.,* 2002). The advection of warm oceanic waters into the Oregon coast has been documented as the result of atmospheric forcing (Pearcy *et al.,* 2002).

Since the intensity of Los Niños and Las Niñas are different each time. Only the strongest Los Niños impacting the west coast of North America (1957-1958, 1982-1983 and 1997-1998) extended to the British Columbia coast and had a huge effect on the physical properties of the water-columns and the biology along the California Current (Lea and Rosenblatt, 2000; Pearcy, 2002; Huyer *et al.,* 2002; Smith *et al.,* 2001 and papers therein).

During El Niño years, the expected scenario off the Oregon and Washington coasts is an enhanced poleward warm, high-salinity flow and enhancement of poleward winds. This results in an increase in sea level, an increase in water temperatures, a decrease in pycnocline depth, and consequently, a decrease in upwelling intensity. The reduced upwelling inhibits the transport of nutrients from the deep, and consequently the waters become nutrient limited, leading to a decrease in primary and secondary production. Large-scale migrations and advections of organisms from higher tropic levels from their habitats occur as a consequence of the hydrographic anomalies produced by El Niño. As stated before, each El Niño is different in terms of timing, intensity and effects. Therefore, the scenario changes slightly for each of the El Niño years and consequently individual El Niño events impact populations of organisms and ecosystem components in different ways.

The 1997-98 El Niño has been the most documented off Oregon. Huyer *et al.,* 2002 compared the hydrographic conditions off Oregon during El Niño 1997-98 to El Niño 1983 and to normal averaged conditions. They claim the 1997-98 El Niño was stronger than the 1983 El Niño and suggested that the warming was due to the propagation of coastal trapped-waves, which strongly increased the northward flow and depressed the isotherms. Corwith and Wheeler (2002) showed how reductions in upwelling conditions caused nitrate to be the primary limiting nutrient in phytoplankton production and this led to decreased chlorophyll-a concentrations in 1997-1998. In addition, Peterson and Keister (2002a) documented a decrease in zooplankton biomass off Oregon, and Peterson *et al.,* (2002b) showed a shifting in zooplankton species composition from subartic to subtropical species off Oregon. Finally, Pearcy el *al.,* (2002) reported the invasion of warm water nekton species off Oregon during the summer of 1997. There were no studies of the 1997-1998 event off the Washington coast. However, the effects of El Niño during 1997-1998 were reported off British Columbia, Canada, and the Gulf of Alaska suggesting similar responses to those on Oregon (Mackas *et al.,* 2002).

Typically, El Niño is followed immediately by La Niña. La Niña has less dramatic effects on the circulation off Washington and Oregon and it generates less biological impacts than El Niño. Smith *et al.,* (2001) showed how El Niño has a bigger effect in the salinity and temperature fields off Oregon than during La Niña events. In addition, individual La Niña signals are less spatially variable in the CCS. For these reasons, La Niña's effects are not as well documented in the CCS as are El Niño effects.

The next climatic phenomena influencing the CCS, which is superimposed on the ENSO events, has been named the Pacific Decadal Oscillation (PDO) (Mantua *et al.,* 1997). The PDO is an index constructed from observations of sea surface temperature and sea level patterns in the North Pacific. Within the PDO index, two phases or regime periods have been identified: a cool (negative phase/regime period) and a warm (positive phase/regime period). The cool phase is characterized by cooler than averaged sea surface temperatures along the west coast of the North American continent and an overall warming in the central Pacific. A warm phase is characterized by warmer than average sea surface temperature along the west coast of the North American continent and an overall cooling in the central Subartic Pacific. These PDO positive and negative phases mainly identify an east-west pattern across the North Pacific Ocean. During the 20th century, the PDO index has well represented the North Pacific climate variability on multidecadal scales; although since 1999 it has been hypothesized that the Pacific climate might be experiencing other type of spatial patterns that are not reflected in the PDO (Bond *et al.,* 2003).

The term “regime” period was originated by studies addressing inter-decadal variability. These studies revealed spatial patterns in the ocean and atmosphere of the North Pacific that remained steady for ten or more years (Minobe, 1997; Mantua *et al.,* 1997). A given spatial pattern changes to the other spatial pattern every few tens of years. Each spatial pattern that remains steady for a period of several sequential years is called a regime and the rapid change or shifts in periods are called “regime shifts”.

Several independent studies have identified several warm and cold phases in the past century (e.g. Mantua *et al.,* 1997, Minobe, 1997). It is well recognized that cool phase regimes have dominated from 1900 to 1924 and from 1947 to 1976, and that warm phase regimes have prevailed from 1925 to 1946 and from 1976 into 1998. Recently, several authors suggested a reversal to a PDO cool phase regime conditions in 1998/1999 (Peterson and Schwing, 2003; Chavez *et al.,* 2003). These authors reported major changes after 1998 in the oceanography and biology in the CCS. For example, in the northern California Current zooplankton biomass doubled and switched from warm-water to cold-water species dominance. Chinook and coho salmon stocks rebounded and anchovy abundance increased (Peterson and Schwing, 2003). However, Bond *et al.,* 2003 presented an alternative hypothesis claiming that the North Pacific did not shift into a new PDO cold regime phase. Instead, they suggested a new north-south spatial pattern is emerging in the North Pacific, which has been called the Victoria pattern. The Victoria pattern also has a regime-like character since it was steadily negative from 1989 to 1998. Then it shifted very strongly to a positive phase between 1998-1999. This shift had a strong effect on the CCS. It produced wind patterns similar to those observed during the cold regime PDO phase (1947-1976), creating cooler sea surface temperatures in the CCS, similar to a "cold" regime period.

There is a lack of knowledge of what causes the steady spatial patterns of the PDO and what mechanisms produces the shifts in the PDO oscillations, even less is known about the Victoria pattern. Therefore, it is not possible to predict PDO shifts and its consequences on the ecosystem. However, there are ecosystem and climatic observations as well as paleo-records suggesting that the regime shifts are natural phenomena in the north Pacific climate, in the ocean system and in the marine ecosystems (Baumgartner *et al.,* 1992). It has been also suggested that the magnitude of ENSO cycles is strongly dependent on the phase of the PDO in the North Pacific. This depends in what regime period the events are developing. Las Niñas are stronger during the cool phase of the PDO and Los Niños are stronger during the warm phases of the PDO (Gershunov and Barnett, 1999; McGabe and Dettinger, 1999).

There is significant evidence showing how both phases of the PDO index and the rapid regime shifts have had an effect on the physics and biology of the CCS and in the North Pacific marine ecosystems. The warm or positive phase of the PDO is associated with an intensification of the Aleutian Low pressure cell and a warming of the surface waters along the west coast of the U.S. Thus, in the CCS, a warm phase implies warmer surface waters, which deepen the thermocline. Consequently, the CCS experiences a shoaling of the mixed layer depth, which reduces the rate of supply of plant and nutrients to the surface (Roemmich and McGowan, 1995(a)). This results in a reduction in the productivity off the west coast of the U.S. Hare et *al.* (1999) show how salmon production off the west coast of the *U.S.* weakens during a warm PDO phase and conversely, how a cool PDO phase favors high salmon production. Roemmich and McGowan (1995 a,b) spatially averaged measurements of zooplankton in the CCS and showed that zooplankton declined by over 70% between the 1987 and 1993. Fisheries' data showed how pelagic catch decline accelerated after the 1976-1977 regime shift (McGowan *et al.,* 1998). In addition, McGowan *et al.,* (1998) described how most of the sectors of the ecosystem in the CCS responded to the climatic regime shifts from southern species moving to northern latitudes, a general decrease in the secondary productivity, and fish landings and major declines in seabirds along the CCS.

In contrast, cold regimes had been accompanied with enhanced coastal ocean biological productivity in the CCS. During cold regime periods a strong North Pacific High develops, leading to strong anticyclonic winds (southward winds) and consequently to strong coastal upwelling in the CCS. This has resulted in a doubling in the zooplankton biomass and a shift from warm to cold species in the California current (Peterson and Schwing, 2003). Chavez *et al.,* (2003) also detected that phytoplankton have doubled off central Oregon and Mackas *et al.,* (2001) and Mackas *et al.,* (2003) detected an increase in biomass in cold species of copepods off British Columbia. Chinook salmon in 1999 have also reached levels not seen since 1950's and coho salmon survival rate has increased considerably so that the population has begun to rebound (Peterson and Schwing, 2003).

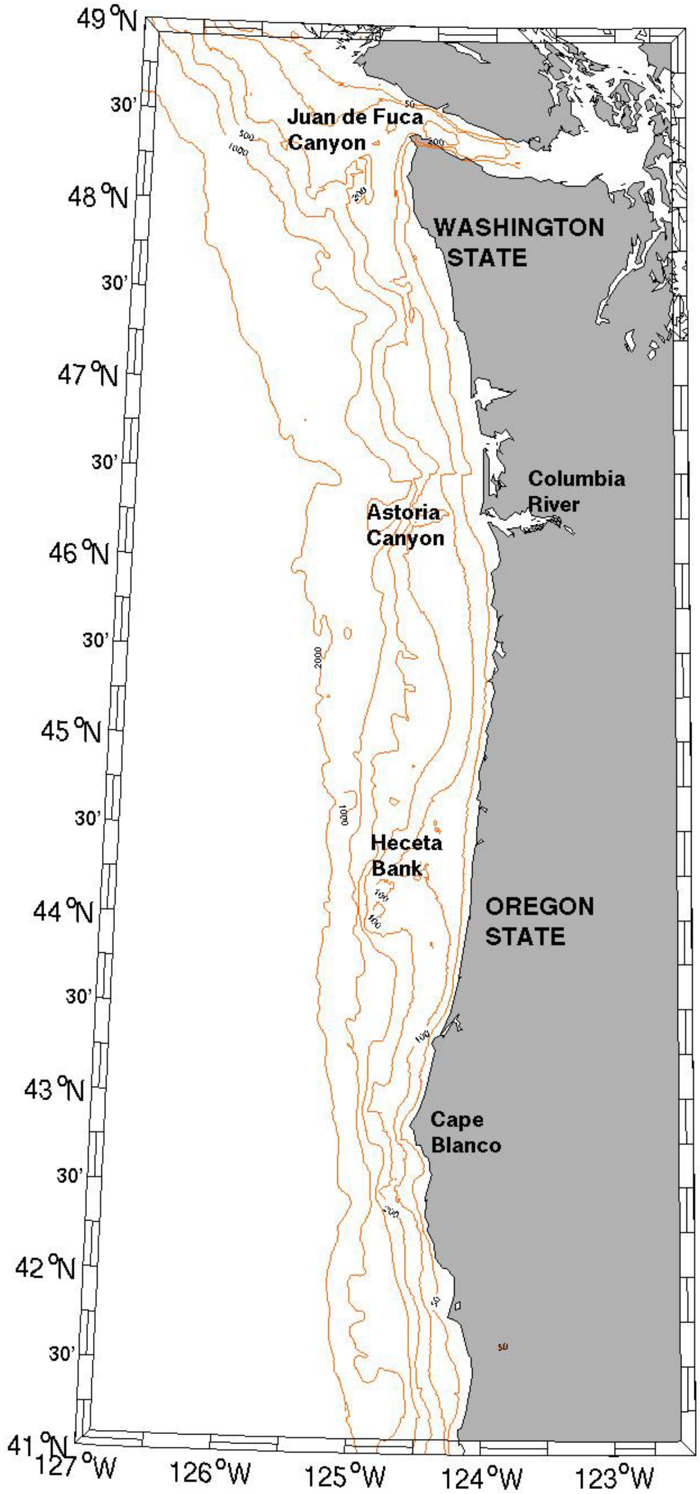


Figure 2-1 Study area. Orange contour lines delineate bathymetry at 50, 100, 200, 500, 1000 and 2000 m depth. Map shows the general locations of Juan de Fuca Canyon, Astoria Canyon and Heceta Bank.

3 METHODOLOGY

3.1 Oceanographic Data

The oceanographic parameters selected for this study were temperature, salinity, chlorophyll-a concentrations and ocean current velocity. These oceanographic variables were selected for their relevance to groundfish ecology, their potential as descriptors of ocean habitats for fish and their potential use in fisheries science and management.

Oceanographic variables can be used to identify ocean habitats. Temperature and salinity distributions depict horizontal gradients associated with subsurface processes, air-sea interactions and river inputs. For example, thermal fronts and upwelling regions, among other physical structures, can be readily identified in temperature and salinity fields. In addition, there are many physiological studies documenting how temperature and salinity can directly and indirectly affect fish and fisheries (Cushing, 1975 and 1982; Francis, 1990). Fish are able to perceive temperature changes of less than 0.1^{o}C (Bull, 1952) and have specific temperature tolerances and preferences (Leavastu and Hayes 1981). Some species of fish might tolerate huge changes in temperature and salinity, while others might tolerate only small ranges in environmental variables. Temperature changes may directly affect fish distribution, feeding, growth, reproduction, biological rates and hatching of eggs as well as fish survival in general. Changes in temperature may also indirectly affect fish food sources, as well as predator abundance.

Salinity can have an influence on the metabolism, behavior and migration of fish. There are two ways salinity can have an effect on fish. First, saltwater fish intake water or "drink" and therefore they have inbuilt mechanisms to maintain their body salts at a constant level, which differ from the outside water. Second, salinity affects fish flotation;

saltier water being more dense and therefore has more lift than freshwater. In the ocean, abrupt salinity changes are found offshore of river mouths and estuaries. These differences between seawater (3.5 % by weight) and fresh water (0% by weight) can be enormous. Salinity also changes quickly across upwelling regions and across different water masses. Each fish may have different tolerance levels to make these transitions and different levels of adaptation to become accustomed to the natural changing ocean conditions.

Chlorophyll-a concentrations can also be used as a habitat descriptor since it is a good indicator of primary production, which is then available as food to subsequent higher trophic levels, including fish. Finally, ocean currents either produced by wind, buoyancy input, tides or large-scale circulation, may also play an important factor creating habitats. Ocean currents transport food, nutrients and oxygen, making some areas more productive and habitable than others. Strong to moderate wind and subsequent surface ocean currents deepen the mixed layer, bringing nutrients from the deep ocean up to the surface, enhancing primary and secondary production, and eventually enriching the food web creating productive habitats. Fish in these habitats will tend to suffer less from starvation (Lasker, 1975). In addition, strong to moderate ocean currents can enhance the counter rate of passively drifting larvae and their food (Rothschild and Osborne, 1998), also reducing starvation. On the other side, weak currents may facilitate their swimming, thus reducing energy costs to maintain location in their preferred habitats.

3.1.1 *Data Sources*

The oceanographic data were derived from a variety of sources including remotely sensed data from satellite sensors and HF land-based coastal radars, and in-situ measurements from CTD instruments, Niskin bottles, chlorophyll-a fluorometers and shipboard ADCPs. The satellite sensors measure sea surface temperature and surface chlorophyll-a concentrations. The CTDs, Niskin bottles and fluorometers measure subsurface temperature, salinity and chlorophyll-a concentrantions. The HF radars measure surface ocean velocity, and ADCPs measure subsurface current velocities.

3.1.2 *Remotely Sensed Data*

The remotely sensed data were comprised of satellite measurements of sea surface temperature and chlorophyll-a concentrations, and land-based HF radar measurements of surface current velocity. The source of the sea surface temperature (SST) satellite images was the Advanced Very High Resolution Radiometer (AVHRR). Individual images have 1-km spatial resolution and thermal resolution of 0.1°C. Roberto Venegas (Oregon State University) provided 8-day composites of SST off the Oregon and Washington coasts from September 1997 to August, 2003. These composites were the result of taking the warmest pixel from any image during an 8-day period, which created the composite images. The spatial extent of the images was 41 - 48.5^{o}N and 127-124.8^{o}W. These composites were used to create monthly means from September 1997 to August 2003. The method used to create the monthly means using the composites was that if all the days within the composite belonged to a unique month, then the composite was assigned to that particular month. However, if the composite contained days from two consecutive months, the composite was assigned to the month that contained the most number of days within the composite. Once all the composites were assigned to a month, a simple mean was calculated for each month.

The source of the chlorophyll-a satellite images was the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) onboard the SeaStar spacecraft. Dr. Andrew Thomas (University of Maine) provided monthly composites of surface chlorophyll-a concentrations for the Northeast Pacific from September, 1997 to August, 2003. The original spatial extent of the images was 20-55^{o}N and 135-105^{o}W with a spatial resolution of 4 kilometers. The images were in a hierarchical data format (HDF) and were stored as grids with an equidistant cylindrical projection. The concentrations were reported in milligrams per cubic meter. All the monthly satellite images were clipped to the geographical extent of the study area.

Surface current data were obtained from an array of five SeaSonde HF coastal radars located on the central Oregon coast, between 44.1 and 45.1^{o}N (Kosro, 2005). These are the only coastal radars located along the Washington and Oregon Coasts. The radars cover a 100 km alongshore and up to 40km cross-shelf region of relatively complex topography due to the presence of Stonewall Bank and Heceta Bank (Figure 2.1). The coastal radars provide surface currents every 1 hour, 2-km resolution in range and 5 degrees in azimuth (Kosro, 2005). Dr. Mike Kosro (Oregon State University) provided monthly means surface currents from April 2002 to March 2003. The data covered a year-long cycle of surface currents for the central Oregon coast. The geographic extent of the data is approximately 44.1 to 45.1^{o}N and 124.6^{o}W to the Oregon coast.

3.1.3 *In Situ Data*

The in situ instruments used in this study were CTDs, Niskin bottle samples, chlorophyll-a fluorometers and shipboard ADCPs. These state-of-the-art instruments provide three-dimensional fields of temperature, salinity, density, velocity and chlorophyll-a off the Oregon and Washington coasts.

3.1.3.1 *CTD and Bottle Samples*

The main source of CTD casts and water samples was the National Oceanographic Data Center (NODC). The NODC provides access to worldwide oceanographic data and products, and allows easy access to the World Ocean Atlas/Database. This database offers a "WODselect interface" with a retrieval system, which allows public users to search and retrieve oceanographic data from the World Ocean Database 2001 (WOD01). The oceanographic data was retrieved from this interface by selecting instrument types, dates, geographic coordinates and measured variables. For more information, see www.nodc.noaa.gov.

The data retrieved for this study came from two types of instruments defined by the WOD01 database: the Ocean Station Data (OSD) instrument, and the high-resolution CTD data instrument. The OSD instrument contains bottle data, low-resolution CTDs and biological tows. The second type of instrument is the high-resolution CTD and, as it implies, gives high-resolution CTD data. The oceanographic variables extracted from both types of instruments consisted of temperature, salinity and chlorophyll-a. The query included all the data available from 1930 to 2004, and the geographic extent desired was 41 to 49^{o}N and 127 to 123.8^{o}W, which covered the entire Oregon and Washington coasts.

The NODC was an excellent source of quality oceanographic data. However, there is a time lag between the day the oceanographic cruises occur and the day the data is submitted to the NODC. There was no data submitted to the NODC for the Oregon and Washington coasts after the year 1999. However, oceanographic datasets were available from two major OSU oceanographic programs and therefore they were added into the main oceanographic data set. Since 1999, Oregon State University has carried out two major oceanographic research programs off the Oregon coast collecting very valuable oceanographic data with state-of-the-art instruments. One program is the Global Ocean Ecosystems Dynamics Northeast Pacific (GLOBEC-NEP) program and the other is the Coastal Ocean Advances in Shelf Transport (COAST) program. These programs used an array of state-of-the art instruments, such as CTDs and fluorometers mounted on rosette and a CTD carried by a towed underwater vehicle to measure temperature, salinity and other variables of the water-column. All the CTD casts and all the water samples taken with Niskin bottles mounted on a rosette deployed by these programs were utilized in this study and combined with the CTDs obtained from the NODC database.

In addition, this study also included the CTD casts deployed by the NOAA Northwest Fisheries Science Center in the 2003 Integrated Acoustic and Trawl survey of Pacific hake, in the U.S. and Canadian Waters off the Pacific Northwest coast. Unfortunately, the 2001 Integrated Acoustic and Trawl survey of Pacific hake was not added to the database due to difficulties in data accessibility. Lastly, Dr. Bill Peterson (NOAA NWFS and OSU) provided all the CTDs sampled along the Newport Hydrographic (NH) line during the year 2004. The NH line is located at 44.6^{o}N off the coast of Newport in Oregon. It stretches out 157 km covering a relatively wide shelf. The NH line is composed of 12 stations. The most inshore station, NH-1, is 2-km from shore at 124.06°W and the most offshore station, NH-85, is 157 km offshore at 126.05°W. The GLOBEC and COAST programs, the hake survey and Newport line stations have added invaluable three-dimensional fields of oceanographic data during the summers of 1999 to 2004 covering the continental shelf and slope of the Oregon coast. In addition, in January-February 2003, a wintertime COAST cruise was carried out off central Oregon. The hake survey was the only cruise covering both the Washington and Oregon continental shelf and slope.

3.1.3.2 *ADCP*

The main source of the ADCP data was the Joint Archive for Shipboard Acoustic Doppler Current Profiler (JASADCP) that was established by the NODC and the National Coastal Data Development Center (NCDDC) (in collaboration with the E. Space Firing Acoustic Doppler Current Profiler Laboratory at the University of Hawaii) to archive, review, document and distribute shipboard ADCP datasets. Other sources of ADCP data were the GLOBEC and the COAST programs carried out by Oregon State University (OSU). Unfortunately, the ADCP data acquired by the 2001 and 2003 Integrated Acoustic and Trawl survey of Pacific hake surveys were not processed in time for this study. The ADCP data retrieved from the JASADCP and OSU oceanographic cruises for the study area ranged from 1991 (the earliest time available) to the year 2004. The ADCP data were given as a standard subset of absolute currents at hourly and 10 m intervals. If absolute currents were not available because of lack of navigation, currents relative to the mean over a reference layer usually 50 to 120 m, were provided. The shallowest measurement level is usually 20-30 m below surface and the deepest measurable level is around 350 m. This depends on the instrument configuration and the transducer depth. For more information about the JASADCP go to http://ilikai.soest.hawaii.edu/sadcp/.

3.2 Assembly and Consolidation of Datasets

The first objective of this study was to identify, assemble and consolidate existing oceanographic datasets for the Washington and Oregon coasts. Appendix 1 includes a summary of all the oceanographic data collected and consolidated in this study. The approach used was to organize and merge all the datasets, first by instrument type (e.g., satellite sensors, high-quality CTDs, low-quality CTDs) and then by oceanographic variable (e.g. high-quality CTD for temperature, high-quality CTDs for salinity). Each of the final output files contained geographic coordinates, depth, date and the oceanographic variable.

Through the assembling and merging of the oceanographic data, this study provides datasets with an improved three-dimensional spatial and temporal coverage and resolution for the Washington and Oregon coasts for each of the oceanographic variables. Uniform and continuous data coverage is necessary to obtain a broad spatial picture of the oceanographic conditions of the area of study and is required for statistical analyses, fisheries research and GIS routines to work.

3.3 Computation of Ocean Data Products and Maps for Fisheries Science and Management

3.3.1 *Identification of Relevant Computations for Fisheries Research*

During the assembling and consolidation of the datasets, this study was faced with two challenges. The first challenge was the identification of which oceanographic combinations in terms of averages, medians, running averages etc. were the most useful for fisheries research and how oceanographic data could be organized and compressed for comparisons with fisheries data. The second challenge consisted of how to transform the oceanographic data into a practical and functional format so fisheries scientist and managers could have easy access to it.

The approach taken to decide what ocean data products were the most appropriate to represent the oceanographic processes off the Oregon and Washington coasts and for comparison with fisheries data was the evaluation of the temporal and spatial resolution and coverage for each oceanographic variable the entire region of study. It was decided to compute climatological monthly means, standard deviations and coefficient of variations for each variable at different depths. The climatological monthly means and their respective mapping indicates the average ocean conditions for the study area. They represents the best estimate for the average in a given month, which gives an idea of what the general oceanographic conditions are like at different depths for every month off the Oregon and Washington coasts. Climatological monthly standard deviations and coefficient of variations were computed because they give a sense of how much oceanographic variables vary through time. They describe the variability of each of the oceanographic variables over time, which helps to identify regions throughout the study area that are subject to more environmental variability. Thus, they allow the delineation of what areas are more variable than others. Climatological monthly coefficients of variation are calculated by dividing the standard deviation by the mean. Therefore, they are normalized and this allows comparing the variability among different type of datasets which have different scales such as temperature and salinity.

The second challenge referred to transforming the oceanographic data into a practical and functional format for fisheries scientists and managers. In this case, the approach taken was to create a multilayer GIS database where all the oceanographic data can be organized. After the computations were completed, the oceanographic layers were imported into ArcGIS 8.3. Due to time constrains, the import of the climatologies into GIS was only partially done. This will be completed in the near future. This is crucial as the GIS will ensure compatibility regarding projection and distance units among the data, as well as will facilitate the future integration of other layers of information, such as dissolved oxygen concentration or mixed layer depth. Eventually, this tool will become accessible to all users: scientists, fisheries managers and policy makers.

3.3.2 *Gridding, Computations of Climatological Monthly Means, Standard Deviations and Coefficients of variation and Mapping*

It is highly advantageous that after the gridding and computation of all ocean data products planned in this study, the data share a common geographic extent and a common and uniform spatial grid and resolution. This makes the process of importing the oceanographic layers of information into a GIS more manageable, and ultimately facilitates the overlay and analysis of the layers in the GIS or any other type of fisheries statistical analysis. For these reasons, all the oceanographic data were gridded to a common spatial resolution, with the exception of the remotely sensed data from satellite and coastal radars, which were left in their original fine spatial resolution.

Three different schemes using Matlab (Version 7.1) were developed to grid, compute and map the climatologies for each of the following types of data: remotely sensed data (SST, surface chlorophyll-a and surface current velocity), CTD, Niskin bottles and fluorometers data (temperature, salinity and chlorophyll-a) and ADCP data (subsurface current velocity). Although, the methodology to grid, compute climatological monthly means, standard deviations and coefficients of variation, and plot the climatologies for each of the data types are very similar, each source of data required a slightly different methodology.

3.3.2.1 *Scheme for Remotely Sensed Data*

The data obtained from remote satellite sensors and HF coastal radars were already gridded. Therefore, the data were already prepared for the computation of the climatological means, standard deviations and coefficients of variation.

Monthly climatologies for SST were computed in two steps: first, monthly means were computed from a 6-year period (September 1997 to August 2003) of 8-day composites (see section 3.1.2 for details); second, each monthly mean was grouped into its corresponding months and then averaged. This procedure created the SST climalological monthly means. A climatological standard deviation and a climatological coefficient of variation were also computed for each month.

The satellite images for surface chlorophyll-a concentrations were already provided as monthly means. Therefore, the climatological monthly means were obtained by grouping each monthly mean into its corresponding month and then averaging. A standard deviation and a coefficient of variation were also computed for each month. Subsequently, each of the climatological monthly means for chlorophyll-a concentrations were log transformed to account for the log-normal distribution of this variable and to compress the high values and spread out the low values by expressing the values as orders of magnitude (McCune and Grace, 2002), which are characteristic of chlorophyll-a concentration values. All the SST and chlorophyll-a climatological monthly means, standard deviations and coefficients of variation have been plotted in Matlab and imported into a GIS.

The surface currents measurements from HF coastal radars assembled in this study only cover a one year cycle (April 2002 to March 2003). Therefore, climatological monthly means were not computed. The monthly means were plotted in Matlab and imported into a GIS.

3.3.2.2 *Scheme for CTD, Niskin Bottle and Fluorometer Data (Temperature, Salinity and Chlorophyll-a)*

A scheme was developed in Matlab to grid, compute and plot monthly climatological means, standard deviations and coefficients of variation for the randomly distributed temperature, salinity and chlorophyll-a fields obtained from CTD casts, fluorometers and Niskin bottles. The same scheme was applied to each of the fields on a monthly basis at different depths. In the case of temperature and salinity, it was applied at 0, 50, 100, 500, 100 m and at the bottom of the seafloor. In the case of chlorophyll-a, it was applied every 10 m until the chlorophyll-a concentration disappeared, and also at the bottom of the seafloor. The bottom of the seafloor was defined as all measurements within 10 m from the bottom.

The scheme was composed of six major steps. The first step consisted of selecting all the CTD casts within the targeted month without regard to year. Again, the reason why all the years were combined was to obtain sufficient spatial coverage for each month of the study area and thus compute the climatologies. In the second step, each CTD cast within the targeted month was vertically averaged around a chosen depth. All the CTD measurements were averaged around 0, 50, 100, 500 and 1000 m with a buffer of 5 m above and below each depth to optimize the number of CTD measurements at each depth.

For example, when the goal is to compute a climatological monthly mean at 50 m depth, all the CTDs between 45 m and 55 m depth were averaged.

In the third step, all the CTD measurements were spatially averaged and gridded to 0.32^o longitude (~25.3km) and latitude (~35.5km) resolution. In order to calculate the spatial average, a grid was defined and subsequently, the CTDs casts falling within each grid box were averaged. This step resulted in the generation of a climatological mean. The climatological standard deviations were generated by computing the standard deviation at each grid box using all the CTD observations at each of the grid boxes, and the climatological coefficients of variation were generated by dividing the climatological standard deviation by the climatological mean at each of the grid boxes. At this step of the computation, if outliers became an eminent source of noise, they were removed. In order to remove outliers, a "standard deviation" filter was applied in this step to remove any noisy data (outliers). This filter consisted of removing outliers found in each of the grid boxes. A CTD observation was considered an outlier, and therefore not used to compute the climatologies, when its value was bigger (smaller) than the mean of the grid box plus (minus) two times the standard deviation of the grid box. The spatial resolution for the grid was determined with two things in mind. The first thing was to preserve the spatial details of oceanographic processes, such as upwelling regions and some of its mesoscale activity, and the second was to avoid a division so fine that the grid would be composed of mostly empty cells. A resolution of 0.32 degrees (longitude ~25.3km and latitude ~35.5km) was found to be a good compromise for the surface layers (0, 50,100 meters). However, for the 500 and 1000 m layers, some of the monthly climatologies were composed of mostly empty grids.

The fourth step consisted of interpolating the spatial means, spatial standard deviations and spatial coefficients of variation computed for each grid box to get a broader spatial picture for each of the oceanographic fields. A Unix-based program called ZG, developed by Ian Crain in 1978 (unpublished) and further developed by Steve Pierce (Oregon State University), was used to interpolate the data. ZG uses a pseudo-spline method to interpolate the data. After the interpolation, some of the climatological means still had some observable noise. The noise data consisted mostly of low-resolution CTD casts obtained from the NODC OSD instruments, which were made before the 1970s. Although these CTD casts are providing some noise in the climatologies, the addition of the CTDs retrieved by the OSD instruments substantially improved the spatial coverage of the study area. Therefore, the fifth step consisted in spatially smoothing the climatological means to remove some of the noise. A spatial filter from the statistical Matlab toolbox was applied to each of the climatologies. This filter removed small-scale noise using a two-dimensional median filter. This median filter reduced the noise and at the same time preserved the edges. It performed the median filtering by using a 3-by-3 neighborhood grids. Finally, the climatological means, standard deviations and coefficient of variations for each field and depth were plotted in Matlab for initial screening and visualization. The climatological monthly means, standard deviations and coefficients of variation for temperature, salinity and chlorophyll-a will be imported into a GIS in the near future.

3.3.2.3 *Scheme for the ADCP Data*

The scheme developed in Matlab to grid, compute and plot monthly climatological means for subsurface current velocity was composed of four steps. The first step consisted of selecting the ADCP observations within the targeted month without regard to the year. The second step consisted of vertically averaging all the ADCP observations around a chosen depth for each targeted month. The ADCP data were averaged around 30, 50, 100 and 300 m with a buffer of 5 m above and below each depth to optimize the number of ADCP observations at each depth. In the third step, all the ADCP observations were spatially averaged and gridded to 0.32^{o} resolution. All the ADCP measurements falling within each grid box were averaged. In order to average the ADCP measurement, first the u (cross-shore) and v (alongshore) velocity components were averaged individually in each of the grids and then the mean speed was calculated for each of the grid point. This resulted in the generation of a monthly climatological mean for current velocity at the targeted depth for each grid box with data. Only the mean velocities with mean speed greater than the standard error of the mean speed were used for plotting. The standard error of the mean speed was estimated as the ratio of the standard deviation of the mean speed to the square root of the number of ADCP observations within each of the grid boxes. Each of the climatological means for current velocity were plotted in Matlab for initial screening and visualization. The climatological monthly means for current velocity will be imported into a GIS in the near future. Climatological standard deviations and coefficients of variation were not computed for current velocity.

3.4 Statistical Analysis

In this section, an example of how oceanographic data collected in this study can be used to improve fisheries research and eventually manage fisheries resources within an ecosystem-based management approach is presented. Catch data from the 2004 West Coast groundfish bottom trawl survey was used to investigate if groundfish distributions and abundances were associated with any particular ocean habitat or particular environmental variables.

3.4.1 *Fish Data for the Statistical Analysis*

The Fisheries Resource Analysis and Monitoring (FRAM) Division of NOAA's Northwest Fisheries Science Center (NWFSC) performed the groundfish bottom trawl survey in the summer of 2004. The 2004 West Coast groundfish survey was the most appropriate for this study, since it had a depth-stratified and random sampling design and it covered the shelf and slope off the Washington and Oregon coasts (Keller *et al.,* in review**).** Complete details of the bottom trawl survey are available from Keller, *et al.,* in review).

The survey extended approximately from 48^{o}N (northern Washington coast) to 32^{o}N (southern California). However, in this study, only the trawls within the study area were used (Figure 3.1) and they ranged in depth from 50-1400 m. Catches from each trawl were classified to species level or to the lowest taxonomical level, counted and weighed. Therefore, each trawl produced data on depth, trawl location, biomass for each species in kg and area swept by the trawl in km^2. For the analysis, densities (kg km $^{-2}$) were computed for each species in each trawl. Within the study area, 252 trawls and 153 fish taxa made up the total catch. The analysis focused on the 28 most abundant species, which made up 95% of the catch biomass (Table 3.1). All the 28 taxa, except three species, technically are classified as groundfish species by the Pacific Coast Groundfish Fisheries Management Plan. The three exceptions are giant grenadier, slender sole and sandpaper skate, but because they were part of the 95% of the catch biomass and all the 28 species were demersal fish, we included them in the analysis. For the purpose of this study, we will refer to the 28 species as groundfish throughout the document. This created a fish matrix composed of 252 rows (the number of hauls within the study area) and 28 columns (the most abundant species in the study area), which was incorporated into the statistical analysis. Prior to the analysis the fish matrix was log transformed to y'=log(y+1) to reduce the effects of the abundant species.

3.4.2 *Ocean Data for the Statistical Analysis*

Measurements of the oceanographic conditions at different depths for the study area at the time of the fish survey were not available. This case demonstrates how the ocean data compiled and manipulated for this study become very useful and valuable. However, there are three things to keep in mind: 1) the climatologies computed in this study in section 3.3 represent the best estimate for the average oceanographic conditions at a given month from the earliest time available (CTD data go back to the 1930s, satellite data go back to 1997 and ADCP data go back to 1991) to the year 2004; 2) the 2004 trawl survey makes up only one year within the time range of the climatologies; 3) this period of time (1930s to 2004) was characterized by changing oceanographic regimes as a result of changes in the atmosphere-ocean system. For these reasons, the oceanographic conditions off the Washington and Oregon coasts during the year 2004 were examined to see if the year 2004 had similar oceanographic characteristics to either a cold regime or a warm regime period.

Since the 1940s there has been one major cold regime period (1947-1976) and one major warm regime period (1977-1998), which have been well identified with the PDO index. However, in 1998-1999 there was an apparent shift into a new atmospheric-oceanic state, which has been identified as the Victorian Pattern, named after the place where its significance was first identified (Bond *et al.,* 2003; Rodionov *et al.,* 2004). On a basin-wide scale, the North Pacific Ocean from 1999-2002, in terms of sea level pressure and sea surface temperature, did not resemble either the period before or after the 1976-1977 regime shift (Bond *et al.,* 2003). Locally, the 1998-1999 shift has had a strong effect in the CCS, producing wind patterns, and consequently oceanographic conditions similar to those observed before the 1976-1977 regime shift (Rodionov *et al.,* 2004). The winter of 2002-2003 was a moderate El Niño year.

Based on the uncertainty of what ocean conditions were present during 2004 off Washington and Oregon, two types of analyses were carried out to check if the oceanographic conditions during 2004 had the typical characteristics of a cold or warm regime year. The first analysis consisted of comparing the climatological monthly mean of temperature for each of the regimes (cold regime 1947-1976, warm regime 1977-1998, “time-period” 1999-2004) and monthly means of temperature for 2004 at the Newport hydrographic line at 45 m depth (Figure 3.2). The observations included in the climatological monthly means and the monthly means covered an area of 1234 km^2 from 124.7 to 124^oW and from 44.5 to 44.7^oN. The oceanographic characteristics of the year 2004 were more similar to the oceanographic characteristics of the climatological monthly means for the cold regime period (1947-1976) and during 1999-2004 than for the warm regime period (1977-1998) (Figure 3.2).

The second analysis consisted of comparing the climatological monthly means of temperature of each of the regime periods and the time period 1999-2004 to the monthly means for temperature for the year 2004 at each of the stations along the Newport hydrographic line at 45 m depth (Figure 3.2). The monthly means for the year 2004 are consistently more similar to the climatological monthly means of temperature for the cold regime period and from 1999-2004 for each month and each station along the Newport line than to the warm regime period temperatures (Figure 3.3). For these reasons, in this study, the time period from 1999-2004 was considered to be a “cold” regime period.

Given that the oceanographic conditions for the year 2004 were similar to the cold regime period (1947-1976) and the “cold” regime periods from 1999-2004, the historical oceanographic data (when possible) were divided into three groups, the 1947-1976 cold regime, the 1977-1998 warm regime and the 1999-2004 “cold” regime period. Subsequently, both cold regimes’ oceanographic data were combined (when possible) to get a better data coverage of the Washington and Oregon coasts (figures 3.4, 3.5, 3.6). The first attempt at combining the data was to use only the oceanographic data for the time period of 1999-2004 to get a full coverage of the oceanographic conditions off Washington and Oregon. It turned out that the data offered limitations in the spatial coverage of the study area. Therefore, oceanographic data from two cold regime periods were combined to get better coverage off the Washington and Oregon coasts. This operation improved the spatial and temporal coverage of the oceanographic variables covering the entire Washington and Oregon coasts. Again, this analysis attempts to reproduce what oceanographic conditions are like during cold regime conditions and assumes those conditions are the ones manifested in the year 2004 off the Washington and Oregon coasts.

In addition, the historical oceanographic data were divided into two main time periods, one for summer upwelling conditions and the other for winter downwelling conditions. These two periods were separated based on the timing of the spring and fall transition, which characterizes temperate coastal areas. The summer upwelling season included the months from May to October. The spring transition generally occurs in May. The winter downwelling season included the months from November to April. The fall transition typically occurs in November. The exact timings for the spring and fall transitions are not relevant for this study since the historical oceanographic datasets included a large range of timings for the transitions, but it could be relevant when looking at multiple years.

Given that the fish survey was conducted in the months from May to October, only the ocean data falling between the spring and fall transition time period (May to October) were used. This is summer upwelling conditions. Cold regime summer climatological means, standard deviations (STD) and coefficients of variations (CV) were then computed for each variable (temperature, salinity, chlorophyll-a and velocity) at three depths (0 and 50 m and near the bottom). When the climatologies were computed, the variables were gridded to a common spatial resolution of 0.16^{o} for compatibility in the statistical analyses. In this case, the resolution of the grid was improved to 0.16^{o} because the grouping of the cold years and the groupings of the months of interest (May-October) considerably improved the spatial coverage of the data for the entire Oregon and Washington coasts. Remember the monthly climatologies computed in section 3.3, were gridded to 0.32^{o} due to fewer data comprising the monthly climatologies. Even the variables with original finer resolution (SST and chl from satellite images) were gridded to 0.16^{o} by averaging all the cells falling within the 0.16^{o} cell. Again, the resolution of the grid was determined to preserve oceanographic details of the area of study, and at the same time, avoid a grid with mostly empty cells. The computations of the climatologies followed the same methodology described in section 3.3.

Following the computation of all the climatological means, STDs and CVs for each variable at three different depths (0m, 50m and near the bottom), a subjective data screening was performed to eliminate redundant climatologies and climatologies with incomplete data coverage. The climatological mean of sea surface temperature from AVHRR was removed and instead the sea surface temperature derived from CTDs was used to compute the climatology. The climatologies made from CTD observations offer statistics that are more reliable since the number of observations is bigger and oceanographic details are more noticeable. Subsurface chlorophyll-a from fluorometers and Niskin bottle samples (Figure 3.5), velocity from HF coastal radars, and subsurface velocity from shipboard ADCPs (Figure 3.6) were removed from the analysis since they did not have enough spatial coverage.

To summarize, the statistical analysis included aspects of the oceanic system that were most complete in terms of area coverage and in terms of describing the ocean habitat where fish live. The analysis included the following variables: the "cold regime summer" climatological means and the CVs of temperature and salinity at 0 m, 50 m and near the bottom from CTD observations, and the cold regime "summer" climatological mean and CV of chlorophyll-a at the surface from SeaWiFs. The geographical coordinates and the depth of the trawls were also included in some of the analysis as variables. In order to incorporate the oceanographic information into the statistical analysis, each oceanographic value for all the cold regime summer climatologies was extracted for each trawl location. So for each trawl location, there was information for a total of 14 different oceanographic variables (Table 3.2). These created an environmental matrix composed of 252 rows (number of hauls (trawl stations) within the study region) and 17 columns (14 oceanographic variables, longitude, latitude and depth at each of the trawl stations), which was incorporated in the statistical analysis.

3.4.3 *The Statistical Analysis: Analytical Approach*

Ordination and classification techniques were used in this analysis to examine patterns in fish species distributions and abundances in relation to oceanographic variables and ocean habitats. The analysis identified ocean habitats using the environmental matrix (defined in section 3.4.2). These habitats were then used to investigate associations between ocean habitats and groundfish distributions for the year 2004.

3.4.3.1 *Identification of Ocean Habitats*

Two different approaches were taken in order to explore how many distinct ocean habitats, in terms of their physical and biological characteristics, exist off the Washington and Oregon coast. The first consisted of a hierarchical agglomerative clustering analysis, and the second was a principal components analysis.

3.4.3.1.1 Hierarchical Agglomerative Clustering Analysis

A hierarchical agglomerative clustering analysis was performed on the environmental matrix composed only of the oceanographic variables (depth, longitude and latitude were not included in the analysis), using Euclidean distances and Ward's linkage method, to partition the distance matrix into a determinate number of groups, which in this case were called "ocean habitats". The distance matrix was successively partitioned into 3, 4, 5 and 6 groups, in order to evaluate what would be the best partitioning to define the most meaningful ocean habitats based on the existing knowledge of processes occurring off the Washington and Oregon coasts. A discriminant analysis was done to summarize the differences among ocean habitats to describe the ocean habitats in detail.

3.4.3.1.2 Principal Components Analysis (PCA)

A PCA was performed on the environmental matrix composed of only the ocean variables (depth, longitude and latitude were not included in the analysis), in order to describe the direct effects of physical and biological forcing on the system and separate discrete regions/groups (which were called ocean habitats) with similar ocean characteristics. Thus, the environmental matrix was transformed into a correlation matrix that was used as input for the PCA calculations.

3.4.3.2 *Investigation of the Association Between Ocean Habitats and Groundfish Distributions and Abundances.*

In order to explore if there was any association between ocean habitats identified in section 3.4.3.1.1 and the 2004 groundfish distributions and abundances off the coast of Washington and Oregon. First, a multi-response permutation procedure was used to test if the ocean habitats differ in species composition. Second, a univariate method called indicator species analysis was used to determine indicator species for each ocean habitat. Finally, two different ordination methods were used to explore in more detail groundfish association with each of the ocean habitats and individual oceanographic variables. The first ordination method used in the analysis was an unconstrained ordination method called non-metric multidimensional scaling. The second ordination method used was a constrained ordination method called canonical analysis of principal coordinates. The combination of both methods is useful to obtain a more complete understanding of the patterns in the multivariate data cloud (Anderson and Willis, 2003). Unconstrained methods are useful for visualizing broad patterns across the entire multivariate data cloud, in our case the fish data matrix. This provided information of the overall pattern of dispersion among points (trawl stations), dispersion among groups (groups of trawl stations) and potential sources of multivariate variability (Anderson and Willis, 2003). In contrast, constrained methods use an *a priori* hypothesis to relate a matrix of response variables (in our case, fish species data) to a matrix of environmental data (in our case, oceanographic continuous variables).

3.4.3.2.1 Multi-Response Permutation Procedure Analysis (MRPP)

With the purpose of testing the null hypothesis of no difference among the ocean habitats (identified in section 3.4.3.1.1) in terms of their species composition, a MRPP analysis (Mielke, 1984; Mielke and Berry, 2001) was undertaken using the software package PC-ORD version 4.1 developed by McCune and Mefford (1999). The distance measure chosen to calculate the distance matrix was Sorensen distance, also called Bray-Curtis distance (Bray and Curtis, 1957). The Bray-Curtis dissimilarity index tends to emphasize differences in relative abundances (Anderson and Willis, 2003).

MRPP is a non-parametric method for testing for group differences and for this reason it does not require distributional assumptions. The analysis provides a test statistic, a *p-value*, and an agreement statistic (*A*). *A* compared within group homogeneity with random expectations. If all the species are identical within groups then, A=1(this is the max value of *A*). This is not realistic for community data. If heterogeneity within the groups equals expectation by chance, then *A*=0 (McCune and

Grace, 2002). In community ecology, usually the value of A is below 0.1 and when A is bigger than 0.3 it is recognized as a high value (McCune and Grace, 2002).

3.4.3.2.2 Indicator Species Analysis (ISA)

An ISA (Dufrêne and Legendre, 1997) was performed to determine indicator species for each ocean habitats identified in section 3.4.3.1.1. The analysis was undertaken using the software package PC-ORD. The purpose of this analysis was to describe the differences in species composition in each of the ocean habitat groups and to describe the value of different species and species relationships to environmental conditions, in our case, ocean habitats (McCune and Grace, 2002). Indicator values are produced for each species by combining information about species abundances in a particular group and comparing it to the main abundances of that species across the groups, and information on the faithfulness of occurrence of species in a particular group. The analysis gives an indicator value for each species in each group, which is expressed as a percentage of a perfect indicator. A species is an indicator of a particular group for which it has the largest indicator value. The analysis also assesses the significance of the indicator values with a Monte Carlo procedure by randomly assigning units (trawl stations) to groups 1000 times (McCune and Grace, 2002).

3.4.3.2.3 Non-Metric Multidimensional Scaling Analysis (NMDS)

With the purpose of characterizing the main patterns of variation among sample units (trawl stations) in the species space and then finding the influence of environmental variability on those patterns, an NMDS analysis was undertaken on the fish data matrix. The environmental data were only used for interpretative reasons. NMDS has been shown to be a robust and very useful unconstrained ordination technique, a method for assessing dimensionality for ecological data (Anderson and Willis, 2003; McCune and Grace, 2002). Previous applications of NMDS in community ecology in the marine system can be found in Palacios (2004) and Reese (2006).

The advantages of NMDS are: 1) it has no underlying model such as a linear or unimodal models; 2) it avoids the assumption of linear relationships among variables (McCune and Grace, 2002); 3) it avoids the assumption of normality in the data; 4) it can identify a much wider range of structures (compared to constrained methods); and 5) it allows the use of any distance measure or relativization. The purpose of NMDS is to arrange similar objects close to one another and dissimilar objects far apart in a small number of dimensions or number of axes. This is accomplished by maximizing the *rank order* correlation between distance in the full-dimensional scale and distance in the ordination space (McCune and Grace, 2002). NMDS uses an iterative search for the best position of *n* samples, which is assessed with a measure of "stress". The stress measure is a function which measures the lack-of-fit between the two distances. Improvements of the positions are accomplished by moving the samples slightly in a direction that decreases the stress, using the method of steepest descent (McCune and Grace, 2000).

In order to choose the best solution, NMDS was conducted in two stages, using the software package PC-ORD. The first stage consisted of running the program with the following configuration: 1) Sorensen distance; 2) sample units configured at random; 3) starting at a six-dimensional solution, stepping down to one-dimensional solution; 4) the initial step length, which is the rate of movement toward minimum stress, was set to 0.2; 5) 400 maximum iterations; 6) 40 runs with real data and 50 runs with the randomized data were used as the basis for the Monte Carlo test of significance for each dimensionality. The Monte Carlo test examined the probability that a similar final stress could not have been obtained by chance. This first stage allowed examination of the scree plot to choose the dimensionality which gives the best solution. A scree plot shows stress versus the number of dimensions. The best dimension is selected by checking if the addition of an axes resulted in a significant improvement in the reduction of stress.

The second stage consisted of rerunning NMDS to determine the final ordination, with the dimensionality chosen in the first stage as the starting configuration. The distance measure, the number of iterations and the stability criterion were kept the same (McCune and Grace, 2003).

The NMDS output also provided a coefficient of determination (r^2), which determines the proportion of variation represented by each axis. It also provided correlations of each individual species and environmental variables with each ordination axes. These are called Pearson and Kendall correlations and are used to measure the strength and the direction of individual species and environmental parameters with each ordination axis. In addition, the color-coding used for the visualization of ocean habitats from the clustering analysis for each of the trawl stations was overlayed in the NMDS ordination plot for interpretative reasons.

3.4.3.2.4 Canonical Analysis of Principal coordinates (CAP)

With the purpose of investigating the variation in groundfish species in relation to both the individual oceanographic variables computed in section 3.4.2 (continuous variables) and the ocean habitats identified in section 3.4.3.1.1 (categorical variables), a CAP developed by Anderson and Willis (2003) was used. Anderson and Willis (2003) argue that CAP is a very useful and flexible procedure for ecological studies, since it allows the investigation of hypotheses visually in reduced dimensions and allows the flexibility of using any dissimilarity distance measure.

A computer program designed by Marti J. Anderson (University of Auckland) to run the CAP analysis was used to perform a canonical analysis for the effects of *X*, if any, on *Y* on the basis of any distance measure and using permutations of the observations. *X* is a data matrix considered the predictor variable and can have the form of either quantitative environmental variables or categorical variables. In this study, the two type of predictor variables were available, the continuous oceanographic variables (oceanographic variables computed in section 3.4.2, longitude, latitude and depths) and the ocean categorical variables (the ocean habitats defined section 3.4.3.1.1). *Y* is the data matrix considered the dependent variable, which in our studies corresponded to be the 28 most abundant species.

This method ordinates ecological species data and displays a cloud of multivariate points by reference to a specific *a priori* hypothesis and takes into account the correlation structure among variables in the response data cloud (Anderson and Willis, 2003). Anderson and Willis (2003) argued that CAP can reveal important patterns in the multivariate data by reference to a relevant hypothesis (Anderson and Willis, 2003), which unconstrained ordination methods such as principal coordinate analysis and NMDS can not reveal. CAP allows the testing of two types of hypotheses. The first type, a hypothesis concerning differences among groups, similar to an analysis of variance (ANOVA). In this study, it was tested if there were any significant differences among the five ocean habitats in terms of the species composition (the null hypothesis is that were not significant differences in multivariate location among groups). The second type of hypothesis is concerned with one or more explanatory continuous variables (Anderson and Willis, 2003). In this study, it was tested if there was any association between any of the oceanographic variables and groundfish species distributions (the null hypothesis is that here there was not a significant relationship with the quantitative environmental variables).

The CAP analysis consisted of five steps (Anderson and Willis, 2003). The first step used the fish species abundance matrix to perform a principal coordinate analysis (PCO). The fish data were made up of the 28 most abundant species, making up 95% of the biomass and were transformed to y'=ln(y+1). This transformation removed any large differences in scale for the fish abundances and avoided the log (zero). The PCO was performed using the using the Bray-Curtis dissimilarity index as the distance measure. In addition, the PCO allows the reduction of the number of dimensions of the system to *m* orthogonal axes, which are used afterwards in the canonical analysis. The second step consisted of choosing the number of axes *m* resulting from the PCO by using the misclassification error proposed by Anderson and Willis (2003). The third step consisted of choosing to perform either a canonical correlation analysis (CCorA) or a canonical discriminant analysis (CDA). The two canonical analyses use the axes obtained from the PCO performed in the first step and included a test permutation. Both analyses were performed to test two different types of hypothesis, but at the same time interrelated.

The CCorA used the continuous oceanographic variables (the cold regime summer climatologies computed in section 3.4.2) to test if there was a relationship between the fish abundances and distributions and any of the oceanographic variables. The purpose of CCorA was to examine fish abundances and distributions in relation to depth, longitude, latitude and each of the oceanographic variables of interest at different depths. The CCorA found the axes that maximize their correlation with linear combinations between the species data and the oceanographic data. The oceanographic variables were not normalized or relativized, so the results could be compared with the results from the NMDS analysis.

The CDA used the ocean habitat groups as categorical variables identified in section 3.4.3.1.1 to test if there were any significant differences in fish assemblages among the five ocean habitats (the null hypothesis is that there ere no differences in fish assemblages among the five ocean habitats). The purpose of this analysis was to look at the effects of the ocean habitats on individual fish species or groups of species.

The fourth step consisted of testing the hypothesis using permutation procedures on canonical test statistics. The hypothesis of no significant relationship between fish abundances and ocean habitats and longitude, latitude, depth and quantitative oceanographic variables was tested by running 9999 permutations on the data to obtain a *p-value* (Anderson, 2001). Finally, the CAP analysis computed correlations to assess relationships. Species loadings (correlation coefficient for individual species with each of the canonical axes) and loadings for environmental parameters (correlation coefficient for individual oceanographic variables, longitude, latitude and depths with each of the canonical axes) greater than 0.3 were considered relevant and therefore interpreted in the results and in the discussion. The species loading allowed for the interpretation of the ordination and the identification of species responsible for the multivariate pattern (Anderson and Willis, 2003). Both of the CAP analyses results were overlayed with color-coded ocean habitats identified in section 3.4.2 for better interpretability of the results. This helped to visualize potential patterns of differences in the location or relative dispersion among groups (Anderson and Willis,2003).

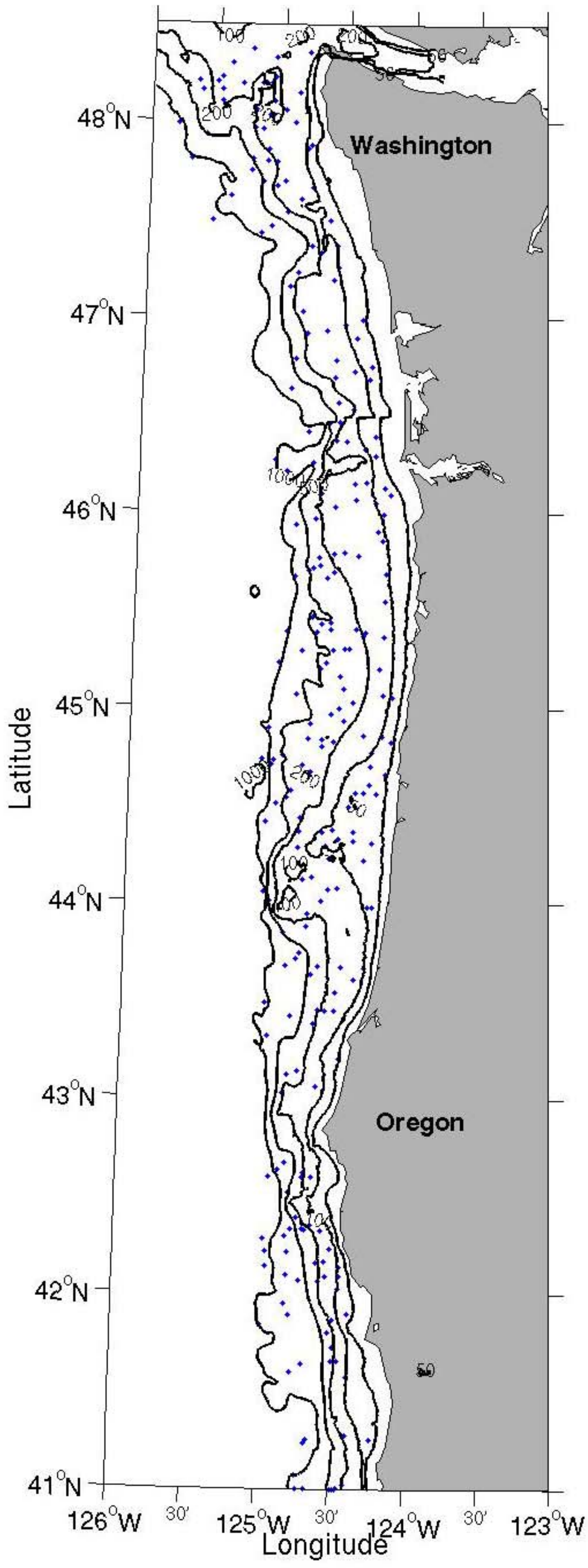


Figure 3-1 Trawl stations within the study region from 2004 groundfish bottom trawl survey.

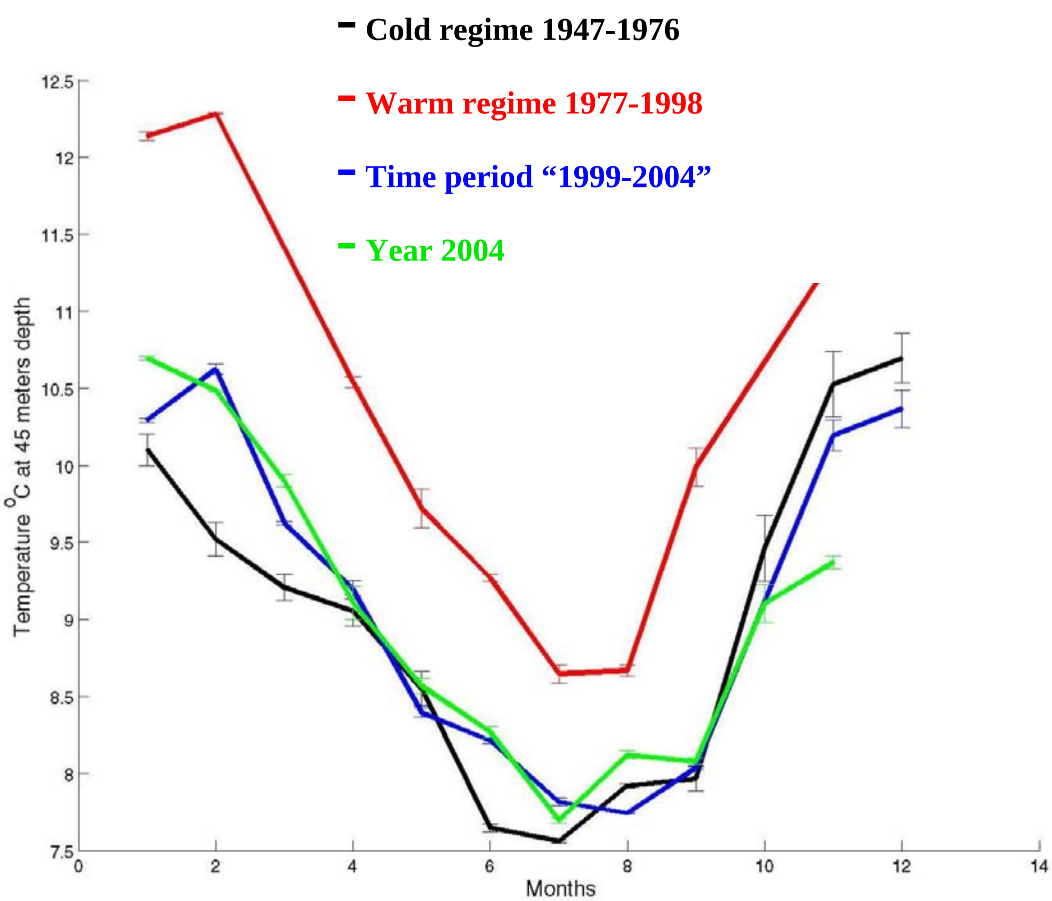
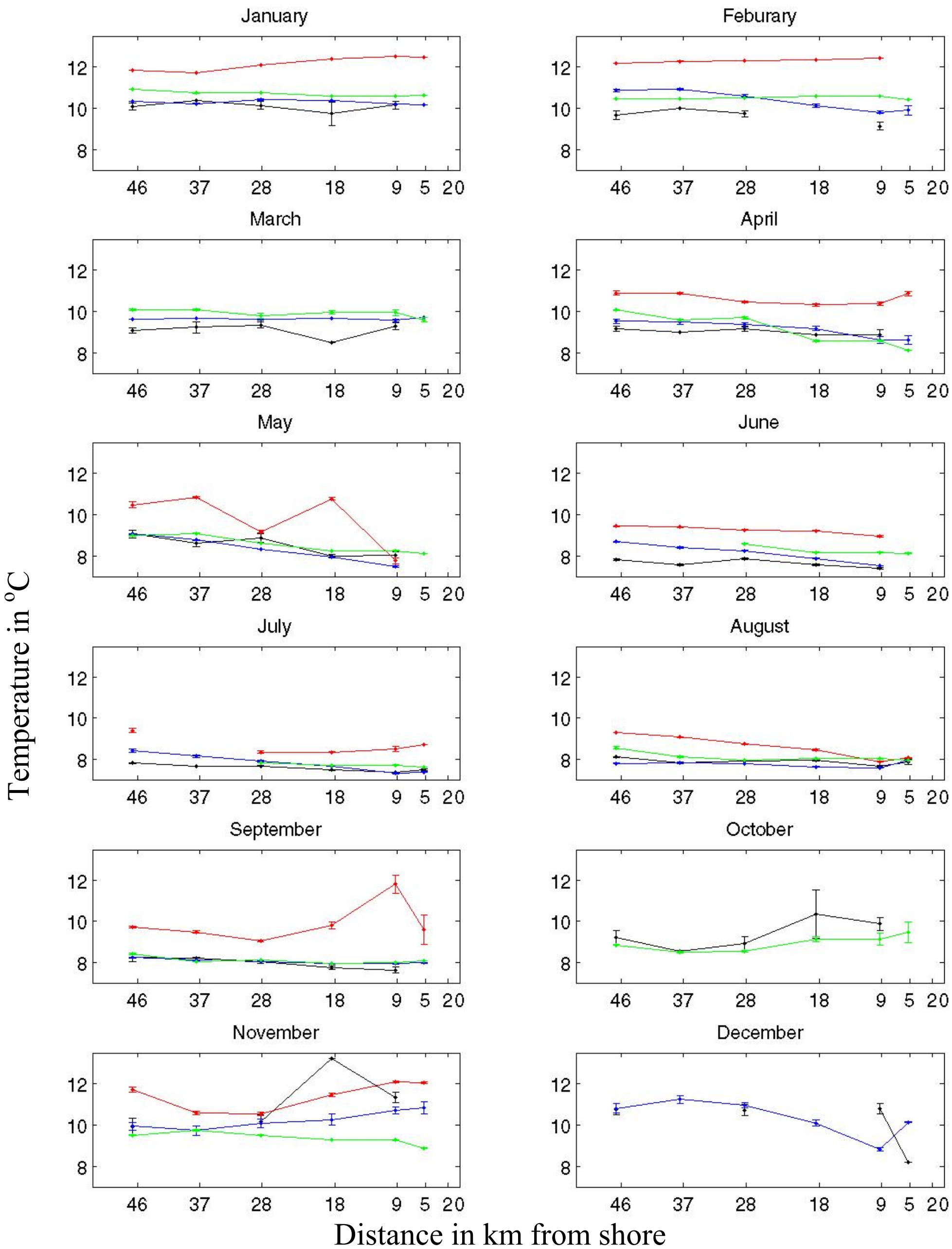


Figure 3-2 Comparison of the climatological monthly means for each regime period and the year 2004 at 45 m depth from 2 km to 51 km offshore along the Newport Hydrographic Line off central Oregon.



- Cold regime 1947-1976
- Warm regime 1977-1998
- Time period "1999-2004"
- Year 2004

Figure 3-3 Zonal profiles of the climatological monthly means of temperature at 45m for each of the regime periods and the year 2004 along the Newport Hydrographic Line off central Oregon.

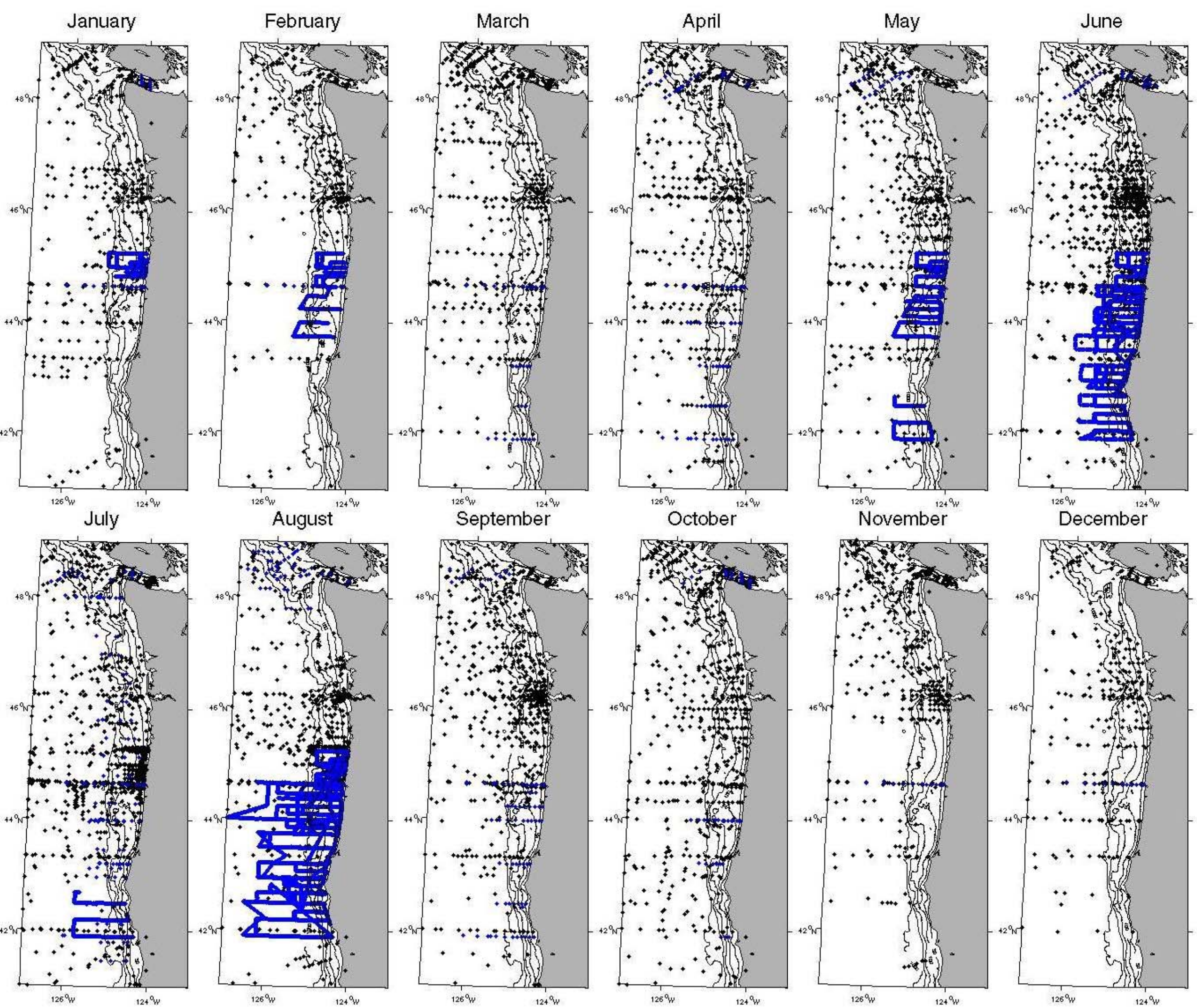


Figure 3-4 CTD locations for the cold-regime (1947-1976) in black and the cold-regime (1999-2004) in blue.

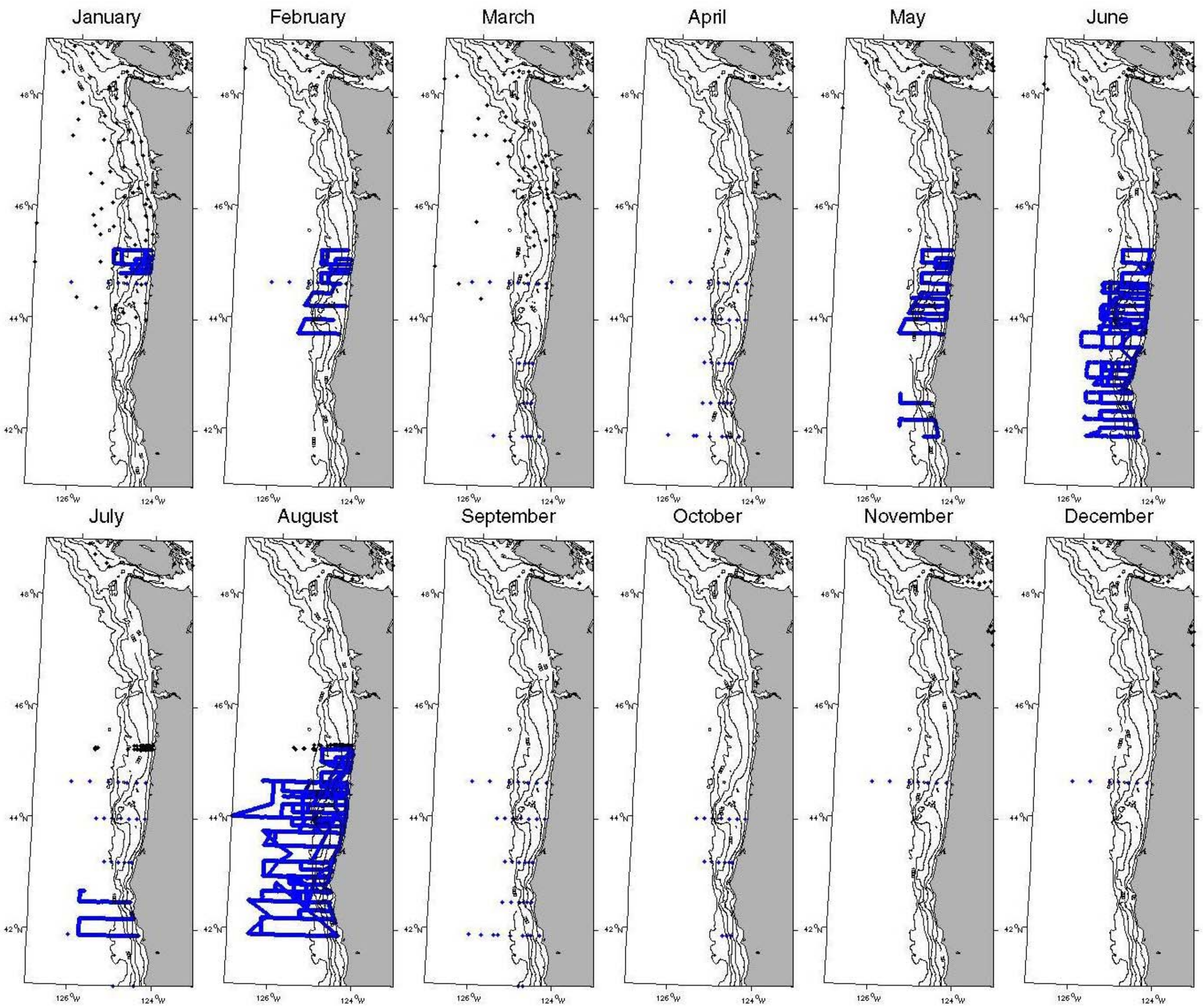


Figure 3-5 Chlorophyll-a samples for the cold-regime (1947-1976) in black and the cold-regime (1999-2004) in blue.

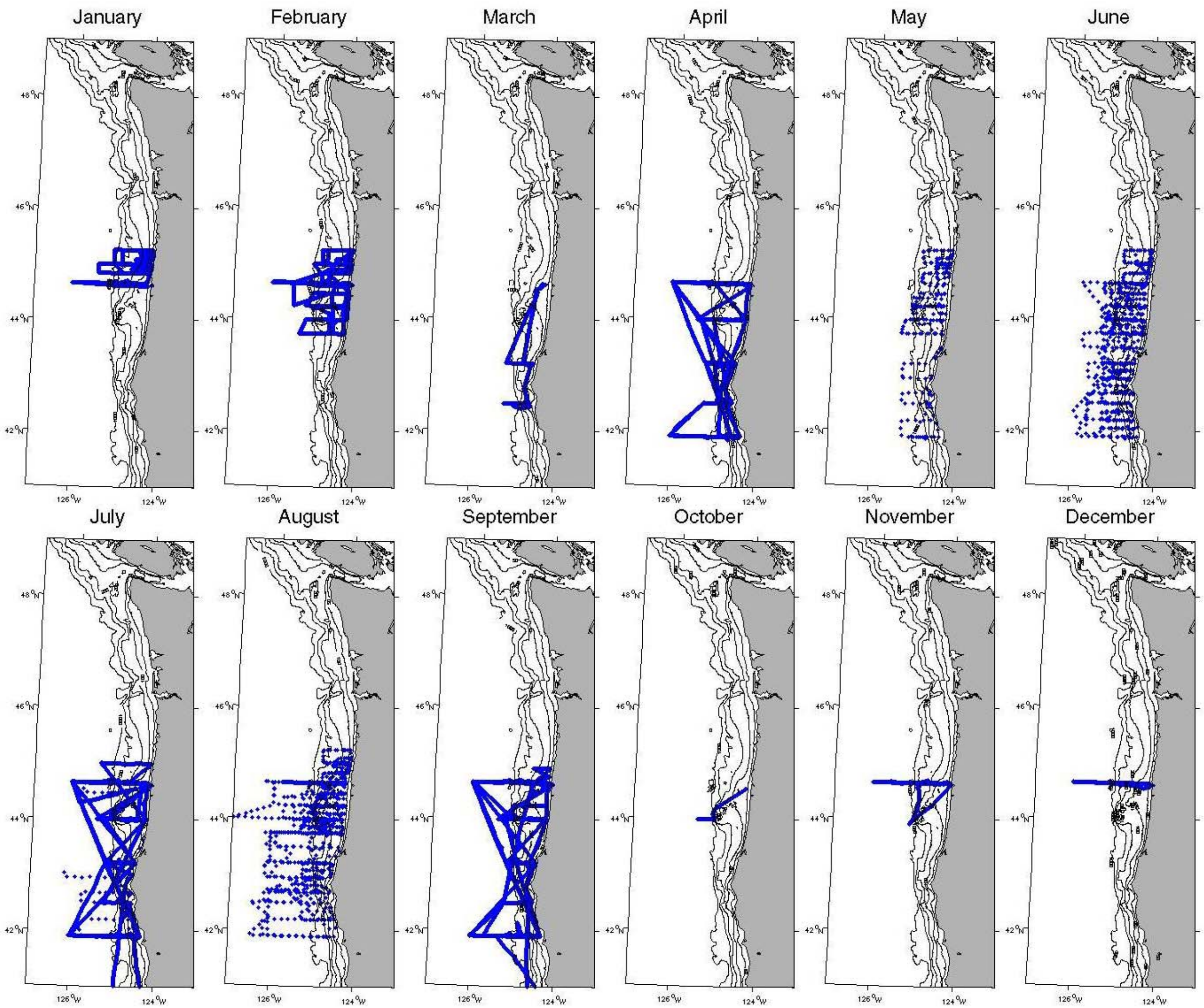


Figure 3-6 **Shipboard ADCP locations for the (1947-1976) (none available) in black and the (1999-2004) in blue.**

Table 3-1 List of 28 groundfish species making up 95% of the total biomass from trawl survey conducted in 2004. Species with an asterisk technically are not classified as groundfish species by the Pacific Coast Groundfish Fisheries Management Plan.

Species Name	Scientific Name	Biomass (kg km^{-2})	Biomass in %
Dover sole	*Microstomus pacificus*	727,165	15.46
Pacific hake	*Merluccius productus*	716,255	15.33
Spiny dogfish	*Squalus acanthias*	448,740	9.66
Sablefish	*Anoplopoma fimbria*	312,430	6.68
Rex sole	*Glyptocephalus zachirus*	237,121	5.09
Arrowtooth flounder	*Atheresthes stomias*	213,781	4.60
Pacific sanddab	*Citharichthys sordidus*	192,869	4.15
English sole	*Parophrys vetulus*	176,037	3.79
Longnose skate	*Raja rhina*	163,903	3.51
Longspine thornyhead	*Sebastolobus altivelis*	151,655	3.27
Sharpchin rockfish	*Sebastes zacentrus*	122,655	2.64
Yellowtail rockfish	*Sebastes flavidus*	92,523	1.99
Pacific grenadier	*Coryphaenoides acrolepis*	92,433	1.99
Shortspine thornyhead	*Sebastolobus alascanus*	90,380	1.94
Canary rockfish	*Sebastes pinniger*	88,320	1.90
Splitnose rockfish	*Sebastes diploproa*	85,092	1.83
*Giant grenadier	*Albatrossia pectoralis*	61,779	1.33
Lingcod	*Ophiodon elongatus*	60,820	1.31
Spotted ratfish	*Hydrolagus colliei*	60,220	1.30
Petrale sole	*Eopsetta jordani*	49,119	1.06
Greenstriped rockfish	*Sebastes elongatus*	47,347	1.02
Big skate	*Raja binoculata*	45,517	0.98
Pacific ocean perch	*Sebastes alutus*	37,121	0.80
Pacific cod	*Gadus macrocephalus*	35,807	0.77
*Slender sole	*Lyopsetta exilis*	33,800	0.72
Darkblotched rockfish	*Sebastes crameri*	30,875	0.66
Stripetail rockfish	*Sebastes saxicola*	27,210	0.59
*Sandpaper skate	*Bathyraja interrupta* and *Bathyraja kincaidii*	23,317	0.50
	Total	4,424,290	94.90

Table 3-2 List of oceanographic data included in the statistical analysis.

Ocean variables used in the statistical analysis
1. Climatological mean for temperature at the surface
2. Climatological mean for temperature at 50 m
3. Climatological mean for temperature at the bottom (10 m above the seafloor)
4. Climatological mean for salinity at the surface
5. Climatological mean for salinity at 50 m
6. Climatological mean for salinity at (10 m above the seafloor)
7. Climatological mean for chlorophyll-a at the surface
8. Climatological coefficient of variation for temperature at the surface
9. Climatological coefficient of variation for temperature at 50 m
10. Climatological coefficient of variation for temperature at the bottom
11. Climatological coefficient of variation for salinity at the surface
12. Climatological coefficient of variation for salinity at 50 m
13. Climatological coefficient of variation for salinity at the bottom
14. Climatological coefficient of variation for chlorophyll-a at the surface

4 RESULTS

4.1 Description of Historical Oceanographic Datasets

The assembling, merging and cleaning of all the oceanographic data collected has been a major achievement of this study. Datasets with an improved temporal and spatial coverage and resolution were created for the study area. Uniform and continuous data coverage is necessary to obtain a broad spatial picture of the oceanographic conditions of the study area and is required for statistical analysis and GIS routines to work. However, each dataset has different characteristics, advantages, and disadvantages that the user should take into consideration.

4.1.1 *Remotely Sensed Data*

Satellite data, including SST obtained from the AVHRR and the sea surface chlorophyll-a obtained from SeaWiFS, offer fine spatial resolution (SST ~ 1km and chl ~5km) and full coverage (Appendix 1, Table 1) for the area of study. However, this type of data has two disadvantages. The first disadvantage is that the temporal coverage is limited to the time period from September 1997 (when the SeaWiFS was launched) to August 2003 (when the data collection for this study was terminated). The second disadvantage is that the satellite data only measures surface properties.

Similarly, HF coastal radar data offer fine spatial resolution (~ 2km). However, one disadvantage is that the data available for this study are limited to the time period from April 2002 to March 2003 (P.M. Kosro, personal communication, 2005). In addition, the radars can only sample the surface waters, and the area sampled is limited to a small region off the central Oregon coast.

Conversely, the in-situ data used in this study (CTDs, Niskin bottle samples, fluorometers and ADCPs) is composed of longer time series of observations, which offered a better temporal resolution and, depending on the data, a good spatial coverage for the study area (Appendix 1, Table 2).

4.1.2 *CTD, Niskin Bottle and Fluorometer Data*

The CTD data (temperature, salinity and depth) gathered for this study, ranged back to the 1930s, making it the most complete data set in term of temporal resolution (Figure 4.1.c and Figure 4.2.c) and, among the in situ data, the most complete in terms of spatial coverage (Figure 4.1.a and Figure 4.2.a). However, the spatial resolutions and coverage is unequal and discontinuous over the study region (Figure 4.1.b and Figure 4.2.b). The CTD sampling effort from the 1930s has been concentrated offshore of the central Oregon coast and to some extent offshore of the northern Washington coast in the Strait of Juan de Fuca, while the Washington coast has been minimally sampled (Figure 4.1.b and Figure 4.2.b). In addition, the areas offshore of the central Oregon coast and offshore of the Strait of Juan de Fuca have been more heavily sampled in the summer months (from May to August) than during the winter months (Figure 4.3). Interestingly, the sampling effort is not only unequal and discontinuous spatially over the study region, it has also been shifting over time and over the seasons (Figure 4.4, a, b, c). The CTD casts illustrated in black covered the time period from 1930s to 1976. The majority of these CTD casts were undertaken by low-resolution CTDs and were classified as an OSD-type instrument by the NODC. The sampling effort and concentration of these CTD casts were scattered all over the study region with high concentrations around the Columbia River plume and in some places followed line transects across shore. The summer season was the most sampled with high concentrations of CTDs offshore of the northern Washington coast, offshore of the central Oregon coast and around the Columbia River plume. In contrast, the winter season was the least sampled overall.

The CTD casts illustrated in blue covered the time period from 1977 to 1997. The majority of these CTD casts were composed of high-resolution CTDs classified by the NODC as high-resolution CTDs. The sampling effort and distribution of the CTD casts, during this period of time concentrated along distinct sampling lines across the study region which are spread unequally from north to south. The highest concentration of CTD casts were found offshore of the Strait of Juan de Fuca. Finally, the spring, summer and fall seasons were sampled more or less equally. In contrast, during the winter season the CTD sampling concentrated only offshore of the Strait of Juan de Fuca and offshore of the Oregon coast.

Lastly, the CTD casts illustrated in red covered the time period from 1998 to 2004. These CTDs are derived mainly from two major interdisciplinary oceanographic programs, GLOBEC and COAST. Since 1998 the sampling effort has been concentrated offshore of the Oregon coast, mainly during the summer season. There are some cruises that were conducted during spring and one during the winter. Another thing to notice is the sampling effort offshore of the Strait of Juan de Fuca has also decreased considerably since1998. Finally, the fall season has barely been sampled since 1998. The exception has been a few line transects off Oregon and some inside and offshore of the Strait of Juan de Fuca.

The collection of Niskin bottle samples attached to the CTD rossete which allowed measurements of chlorophyll-a concentrations in the water column started around the

1960s. The sampling effort and distribution varied among the years, among seasons and among locations (Figure 4.5 and 4.6). The summer months (from May to August) offshore of the Oregon coast have been the most heavily sampled. The majority of the chlorophyll-a observations came from the interdisciplinary GLOBEC and COAST programs.

4.1.3 *ADCP Data*

ADCP measurements, which provide subsurface current velocity, became available off the Washington and Oregon coasts beginning in 1991(Figure 4.7c). Since 1991, most of the studies involving ADCP collection have been concentrated off the Oregon coast (Figure 4.7a), with the central Oregon coast being the most heavily sampled over time (Figure 4.7 b). The Washington coast has never been sampled for ADCP measurement with the exceptions of few a ship lines transiting through in some of the months. Thus, the available datasets offer a fair coverage only of the Oregon coast, providing a good spatial resolution, especially during the summer months. The ADCP measurements are concentrated during the summer months (from May to September) (Figure 4.8). The months of January, February and November have some cruises, and the measurements are almost non- existent during March, October and December. The ADCP data set created in this study is missing the ADCP data collected during the 2001 and 2003 Integrated Acoustic and Trawl survey of Pacific hake. The data were not processed on time for this study.

4.2 Description of Monthly Climatologies

The monthly climatologies computed in this study represent and describe the seasonal evolution of the major oceanographic processes occurring off the Washington and the Oregon coasts at different depths. In this section, climatological monthly means and standard deviations are described at several depths. For further reference, Appendices 2, 3 and 4 include the climatological means, standard deviations and coefficients of deviations, respectively, that are not described in this section.

4.2.1 *Description of Satellite Climatology Maps*

The climatological monthly means for sea surface temperature show the seasonal progression of downwelling and upwelling off the Washington and Oregon coasts (Figure 4.9). From November to April, the sea surface temperature varies from north to south with northern latitudes having lower temperatures than the southern latitudes. From May to October, the surface layer of the ocean starts progressively stratifying vertically as the upwelling season begins. As a result, cold waters coming from the deep rise near the coast (Figure 4.9. cold upwelling water delineated in blue) and warmer waters reside offshore (Figure 4.9. warm waters delineated in red). A larger upwelling region, represented in blue in Figure 4.9, is located offshore of the Oregon coast implying that upwelling intensity is stronger off the Oregon coast than off the Washington coast. On the Oregon coast, the upwelling region is bigger than off Washington, reaching its lower temperatures during the months of June and July. The upwelling region has the bigger extent offshore of Cape Blanco and it is also evident over the Heceta Bank region. During the months of August and September, the upwelling region persists off Cape Blanco and over Heceta Bank, but occupies a smaller region than in the months of June and July. However, in October the upwelling area offshore Oregon grows again considerably over Heceta Bank and offshore of Cape Blanco. At the same time, the coastal waters of the Strait of Juan de Fuca and the northern Washington coast also show characteristics of an upwelling region. The growth in spatial extent of the upwelling region off Washington and Oregon during early Fall is likely due to wind mixing eroding the warm surface layer to revel the upwelled water below.

The climatological monthly means for sea surface chlorophyll-a (Figure 4.10 and Figure 4.11 (chlorophyll-a log transformed)) also show the seasonal progression of surface chlorophyll-a concentrations off the Washington and Oregon coasts. In general, chlorophyll-a concentrations are higher near the coast during the upwelling season and lower during the winter months.

Along the Washington coast chlorophyll-a concentration of at least 4-5 mg m^{-3} are persistent all year round. Chlorophyll-a increases progressively towards the summer months, reaching the maximum concentration from June to September and then decreasing progressively towards the winter months. Chlorophyll-a reaches its minimum concentration during December, January and February. Along the Oregon coast, the seasonal cycle of surface chlorophyll-a concentrations is different. During the winter months, the chlorophyll-a concentrations are very low, lower than along the Washington coast. Then, chlorophyll-a concentrations progressively increases near the coast towards the summer months reaching higher concentration during the months of July and August. The highest concentrations of chlorophyll-a are concentrated over Heceta Bank, the Columbia River plume and around Cape Blanco. Nonetheless, the most distinctive features in the climatologies are, first, the continental shelf off Washington the coast has higher and more permanent chlorophyll-a concentrations than the Oregon coast all year round, and second, the Heceta Bank region holds high concentration of chlorophyll-a almost all year round, excluding the month of December (Figure 4.11).

4.2.2 *Description of HF Costal Radar Monthly Surface Velocity Maps*

The spatial maps in Figure 4.12 show monthly means of surface current velocity off the Oregon coast. Climatologies were not computed for surface current velocity because this study collected surface current velocity data only for one year. The monthly means of surface current velocities provides knowledge of the seasonal varying spatial structure of the shelf currents off the central Oregon coast. Surface currents respond mainly to the seasonal wind cycle. In addition, this is a region of relative complex bathymetry due to the presence of Heceta Bank and therefore it is expected that the currents also will respond to the non-uniform local topography of the region (Barth et al, 2005(a) and Castelao and Barth, in press).

Due to the seasonal wind patterns, the seasonal varying structure of surface current velocity can be summarized in two main seasons, the downwelling season and the upwelling season. In the upwelling season (from March to October), surface current velocities are equatoward. From May to July, an equatoward jet is observed offshore and around the Heceta Bank region, which persist with velocities up to 0.7-0.9 m s^{-1}. The jet is strongest in the month of July. In August and September the jet becomes progressively weaker. In the northern region of the Heceta Bank, the equatorward jet tends to follow the bathymetry (the isobaths), usually at its maximum velocity. By contrast, in the southern part, the jet loses intensity and the transport becomes cross-shore. The southern and inshore region of the Heceta Bank region has the lowest surface velocities throughout the upwelling season. The months of March, April and October also have equatorward surface velocities, however, the velocities are weaker. This might be because these months are considered the transition months between upwelling and downwelling conditions.

During the downwelling season (November-February), the currents are mainly poleward. November and December have stronger surface velocities than January and March. The velocities are especially strong (vel ~0.6 m s^{-1}) in the northern region of Heceta Bank and close to shore during November and December.

4.2.3 *Description of Climatological Maps from CTD Data*

The climatological monthly means for sea surface temperature at 0 m (Figure 4.13), and 50 m depth (Figure 4.14) and near the bottom (Figure 4.15) also reflect the seasonal progression of the downwelling and upwelling phenomena off the Washington and Oregon coasts. The climatological monthly means for temperature obtained from CTDs at the surface (Figure 4.13) resemble the climatological monthly means of sea surface temperature obtained from satellite (Figure 4.9). From November to April, sea surface temperatures at 0 and 50 m depth were colder in higher latitudes and warmer in lower latitudes (Figure 4.13 and 4.14). In the months of January and February, a pool of warm water develops over the Heceta Bank region. Downwelling conditions might be transporting surface waters inshore and pushing them towards deeper depths. The warm pool of water was not noticeable in the satellite climatological monthly means.

In May, the upwelling season begins and the waters become vertically stratified (Figure 4.13 and 4.14). As in the satellite climatological means, the climatological monthly means computed from CTD observations show the upwelling phenomena is more apparent off the Oregon coast than the Washington coast in the surface waters. The CTD climatological monthly means at 0 m show that the upwelling region is bigger during the moths of June and August. In contrast, the satellite climatological means show that the upwelling region was bigger during the month of July. These differences are due to averaging the first top 5meters of CTD observations to get the climatological monthly mean.

Although the upwelling region appears to be bigger off the southern Oregon coast than off the Washington coast and the northern Oregon coast at the surface waters (Figure 4.13), CTD climatological means for temperatures at 50 m show the opposite (Figure 4.14). At 50 m, the upwelling region covers the entire continental shelf off the Washington coast and also the northern half of the Oregon coast. These locations have a wider continental shelf than the southern Oregon coast, making the upwelling region larger. The reason why the upwelling region is less noticeable at 50 m off the southern Oregon coast around Cape Blanco is curious, given that it clearly shows up in 50 m salinity (Figure 4.20). Evidently, temperature is a less faithful indicator of upwelling in this region.

The climatological monthly means for temperature at 10 m above the bottom (Figure 4.15) shows the typical horizontal stratification of the ocean. Generally, water temperatures decrease with increasing depths. Temperatures are warmer in shallower depths than in deeper depths all year round (Figure 4.15). However, temperatures at shallower depths are different off the Washington and the Oregon coasts during the upwelling season. The Washington coast has warmer temperatures in the shallower continental shelf during the summer months than the shallow Oregon continental shelf. This suggests that the upwelling intensity is stronger off the Oregon coast than off the Washington coast.

The standard deviations of temperature at the surface are higher (some regions reach standard deviations of 2^{o}C) and extend over a larger area than at 50 m or near the bottom (Figure 4.16, 4.17, and 4.18). This implies than surface waters are more variable than deeper waters. The upwelling region, especially off the Oregon coast, has a higher standard deviation than off the Washington coast. This might be because the upwelling intensity is higher and varies more over time off the Oregon coast. In addition, the area around the Columbia River plume also shows high standard deviation at the surface, especially from June to October. At 50 meters, the Columbia River area shows high standard deviations only for the months of October and November. In November, the entire Washington coast shows high standard deviations around the coast. Interestingly, the climatological monthly standard deviation near the bottom (Figure 4.18) show that the area around the Columbia River plume has high standard deviation from May to October. The months of June and October have the highest standard deviations. The data coverage is scarce during the winter months, making interpretations more difficult.

Climatological monthly means for salinity at the surface (Figure 4.19), at 50 m (Figure 4.20) depth and near the bottom (Figure 4.21) are mainly characterized by uncovering the Columbia River plume all year round and the upwelling region during the summer months. At the surface, the climatologies illustrate the Columbia River plume very clearly (Figure 4.19, blue depicting fresh waters). During the winter months, the plume is located near the Washington coast and during the summer months it is located off the Oregon coast (Figure 4.19). The Columbia River plume influence is stronger and covers a bigger region during the months of June and July. This is when the offshore Ekman transport of surface water and increased mesoscale variability transport the plume water offshore. In contrast, the climatologies at 50 m depth clearly depict the area influenced by the upwelling phenomenon (Figure 4.20, the upwelling region is depicted in red implying salty water). The upwelling season starts very weakly during March and April, around Cape Blanco. Then, it grows and intensifies throughout the summer months covering the entire coast, and disappearing in the month of November. August shows the largest upwelling region.

Generally, the salinity field corresponds quite well to the temperature field in the upwelling region. As expected, the upwelling phenomenon is associated with low temperatures and high salinities. However, the salinity field shows up much stronger the upwelling region during the months of July to September around Cape Blanco, while the temperature field does not show it for this area. As mentioned before, temperature has showed up to be a less faithful indicator of upwelling in this region. During the winter months, the salinity field outside of the Columbia River plume is very uniform with slight higher salinities in southern latitudes.

The climatological monthly means for salinity at the bottom correspond very well with the climatological monthly means for temperature at the bottom. As expected, salinity increases with increasing depths. The salinities are lower in shallower depths than in deeper depths all year round (Figure 4.21). However, the Washington and Oregon coasts show different characteristics at shallower depths. The shallower waters off the Washington coast have lower salinities than the waters off the Oregon coast. This could be the combination of two things; first, the upwelling intensity might be higher off Oregon than in Washington, therefore increasing the salinity in the Oregon coast. Second, the Washington coast has more and larger rivers discharging fresh water into the Pacific Ocean, therefore decreasing the salinity in this region. From north to south, the rivers are the Soleduck, Bogachiel, Hoh, Queets, Quinault Humptulips and Chehalis. Therefore, the water discharge of these rivers might be affecting the water temperatures off the Washington coast.

The climatological standard deviation for salinity shows that the highest variability in the salinity field is found on the surface waters around the Columbia River plume (Figure 4.22). The pattern is different among the winter and summer months. From September to May since the plume is located off the Washington coast, the salinity fields show higher variability off the Washington coast. From June to August, the salinity fields are more variable off the Oregon coast and the area influenced by the Columbia River plume is larger and extends further offshore. Climatological monthly coefficients of variations for the salinity field (found in Appendix 4) depict the areas with higher salinity variations better. From March to May the nearshore waters off Washington show high standard deviations and high coefficient of variations. However, the highest variability is found during the months of June and July. The months of June and July have the largest and most variable Columbia River plume. As mentioned before, this is when the offshore Ekman transport of surface water and increased mesoscale variability transport the plume water offshore. The river plume from August to November shows the lowest variability in salinity, this is when the Columbia River discharge is at the lowest level of the year.

The climatological standard deviations at 50 m (Figure 4.23) are very low all year round compared with the standard deviations at the surface. There are three regions where the salinity field is a little bit variable. The first region is the area inside and offshore of the Strait of Juan de Fuca all year round. The second variable region is located off the Washington coast (next to the coast), having the highest standard deviation values in October and November. The large number of rivers in Washington State, including the Columbia River, and their year-to-year differences in river discharge might be causing the high standard deviations found off the Washington coast. Interestingly, the Columbia River has the lowest discharges at this time of the year and still it has the highest variation. The third region is situated offshore of Cape Blanco in the upwelling region during the summer months. This region is more variable during July and August. This variability may be caused by the year-to-year variations in the upwelling intensity in this region. The climatological monthly standard deviations at 10 m above the seafloor (Figure 4.24) show higher variability in the salinity field in the shallower continental shelf. This is because shallower waters are exposed to the Columbia River discharge. Again, the Columbia River plume region shows the highest variation in the salinity field all year round. Interestingly, the months of January and February show little variation over the continental shelf off the Oregon coast. However, the data coverage is more limited in the climatologies showing salinity variations at the bottom of the seafloor during the winter months and therefore we should be more cautious with the interpretations.

The monthly climatologies for the chlorophyll-a field are the most incomplete in terms of data coverage and spatial resolution. The spatial distributions of bottle samples collected in the study area since 1959 on a monthly basis were shown in Figure 4.6. During the late winter and early spring months (only from January to March), most of the bottle samples are found off the Washington coast. There are few bottle samples collected from October to December and therefore the climatologies for these months are useless. From January to March the climatological monthly means at the surface shows chlorophyll-a concentration of ~1-1.5 mg m $^{-3}$ close to the shore (Figure 4.25 and 4.25b). The concentrations decrease away from shore. The chlorophyll-a concentrations appear to be slightly higher north of the Heceta Bank region than off the Washington coast in January. In addition, chlorophyll-a concentrations also decrease with increasing depth. The climatological monthly means at 0 m, 20 m, 40 m, 60 m and 80 m (Figure 4.25, 4.26, 4.27, 4.28, 4.29, 4.30, respectively) show how chlorophyll-a concentration decrease from ~1.5 mg m $^{-3}$ at the surface to ~0.2 mg m $^{-3}$ at 80 m depth off the Washington coast. The climatological monthly standard deviations at all depths (Figure 4.31, 4.32, 4.33, 4.34, 4.35, 4.36) show no variability in the chlorophyll-a field during these winter months.

During late spring and the summer months (from April to September), most of the bottle samples are found off the Oregon coast. During these months, the climatological monthly means at the surface (Figure 4.25) show high concentration of chlorophyll-a (more than 10 mg m $^{-3}$) over the continental shelf. As expected, chlorophyll-a concentrations decrease offshore. However, there are some distinct differences among the summer months. In May, high chlorophyll-a concentrations are found over the Heceta Bank region (Figure 4.25a). As the upwelling season develops throughout the summer months, the chlorophyll-a concentrations also expand covering a larger area (Figure 4.25) and the Heceta Bank region maintains its high concentrations (Figure 4.25).

In August, the high chlorophyll-a concentrations are found farther offshore and have a patchy distribution. In September, the chlorophyll-a concentrations decrease around Cape Blanco and are maintained over the Heceta Bank region (Figure 4.25). The climatological monthly standard deviations offshore of the Oregon coast also showed that the chlorophyll-a field is also variable over time and across the regions. In the upwelling region, the chlorophyll-a concentrations show higher variability than in the offshore region (Figure 4.31). The Heceta Bank region is highly variable (~2 stds) throughout the upwelling season (from May to September). The region around Cape Blanco is more variable from June to August, August being the more variable in terms of the area being affected by the high variability. The variability in the chlorophyll-a field decreases with depths (Figure 4.32, 4.33, 4.34, 4.35, 4.36, 4.37).

At 20 m depth, the month of July has the highest standard deviation values in the Heceta Bank region (Figure 4.32). This variability decreases with depth and disappears after 50 m (Figure 4.34). In August, there are two highly variable areas (~2std) at 20 m depth, the Heceta Bank region and a pocket offshore of Cape Blanco. In the Heceta bank region, the variability decreases with depths and it is still visible at 100 m depth (~0.4 stds) (Figure 4.36). In the region offshore of Cape Blanco, chlorophyll-a concentrations show high standard deviation values (~2stds) at the surface and at 20 meters, decreases to 0.4 at 80 m depth and is 0 at 100 m depth. At 100 m depth (Figure 4.36), only the month of June and August show slight variability (~0.4 stds) over the Heceta Bank region.

There are some bottle samples offshore of the Washington coast from May to September (Figure 4.6). In this region, the climatological monthly means at the surface (Figure 4.25) show high chlorophyll-a concentrations ~ 10mg m ^{3} in the Strait of Juan de

Fuca. In addition, there are also high chlorophyll-a concentrations (from 7 mg m ^{3} to above 10 mg m ^{3}) around the Columbia River plume in July and August. The climatological monthly standard deviations show that this region is highly variable (~ 2stds). There is no data at deeper depths for this region.

4.2.4 *Description of Climatological Maps from Shipboard ADCP Data*

The climatological monthly means for subsurface current velocity computed at 30, 50, 100 and 300 m depth describe the seasonal variation of current velocities as a response to seasonal winds and the non-uniform local topography in the study region. As previously described in section 4.2.2, the seasonal varying spatial structure can be described mainly in two seasons, the downwelling and the upwelling season. The ADCP measurements are limited to the Oregon coast. In addition, there is not enough data for the months of January, March, October and December. Therefore, climatologies were not computed for these months.

Climatological monthly means for current velocity at 30 m depth were shown in Figure 4.43 and 4.44. When comparing the climatological monthly means of current velocity at 30 m (Figure 4.43 and 4.44) with the monthly means of surface current velocities from the HF coastal radars (Figure 4.12), there are three things to notice. First, the spatial structure of the currents in the climatologies obtained from ADCP observations are more variable than the spatial structure of the surface velocity currents obtained from the HF coastal radars. This is because the monthly means obtained from the HF coastal radars are computed with a large number of observations and all of them correspond to the same month. In contrast, the climatologies obtained from ADCP observations are computed with fewer observations and the observations come from different years. Second, current velocities are considerably weaker at 30 m than at the surface. Third, most of the climatological monthly means from the ADCP observations are made up of months that cover mainly the upwelling season. The winter months have been less sampled and therefore there is limited coverage. Consequently, there is limited knowledge about the spatial current structure during the downwelling seasons. In contrast, the HF coastal radars provide surface current velocity all year round.

Although the climatological means from ADCP observations show significant spatial variation, still they reveal the seasonal evolution of subsurface current velocity off the Washington and Oregon coast. Current velocities at 30 m are equatoward from April to September (Figure 4.43 and 4.44). In May, the equatoward jet is developed with velocities ~ 0.3-0.4 m s^{-1} and follows the topography contours. By June, the equatoward jet has moved slightly offshore bordering the Heceta Bank region. During these months, the southern and near-shore regions of the Heceta Bank are exposed to weak current velocities (vel < 0.1 m s^{-1}). The months of July, August and September show the highest spatial variation in the current velocity field. During these months, the equatoward jet is visible and it tends to follow the isobaths. However, the velocities in the region offshore of Cape Blanco are spatially variable. For example, in August offshore of Cape Blanco, the currents move offshore crossing the isobaths and then turn south. The month of September is also spatially variable. Some of the velocity vectors are equatoward and some poleward. However, a weak equatoward jet is visible offshore of Oregon and the Heceta Bank region is characterized by having weak current velocities (< 0.5 m s^{-1}).

In contrast, in November the climatological mean at 30 m show poleward currents and strong current velocities close to shore, especially in the Heceta Bank region, which during the entire upwelling season is characterized by weak velocities. The month of February is more spatially variable. During February, the Heceta Bank region is characterized by having weak equatoward currents. In addition, the region south of Heceta Bank has several poleward vectors and offshore of Heceta Bank the currents are stronger and flow cross-shore towards the coast.

The climatological monthly means of current velocity at 50 and 100 m depth (Figure 4.45, 4.46, 4.47, 4.48) show the same spatial patterns as the monthly climatologies at 30 m depth but with weaker velocities. However, the climatological monthly means of current velocity at 300 m depth (Figure 4.49 and 4.50) show distinct spatial patterns. This is because at 300 m depth the poleward current, also called California Undercurrent, become apparent. From May to July, the California Undercurrent is noticeable. Most of the current vectors are poleward and the current velocity is less than 0.2m s^{-1} especially in the areas close to shore. In August, the area close to shore shows poleward currents, however, the offshore areas the currents are moving offshore and then turning south. The months of September, November and February have highly variable currents and it is hard to establish a general pattern. Vertical sections of climatological monthly means for current velocity at the Newport Hydropraphic Line are included in Appendix 5.

4.3 Statistical Analyses

4.3.1 *Fish Data*

Only the 28 species (Table 4.1) that made up 95% of the total biomass were incorporated into the analysis. The beta diversity decreased from 7.9 (when 253 species) to 1.5 after the rare species were removed, leaving only 28 species. Beta diversity is a measure of amount of compositional change represented in a set of sample units (in this case the trawl hauls) (McCune and Grace, 2002) and emphasizes the mixture and heterogeneity of communities. The most abundant 28 species of groundfish had broad latitudinal ranges occupying the entire study region. The exception was that yellowtail rockfish and Pacific cod that did not inhabited the region south of Cape Blanco. In addition, all the species showed a preferred depth range with the exception of sablefish, shortspine thornyhead, longspine thornyhead, dover sole, Pacific hake, longnose skate and sandpaper skate which inhabited a much broader depth range.

4.3.2 *Cold Regime Summer Climatologies*

The cold regime "summer" climatologies computed in section 3.4.2 were composed of oceanographic data that belong to the months from May to October (in this study this period of time was referred as summer) and fell within a cold regime period (1947-1976 and 1999-2004). Therefore, the following description of these climatologies represent the best estimate for the oceanographic conditions present during the summer upwelling conditions of a cold regime year. Once more, this analysis used the climatologies to represent the oceanographic conditions during cold regime conditions in the summer, and assumes those conditions are the ones manifested in the summer of the year 2004 off the Washington and Oregon coasts.

The cold summer climatological mean for temperature at the surface (Figure 4.51a) clearly delineates the cold upwelling region (in blue) versus the warm offshore waters (in red). The upwelling region is more visible off the Oregon coast than off the Washington coast. Off the central Oregon coast, the cold upwelling waters are contained within the continental shelf and cover the Heceta Bank region. In contrast, the upwelling region off the southern Oregon coast extends to deeper waters. The standard deviation (std) (Figure

4.451b) and coefficient of variation (CV) (Figure 4.51c) of this climatology showed that the surface waters are variable, on average the entire study region had standard deviation values of ~1.5^{o}C. The higher values (std >3^{o}C and CV >0.25) are found offshore off the Washington coast. In addition, an area south of Cape Blanco also showed high standard deviation values (std ~2^{o}C) and high coefficient of variation values (CV ~0.15). The least variable areas are found in the deep offshore waters.

The cold summer climatological mean for temperature at 50 m (Figure 4.52a) demarcates an upwelling region extending from the northern Washington coast down to the southern Oregon coast. At 50 m depth, the upwelling region off the Washington coast extends further offshore than off the Oregon coast except the wide upwelling region over the Heceta Bank. This is because the continental shelf off the Washington coast is wider than off the Oregon coast. Notice that the upwelling region off the Washington coast could not be observed in the temperature climatology at the surface. The variability in the temperature field (Figure 4.52b and c) is high again in the offshore areas (std>1^{o}C and CV~0.15). These high values could be the result of merging CTDs from different periods of time and using different instrumentations for their collections, or also it could be due to few measurements and bad observations. Remember that most of the CTDs located off the Washington coast were collected in the regime period from 1947 to 1976 and most of the CTDs located off the Oregon coast were collected in the GLOBEC and COAST programs after 1998. In addition, notice the high standard deviation and coefficient of variation values (std>1^{o}C and CV> 0.15) in the northeastern near-shore region off the Washington coast.

The cold summer climatological mean for temperature at the bottom (Figure 4.53a) show largely the general stratification of the ocean. Shallow waters are warmer (in red) and as depth increases, water temperatures decrease (cold waters in blue). As previously described in section 4.2.3, during the summer upwelling season, the near-shore deep waters off the Washington coast are warmer than the near-shore deep waters off the Oregon coast. Upwelling intensity might be stronger off the Oregon coast, dropping the temperatures at the bottom of the seafloor. Also, as previously discussed, freshwater river discharge is greater off the Washington coast. Therefore, this might be another factor influencing the nearshore waters off the Washington coast. The standard deviation and coefficient of variation (Figure 4.53 b and c, respectively) show high variability in the temperature field off Washington coast and on the Columbia River plume. In addition, waters near Cape Blanco were also variable and to a smaller extent over the Heceta bank region.

The cold summer climatological mean for salinity at the surface (Figure 4.54) strongly demarcates the riverine fresh waters from the saltier ocean waters. The most noticeable fresh water signature is the Columbia River plume, which extends offshore and towards the south. There is also a pool of fresh water located next to the Washington coast. Finally, off Vancouver Island in Canada, there is also a small freshwater signature. The highest variability in the salinity (Figure 4.54b and c) is found on the Columbia River plume (std>1^{o}C and CV> 0.05). The river plume variability affects a huge area off the Oregon coast. In addition, the near-shore waters off the Washington coast also have high variability (std~1 ^{o}C and CV~0.03) as well as the upwelling region off Cape Blanco (std~1 and CV~0.025).

At 50 m, the cold summer cliamatological mean for salinity (Figure 4.55a) demarcates clearly the upwelling region (salty waters in red) from the oceanic offshore waters (in green). The upwelling region extends all the way from the northern Washington coast to the southern Oregon coast. Notice how the salinity within the upwelling region increases towards the south. Off the Oregon coast, especially off Cape Blanco, the upwelling region extends further offshore and the salinity is higher than of Washington coast. This might be caused by more intense upwelling and by the small influence of freshwater river discharge from the Oregon coast. The large number of rivers in Washington State might be diluting the upwelling signature. The variation in salinity at this depth (Figure 4.55b and c) is smaller than at the surface. The high salinity variation at the Columbia River plume is perceived very weakly at these depths (std~0.4 ^{o}C and CV~0.025). In contrast, the Strait of Juan de Fuca and the near-shore area off the Washington coast show signs of still being highly variable at these depths. The near-shore area shows standard deviation values of ~1^{o}C and coefficient of variation values > 0.05. The upwelling region shows smaller standard deviation and coefficient of variation values (std~0.5 ^{o}C and CV~0.035) than the near-shore area off the Washington coast.

The cold summer climatology for salinity at the bottom (Figure 4.56a) shows the natural stratification of the ocean. Salinity at shallower depths is less salty than at deeper depths since salinity increases with depth. The waters off the Washington coast are fresher than off the Oregon coast and there is not a strong gradient of salinity from shallow to deeper waters off the Oregon coast. In addition, the highest salinity variation is found off the Columbia River plume and the Washington coast (std>1 ^{o}C and

CV>0.03). The waters off the Vancouver Island in Canada also show variability in the salinity field (std~0.5 ^{o}C and CV~0.017) (Figure 4.56a and c).

Finally, the cold summer climatological mean for chlorophyll-a (Figure 4.57a) shows highly productive waters within the upwelling region off the Washington and Oregon coast and how the high concentrations are constrained within the continental shelf. High chlorophyll-a concentration extend further offshore off the Washington coast than the Oregon coast as the upwelling region does, except the wide region over the wide upwelling region over the Heceta Bank. As previously mentioned, this is caused by the large size of the continental shelf off the Washington coast being bigger. The standard deviation values show how the continental shelf region is more variable than the offshore waters (Figure 4.57b). In addition, the coefficient of variation shows that the offshore area off the Washington coast, the upwelling region south of Cape Blanco and in at smaller extent the Heceta Bank region are more variable over time relative to their mean concentrations (Figure4.57c). This indicates that these regions are exposed to big blooms of chlorophyll-a (the standard deviations are much bigger than the mean).

4.3.3 *Results from the Statistical Analysis*

4.3.3.1 *Identification of Ocean Habitats*

A classification method and an ordination method were used to identify ocean habitats off the Washington and Oregon coasts.

4.3.3.1.1 Clustering Analysis of the Environmental Data

The clustering analysis was set up to partition the environmental distance matrix into three, four, five and six different groups, with the goal of exploring how many distinct ocean habitats exist off the Washington and Oregon coasts in terms of their physical and biological characteristics. In our case, each group corresponded to a distinct ocean habitat. The distinct groups or "ocean habitats" for each of the cluster analyses undertaken with each partitioning is shown in Figure 4.58.

When the environmental distance matrix was partitioned into three groups (Figure 4.58a), the divisions consisted mainly in the grouping of the trawl stations influenced by the upwelling phenomenon versus trawl stations in the offshore region. The third group consisted mainly of the trawl stations located in the Columbia River plume. When the clustering was set up to divide the environmental distance matrix into four groups, the region south of Cape Blanco came out as an additional distinctive group (Figure 4.58b, in green). Next, the environmental distance matrix was partitioned into five different groups. This time the Columbia River plume and the near-shore area off the Washington coast emerged as two different groups having different oceanographic characteristics (Figure 4.58c, Columbia River plume stations are colored in orange and the near-shore area stations off the Washington coast are colored in red). Finally, when the environmental distance matrix was partitioned into six groupings, a new group emerged by dividing the near-shore trawl stations off the Washington coast into two groups (Figure 4.56d, orange stations and blue stations).

Under careful examination, using the current knowledge on the oceanographic processes occurring off the Washington and Oregon coasts, and the climatologies computed in this study, five groups or "five ocean habitats" were chosen as the number of habitats that most closely represented the natural oceanographic conditions during the summer months off the Washington and Oregon coasts. Additionally, a descriptive table (Table 4.2), which summarizes the differences among groups by averaging each of the ocean variables within each group, was used to further describe and delineate each of the ocean habitats. This table was obtained from a discriminate function analysis.

Thus, the cluster analysis that identified five different ocean habitats (Figure 4.59), characterizes the ocean environment off the Washington and Oregon coasts during the summer upwelling conditions in cold regime years. The first cluster group (n=14) identified in the clustering analysis and represented in red squares in Figure 4.59 is located in the northeastern section of our study region off the Washington coast. This ocean habitat is characterized by having the highest coefficient of variations (CV) of all the habitats (Table 4.2). The highest CVs in a decreasing order were found for temperature at 50 m (CV~0.21), temperature near the bottom (CV~1.16), temperature at the surface (CV~0.12), salinity near the bottom (CV~0.02) and salinity at 50 m (CV~0.1). These CV's indicate that this group is the habitat with the highest natural variability. For this reason, this group was named, the Highly Variable Habitat. Also, notice that surface chlorophyll-a had the highest CVs of all the variables within the High Variable Habitat. However, comparing the CV of chlorophyll-a with all the other habitats, the High Variable Habitat had a low CV for surface chlorophyll-a. In addition, the High Variable Habitat is characterized by having the highest temperature at the bottom and at the same time the lowest salinity at the bottom of the seafloor among all the habitats. A possible explanation for having the warmest bottom temperatures would be that the upwelling intensity off the Washington coast is lower than off the Oregon coast. This is supported by the climatological means computed in this study (Figure 4.51). In addition, the freshwater discharge from the Strait of Juan de Fuca and the large number of rivers in the Olympia Peninsula in Washington State, together with vertical advection and mixing, could be a possible reason why this habitat has the fresher bottom waters.

The second cluster group (n=108), identified in the clustering analysis and represented in blue circles in Figure 4.59, covers the majority of the continental shelf from northern Washington to Cape Blanco. This habitat is characterized by having cold temperatures (T) at the surface (T~12.66) and at 50 m (T~7.97), and having high salinity at the surface (S~31.84) and at 50 m (S~33.13). These conditions describe a typical upwelling region where cold, saline water are brought from deep water to the surface. For these reasons, this group was named the Upwelling Habitat. In addition, the Upwelling Habitat is characterized by having relatively high concentrations of chlorophyll-a (CHL~ 3.6), which is expected in the productive upwelling regions.

The third cluster group (n=52) identified in the clustering analysis and represented in green stars in Figure 4.59 covers the southern region of our study area, south of Cape Blanco and is located over a narrow continental shelf composed largely of deep waters. This cluster group is characterized by having the lowest temperatures at the surface (T~11.5) and the second lowest temperatures at the bottom (T~6.4), and having the highest salinity at the surface (S~32.95) and at 50 m (S=33.54). It also had the second highest salinity (S~34.1) at the bottom. In addition, it has the highest CV for temperature at the surface (CV~0.13). These characteristics describe a very intense and variable upwelling region with high mesoscale activity. For these reasons, this group was named the Highly Variable Upwelling Habitat. In addition, it has the second lowest chlorophyll-a concentration (CHL~2.5) of all the other ocean habitats. An explanation for this characteristic may be that an area of such high mesoscale activity and high surface velocities (Wroblewski, 1977; Huyer *et al.,* 2005) will advect chlorophyll-a concentration offshore.

The fourth cluster group (n=65), identified by the clustering analysis and represented in black diamonds in Figure 4.59, covered the northern and central offshore region of the study area mainly covering the continental slope. This cluster group was located over the deepest waters of the study region. It is characterized by having the warmest surface temperatures (T~14.34), relative low salinities at the surface (S~31.3) and the lowest salinities at 50 m (S~32.6). This offshore area is not affected by the cold, saline waters found in the coastal upwelling region. During the summer months, the surface waters are heated by solar radiation. In addition, since this ocean habitat is located in deep waters, the salinity at the bottom reaches the highest salinity (S~34.17) of all the habitats. Finally, it is distinct from the other habitats since it contains the lowest surface chlorophyll-a (CHL~1.6). This habitat was named, Offshore Habitat.

The last cluster group (n=13), identified by the clustering analysis and represented by yellow crosses in Figure 4.59, is confined to the area influenced by the Columbia River plume. This cluster group was characterized by having the lowest surface salinities (S~28.04) and the second highest surface temperatures (T~13.7) similarly to the Offshore Habitat. In addition, it had the highest CV for salinity at the surface (CV~0.14). In contrast, it had cold temperatures (T~7.8), similar to the upwelling Habitat, at 50 m and the second warmest bottom temperatures (T~7.2). The presence of the Columbia River creates the top layer of fresh water present in the region and the high CV for surface salinity implies that the amount of fresh water discharged by the Columbia River varies over time. A possible explanation for the warm bottom waters could be that the

Washington coast has a less intense upwelling region than the Oregon coast and therefore the bottom waters are warmer off the Washington coast than of the Oregon coast. This group was called the River Plume Habitat. In addition, this habitat had the highest surface chlorophyll-a concentrations (CHL~5.9) of all the other habitats making it the most productive. The stable upper layer created by the river input likely helps this high productivity.

4.3.3.1.2 Principal Components Analysis of Environmental Data

The results of the principal components analysis (PCA) on the environmental matrix describing the ocean characteristics (physical forcing and biological forcing) off the Washington and Oregon are given in Table 4.3 and Figure 4.60. Table 4.3 lists the loadings (eigenvectors) bigger than 1 for the first three principal components (PC). Loadings identify what ocean variables are the biggest contributors to each of the components. The first three PCs explained 64.1% of the variance in the ocean dataset. Figure 4.60 shows the site scores (the scores in each sample unit or in our case trawl station) for each PC. By combining the information from the loadings and the sites of the scores for the first three components, interpretation of the physical forcing described by temperature and salinity and the biological forcing described by chlorophyll-a on the system were made and therefore different regions throughout the study region that are subject to distinct physical and biological forcing were identified.

The first principal component (PC1), which explained 28% of the variance, was characterized by describing the differences between the inshore (upwelling region) and offshore areas (Figure 4.60). Surface chlorophyll-a (loading=-0.46) was the highest contributor in PC1. At the surface, close to shore chlorophyll-a concentrations are high and decrease further offshore. Temperature at 50 m (loading=0.35) came out as an important variable in PC1, depicting the cold water near shore versus warm waters offshore, which also described the upwelling region. In addition, salinity (loading=+0.45) and temperature (loading=0.36) at the bottom of the seafloor explained some of the inshore-offshore variation in PC1. Salinity close to shore is low and increases as depth increases and temperature close to shore is high and decreases as depth increases. Finally, the coefficient of variation for chlorophyll-a at the surface (loading= 0.38) also came out with high loading in PC1. It turns out that the offshore areas, especially offshore of Cape Blanco are more variable in chlorophyll-a than the inshore areas over time. In summary, the first component (28%) described depth variations in temperature and salinity at the bottom of the seafloor, and cross-shore variations in chlorophyll-a concentrations at the surface between the inshore productive upwelling habitats and the offshore less productive deep habitats, but more variable in terms of chlorophyll-a concentrations.

The second principal component (PC2), which explained 23.1% of the variance, depicted mainly the region influenced by the Columbia River plume, which is illustrated in Figure 4.60 in red. The red area is characterized by having low salinities at the surface (loading=-0.41) and at 50 m depth (loading=-0.44) and warm sea surface temperature. In addition, it is characterized by having high CV of salinity at the surface (loading=0.33) implying that there is a year-to-year variation in the river discharge influencing this region. PC2 also depicted the nearshore upwelling region, which is illustrated in Figure 4.58 in blue. The blue area is characterized by having low temperatures at the surface (loading=0.5) and high salinities at the surface (loading=-0.41) and 50 m (loading=-0.45).

In summary, PC2 explains the variation in the surface waters, depicting the river plume signature very well, which is mainly driven by a strong freshwater influence and the year-to-year variation of the river discharge, and differentiating it from the upwelling region.

Finally, the third principal component (PC3), which depicted 13% of the variance, was characterized by differentiating variable habitats, which were characterized by having high coefficients of variation for the oceanographic variables (occurring mostly at 50 m and near the seafloor), from non-variable habitats, which were characterized by having low coefficients of variation for the same oceanographic variables. Figure 4.60 shows variable areas in red and non-variable areas in blue. The red areas are characterized by having a high CV for temperature at 50 m (loading=0.53) and at the bottom of the seafloor (loading=0.34). As expected, salinity at 50 m (loading=0.39) and at the bottom (loading=0.42) also explained some of the variation. In Figure 4.58, PC3 depicts three variable areas, the first one, the near-shore region off the Washington coast, secondly, an offshore region off the Oregon coast and third an offshore region of Cape Blanco. The near-shore region offshore of Washington State is influenced by the Strait of Juan de Fuca. It also has a large number of rivers discharging water into the ocean and the precipitation is also high in the Olympia peninsula. The year-to-year variation in these two factors (freshwater discharge and precipitation) might be creating the variation in the temperature and salinity field in this region. The offshore area off the Oregon coast might be due to the year-to-year variability in freshwater discharge by the Columbia River plume. Finally, the area offshore of Cape Blanco is influenced by the upwelling phenomenon and it is an area of high mesoscale activity. The year-to-year variation in the upwelling intensity might be creating the variability in the temperature and the salinity field.

4.3.3.2 *Fish Community Analyses*

The fish community analyses consisted of the examination of fish distributions and abundances in relation to oceanographic variables (cold regime summer climatologies) and ocean habitats.

4.3.3.2.1 Multi-Response Permutation Procedure

The identification of ocean habitats in the clustering analysis allowed the creation of *a priori* groups (the ocean habitats) and therefore this gave us the chance to evaluate each species role, one at a time, in each of the ocean habitats. Thus, a multi-response permutation procedure (MRPP) was used to compare groundfish species composition among the five ocean habitats identified in the clustering analysis. The MRPP supported the statistical significance of difference among ocean habitat groups in terms of species composition (*p-value*=0.001) (Table 4.4). The nonparametric procedure suggests that the species composition among the five ocean habitats is different. In addition, MRPP found moderate within group agreement (A~0.17). Therefore, the community composition differed strongly among the ocean habitats.

4.3.3.2.2 Indicator Species Analysis

The indicator species analysis (ISA), which determined indicator species for each of the ocean habitats, showed significant species association for all the ocean habitats except for the Upwelling Habitat (Figure 4.61 and Table 4.5). In terms of species composition, the smallest habitats had the most number of species indicators (Figure 4.61). The Highly Variable Habitat (red stations) was characterized by the presence of spiny dogfish

(40.6%), English sole (28.1%), rex sole (25.5%), longnose skate (24.1%), arrowtooth flounder (24%), Dover sole (23.2%), Pacific cod (19%), and yellowtail rockfish (12.2). Big skate was also included in this group, but its indicator value was not significant (*p-value*=0.287). The River Plume Habitat was characterized by the presence of Pacific sanddab (38.7%), petrale sole (36.1%), Pacific hake (30.5%) and spotted ratfish (24.5%). Slender sole, lingcod, and sandpaper skate were also included in the river plume habitat. However, their indicator variable was not statistically significant (*p-value*=0.216, 0.139, 0.363, respectively).

Interestingly, the Upwelling Habitat, which is the biggest habitat, had only two indicator species, greenstriped rockfish (15.8%) and canary rockfish (6.5%). However, their indicator values were not statistically significant (*p-value*=0.171, *p-value*=0.398, respectively). The most characteristic species of the Highly Variable Upwelling Habitat were sablefish (24%), Pacific grenadier (20.5%), striptail rockfish (19.9%) and giant grenadier (18.2%). Finally, the Offshore Habitat was characterized by the presence of shortspine thornyhead (40.7%), longspine thornyhead (29.4%) and Pacific ocean perch (25.1%). Sharpchin rockfish (12.9%), splitnose rockfish (12.1%) and darkblotched rockfish (8.5%) were also grouped in this habitat, but their indicator values were not significant (*p-value*=0.075, 0.138, 0.646, respectively).

Overall, only three species showed indicator values around 40% or higher, spiny dogfish in the Highly Variable Habitat, shortspine thornyhead in the Offshore Habitat and Pacific sanddab in the River Plume Habitat. These were considered high indicator species. The next set of species showing statistically significant indicator values of around 15 to 40%, were considered to be moderate indicator species. Species with indicator values of less than 15% were considered weak indicator species.

4.3.3.2.3 Non-Metric Multidimensional Scaling (unconstrained method of ordination)

A non-metric multidimensional scaling (NMDS) analysis on the community data further indicated that groundfish communities differ among some of the ocean habitats (Figure 4.62). Ordination plots of stations in species space from a 3-dimensional solution after rotation of the axes are shown in Figure 4.62. The stations have been color coded with the ocean habitats identified in the cluster analysis. After rotation of the axes, axis1 capture 3.4% of the variance in the species data, axis 2 capture 77% of the variance and axis3 capture 14% of the variance. The axes from a NMDS analysis are independent of each other, they are arbitrary, they are not perpendicular to each other and they are not cumulative like axes obtained from a principal component analysis. The three-dimensional solution (the three axes together) explains 95% of the variation in the species data. In order to aligned axes with environmental variables, the ordination axes in Figure 4.62a were rotated +25 degrees and in Figure 4.62b were rotated +211 degrees. The rotation allows a better visualization of the data. It does not change the results.

The results from the initial unconstrained NMDS run, which cascaded down from six to one dimension, are shown in Table 4.6. The results were assessed graphically with the scree plot of final stress versus the number of dimensions (Figure 4.63). Big drops in stress and statistically significant *p-value*s are indicators to choose the best ordination solution. Since, the biggest drop in stress was from one-to-two dimensional solutions and the two dimensional solution already explained 91% of variance in fish data, the initial unconstrained NMDS run recommended the two dimensional solution. Therefore, two-dimensional solution could have been potentially chosen for the ordination. However, a the three-dimensional solution was chosen because the three-dimensional ordination illustrated more clearly the association of communities of groundfish species with the environmental variables and ocean habitats. In addition, the Monte Carlo test of significance indicated a better than random solution for all the dimensions (*p-value*=0.0196) (Table 4.6). The final three-dimensional solution was also assessed graphically using plots of stress, instability, step length and magnitude of the gradient vector (Figure 4.64). The NMDS solution found an unstable solution (log(0.02)=-1.66) (Figure 4.64b) because the stress values fluctuate among several values. However, since the instability was interrupted by persistent and low levels (from 9 to 14) fluctuations in stress (Figure 4.64a) with final stress of 9.53 and the total variance explained the NMDS in the fish data matrix was 95%. We judged that the resulting ordination was acceptable. We believed the source instability is caused by the high abundances of specific species found on specific trawl stations, as it will be explained later.

The ordination plots from the three dimensional solution are shown in Figure 4.62. Figure 4.62a displays how the cloud of multivariate points is primarily arranged along axis 2. Based on the color-coding from the ocean habitats identified in the clustering analysis, the ordination has grouped the shallow trawl stations, the River Plume Habitat (yellow stations), the Highly Variable Habitat (red stations) and the Upwelling Habitat (blue station), on the negative side of axis 2 and it has grouped the deeper stations, the Offshore Habitat (black stations), on the positive side of axis 2. However, the green stations, which were classified as the highly Upwelling Habitat, spread along both sides of axis 2. This is because the highly Upwelling Habitat is composed of both shallow and deep stations. Interestingly, the ordination of the points along axis 2 have a circular shape, which was called a banana-type shape for easier interpretation as it will be seen later. Also, to better understand the three-dimensional visualization of the results, imagine that Figure 4.62a is depicting a banana which is lying on a table. The points are creating a banana shape because in both extreme sides of the ordination (in each end of the banana), there are a couple of stations that show higher than average biomass values for specific species. Thus, the stations are pulling the ordination at each side of the banana, creating the banana shape.

In addition, stations are also spreading along axis 3 in Figure 4.62 a, especially in the negative side of axis 2. These are the shallowest station. We expect more scattering of points among the shallower stations, because species composition is more diverse in shallower waters than deep water. Among the shallower stations, the River Plume Habitat (yellow stations) seem to be grouping in the negative side of axis 3, and the Highly Variable Habitat (the red stations) and Upwelling Habitat (the blue stations) are scattered along both the negative and positive side of axis 3. This suggests that the groundfish community composition is slightly different in the River Plume Habitat. Finally, the deep stations in the positive side of axis 2 are more clustered together (they do not spread out as the shallower stations) and what this means is that the species composition is more uniform in the deep stations.

The multivariate fish data cloud in the NMDS ordination plot of axis 1 versus 2 (Figure 4.62b) is reproducing a similar data cloud but from a different angle. Imagine the banana is lifted up and it is set upright on the table. This is what ordination plot is showing. The stations are still primarily aligned with axis 2, which explain the variation of species composition between shallow and deep species. In addition, axis 1 is showing how the shallower stations (blue, yellow and red) have more heterogeneous species compositions than the deeper stations. However, this time the pattern in the shallower stations is more apparent. The highly Variable Habitat (red stations) and the River Plume Habitat (yellow stations) are being clustered in the negative side of axis 1. Even it seems that stations belonging to the River Plume Habitat are grouping together and to some extent, the stations belonging to the Highly Variable Habitat too, with a few exceptions. Some of the stations belonging to the Highly Variable Habitat and the River Plume Habitat do not cluster with the others. The stations belonging to the Upwelling Habitat are scattered all along the entire axes1.

The NMDS analysis also yielded how individual environmental variables correlated with each of the ordination axes (Figure 4.62). The most significant environmental variables that correlated with each of the ordination axis are shown in Figure 4.62. Environmental correlations are interpreted by the direction and magnitude of the vectors in Table 4.8 and in the ordination plots. Four of the fourteen environmental variables, depth, mean salinity at the bottom, mean temperature at 50 m and CV of chlorophyll-a at the surface, had strong positive correlations with axis 2 (r=0.91, 0.63, 0.61 and 0.49, respectively). Mean temperature at the surface had also moderate correlations with axis2 (r=0.31). While mean temperature at the bottom and mean chlorophyll-a concentration at the surface had strong negative correlation with axis 2 (r=-0.74 and r=-0.69, respectively). Longitude had a moderate negative correlation (r=-0.39) with axis 2. The environmental variables with strong correlation on axis 2 explain primarily the natural stratification of the ocean and upwelling characteristics in surface waters during the summer upwelling conditions. The seafloor over the continental shelf is exposed to warmer and less salty waters than the seafloor over the continental slope, which is exposed to colder and saltier waters. However, the coastal surface waters are exposed to cold, salty and nutrient-rich waters, which produce the high chlorophyll-a concentrations along the coast. In addition, a second pattern arises by looking how environmental variables correlated with axis 1 and 3. Chlorophyll-a at the surface was moderately correlated with the negative side of axis 1 and 3 (r=-0.2 and r=-0.2). In this side of the axis, the red and the yellow stations grouped indicating that these stations have moderately higher chlorophyll-a concentrations.

Correlation coefficient (r) between abundances for each species and ordination scores in each of the axes are given in Table 4.7. Most of the species showed intermediate to high correlations with axis 2 (0.4<= |r| >=-0.91), thus differentiating between shallow and deep species. There were seven groundfish species showing a low degree of linear correlation (|r|<=0.3) with axis2. The majority of the species had a negatively correlation with axis 2 indicating that shallow stations have a more heterogeneous composition of species. This indicates that most of variation in species composition and abundances is primarily driven by the natural stratification of the ocean and the upwelling characteristics in the surface waters. Interestingly, the seven species (striptail, darkblotched, splitnose, canary and yellowtail rockfish, and Pacific ocean perch and sharpchin), which did not show correlation with axis 2, did show moderate or weak correlation either with axis 1 and/or axis 3, indicating that other factors such us latitudinal changes and differences in upwelling intensity and freshwater discharges might be explaining their distributions.

Positive correlations with axis 1 were moderate for greenstriped (r=0.54), sharpchin rockfish (r=0.51) and lingcod (r=0.46). While negative correlations with axis 1 were moderate for Pacific sanddab (r=-0.47). Chlorophyll-a at the surface also showed moderate correlations with the negative side of axis 1. This suggests that Pacific sanddab was more abundant in stations with high chlorophyll-a concentration, which was characteristic of the Plume River Habitat (yellow stations) and the Highly Variable Habitat (red stations). Notice how the red, yellow and some blue stations have grouped in the negative side of axis 1. Moreover, Pacific sanddab (r=-0.42) was the only species showing moderately negative correlation with axis 3. Chlorophyll-a at the surface also correlated negatively with axis 3. This suggests again that Pacific sanddab is associated with high concentration of chlorophyll-a. However, notice how this ordination plot has only grouped the yellow and blue stations in the negative side of axis 3. Finally, Dover sole (r=0.65), sandpaper skate (r=0.57), lingcod (r=0.55), slender sole (r=0.52), arrowtooth flounder (r=0.52), darkblotched rockfish (r=0.52) and splitnose rockfish (r=0.52) shows moderate positive correlation with axes 3, which was characterized by having a weak correlation with only temperature at the surface. Sablefish (r=0.47) and shortspine thornyhead (r=0.41) were the only species that showed moderate positive correlation with ordination axis 3 and positive correlation with axis 2 and pacific grenadine and giant grenadine were the only two species that showed negative correlation with axis 3 and positive correlation with axis 2.

4.3.3.2.4 Canonical Analysis of Principal Coordinates (Constrained ordination method)

The following section will present the results from the canonical analysis of principal coordinates (CAP), which is the constrained method of ordination. First, the results from the type canonical discriminant analysis (CDA) will be presented, and second, the results from the type canonical correlation analysis (CCorA). Keep in mind that the CDA analysis purpose was to test if there was any significant difference in fish assemblages among the five ocean habitats and that the CCorA analysis purpose was to test if groundfish species distributions and abundances varied in relation to individual environmental variables (instead of looking it from a habitat perspective).

Type I, CDA

Before, the CAP analysis conducts either a CDA or a CCorA, it conducts a principal coordinate analysis (PCO) on the dissimilarity matrix of the original fish data matrix. The first two PCO axes explained 55.74% and 17.42% of the variability in the original dissimilarity matrix (Fig 4.65). The color-coding in the graph comes from the ocean habitats identified in section 4.3.3.1.1. This graph suggested that there are mainly two different groups. On the positive side of axis 1, the trawl stations from the Offshore Habitat (black points) and the Highly Variable Upwelling Habitat (green points) congregate. They correspond to be the offshore stations. On the negative side of axis 1, the trawl stations from the Upwelling Habitat (blue points), the Highly Variable Habitat (red points) and the River Plume Habitat (yellow points) congregate. They correspond to be the shallower stations. Thus, the scatter of points in this ordination did not suggest there are important differences in species composition among the five groups. However, a MRPP test (nonparametric multivariate analysis for testing the hypothesis of no difference between two or more group of entities) indicated that there were significant differences among the groups (*p-value* <0.0001) (Table 4.4). This led us to investigate the group differences in species composition with the CDA.

The first step in the CDA is to choose the proper number of PCO axes (*m*) to include in the CDA. The goal is to include the number of PCO axes that includes the most salient patterns in the fish data without including extraneous random information (Anderson and Willis, 2003). The analysis itself chose the number of *m* automatically by calculating the misclassification error and choosing the number of axes that minimizes the misclassification error. The number of choices was *m*=6, which achieved the maximum proportion of correct allocations (43.25%). Therefore with *m*=6, the first six PCO axes explained 92.1 % of the variability in the original dissimilarity matrix obtained from the fish data matrix.

The CDA yielded two canonical axes with square canonical correlations of $\partial^2_1=0.47$ and $\partial^2_2=0.1$. The two canonical test statistics were highly significant with a *p-value* <0.00001 using 9999 permutations which is consistent with the result obtained using the MRPP test.

The plot of the first two canonical axes shows primarily an east-west pattern of differences between sample stations (Figure 4.66). This pattern is mainly separating the shallower trawl stations in the Highly Variable Habitat, River Plume Habitat and Upwelling Habitat (red, yellow and blue points) from the deep trawl stations in the Offshore Habitat (black points). Again, the Highly Variable Upwelling Habitat (green points) is spread out along axis number 1. However, a secondary north-south pattern emerges too, but more weakly, separating stations in the northern latitudes (black points) from the stations in the southern latitudes (green points). In this case, the CDA method uncovered some of the group differences that were not easily seen in the PCO ordination (Figure 4.65) and the NMDS ordination (Figure 4.62).

The correlation of individual species with canonical axis 1 and 2 were also interpreted to characterize the multivariate effect (Table 4.9). In addition, the plots of the first two canonical axes (Figure 4.66) also overlays the correlation of species on both CAP axes. The species overlaying or having positive or negative correlation with a specific axis indicates that they have an association with that specific region of the plot and the direction of the vectors and magnitude of the species correlation with the canonical axes help to assess the patterns. Thus, petrale sole (loading=0.83), English sole (loading=0.79), Pacific sanddab (loading=0.67), spotted ratfish (loading=0.59) and rex sole (loading=0.5) had the strongest correlations with the positive side of the canonical axis 1. This suggests that these species are highly associated with the Upwelling Habitat, the River Plume Habitat and the Highly Variable Habitat, which are the shallowest habitats. In contrast, shortspine thornyhead (loading=-0.83), longspine thornyhead (loading=-0.74), giant grenadier (loading=-0.56), Pacific grenadier (loading=-0.54), sablefish (loading=-0.52) and Pacific ocean perch (loading=-0.25) had a negative correlation with canonical axis 1 suggesting that these species are highly associated with the deepest habitats. Finally, there were six species (sandpaper skate, striptail rockfish, darkblotched rockfish, canary rockfish, sharpchin rockfish and dover sole), which showed almost no correlation (less than 0.2) either with the shallow or with the deep habitats.

In addition, canonical axis two also reveals some variation in the community structure of the groundfish species. Sablefish (loading=0.43), giant grenadier (loading=0.31), Pacific grenadier (loading=0.28) and longspine thornyhead (loading=0.2) have high positive correlation with canonical axis two. This reveals that they have an association with the Highly Variable Upwelling Habitat (green). Shortspine thornyhead (loading=0.06) is the only species that weakly correlated with the negative side of canonical axes two. Finally, most of the species correlating positively with canonical axes 1 did not show any high correlation with canonical axes 2 indicating that their preferable habitats are the Highly Variable Habitat, the River Plume Habitat and the Upwelling Habitat (blue, yellow and red habitat), interchangeably. The exception are Pacific cod (loading=-0.3) and lingcod (loading=-0.23), which showed correlation with the negative side of canonical axes two and, longnose skate (0.31) which shows correlation with the positive side of canonical axis two. It seems that these species are associated with different types of habitats but which particular habitat is less obvious from Figure 4.66.

Type II, CCorA

The results from the CCorA showed that the fish species matrix or the fish assemblage structure was highly correlated with the environmental variables (longitude, latitude, depth and oceanographic variables at different depths) (Figure 4.67, m=7,∂_1=0.89, ∂_2=0.49, *p-value*<=0.0001). The number of PCO axes (m) included in the CCorA again was chosen automatically by the analysis by choosing the number of axes that minimizes the residual error. Therefore with m=7, the first seven PCO axes explained 95.96 % of the variability in the original dissimilarity matrix obtained from the fish data matrix.

Results from the CCorA examining the relationship between the groundfish biomass and distributions (only 28 species that make 95% of total biomass) and environmental variables (longitude, latitude, depth and oceanographic variables) are shown in Figure 4.67. Each point in the ordination plot has been color coded by the ocean habitat obtained in the clustering analysis in section 3.4.3.1.1. The ordination plot has ordinated the shallower trawl stations, which are the Highly Variable Habitat, River Plume Habitat and Upwelling Habitat (red, yellow and blue points) on the positive side of canonical axis 1, from the deep trawl stations, which are the Offshore Habitat (black points) in the negative side of canonical axis 1. The trawl stations corresponding to the Highly Variable Upwelling Habitat (green points) overlap both the shallow and deep habitats.

The shallower stations are showing more variations in terms of species distributions and species assemblage structure and environmental variability (they are more spread out). In contrast, the deep stations seem more uniform in terms of species compositions and environmental variability (they cluster closer together). Another observation is that the River Plume Habitat station (in orange) and the High Variable Habitat stations (in red) seem to ordinate on the positive side of canonical axis two.

The first canonical axis explained primarily trends in depth (loading=- 0.93) and trends in salinity and temperature at the bottom (loading=0.76 and loading=-0.64, respectively) (Refer to Table 4.11 and Figure 4.67). The correlation of depth and bottom temperature and salinity with the first canonical axis is expected since temperature decreases with depth and salinity increases with depth. In addition, temperature at the surface (loading=-0.3) and at 50 m (loading-0.59) and salinity at 50 m (loading=0.38) also loaded on the first canonical axis with opposite signs to the loadings of temperature and salinity at the bottom. This is due to upwelling conditions at the surface, which creates cold and salty water conditions in the surface (opposite to what it is on the bottom). Then, chlorophyll-a at the surface (loading=0.69) and CV of chlorophyll-a at the surface (loading=0.49) also loaded on the first canonical axis. This is expected since upwelling conditions create productive waters.

In contrast, the second canonical axis was associated primarily with latitude (loading=0.43), chlorophyll-a at the surface (loading=0.38) and longitude (loading= -0.3). The association of latitude and chlorophyll-a arises because it looks like the Washington coast is more productive than the Oregon coast (Figure 4.57 and Table 4.2). Interestingly, the CV of salinity also loaded with the positive side of the second canonical axis. CV of temperature and salinity at 50 also loaded very weakly on the positive side of canonical axis 2. The CVs are showing high in northern latitudes because the salinity and temperature field off the Washington coast are more variable than off the Oregon coast. In contrast, the CV of chlorophyll-a (loading=-0.27) loaded with the negative site of canonical axis two. The chlorophyll-a field seems to be more variable of the southern Oregon coast. It is less clear why the weak loading with longitude exists since it should mimic the effect of depth since the coastline is almost a straight line.

More challenging is to see how individual species correlate with canonical axes (Table 4.10) and make an interpretation of their association with the environmental variables and the ocean habitats (Figure 4.64). Rex sole (loading=0.74), petrale sole (loading=0.72), spotted ratfish (loading=0.71), English sole (loading=0.68), Pacific sanddab (loading=0.59), arrowtooth flounder (loading=0.59) and Pacific hake (loading=0.59) loaded very strongly with canonical axis 1. This suggests that they are associated with the shallow depths and high productive coastal waters. However, within this group of shallower species there is a lot of variation as it can be seen in the species correlations with canonical axes two. Spiny dogfish (loading=0.59), Pacific cod (loading=0.43), petrale sole (loading=0.34), English sole (loading=0.36), yellowtail rockfish (loading=0.24) and Pacific sanddab (loading=0.25) correlated positively with canonical axes two and therefore they show an association with higher latitudes which are variable in terms of the temperature and salinity field but highly productive. Then, Pacific hake (loading=-0.41), Dover sole (loading=-0.37), splitnose rockfish (loading=-0.36) and darkblotched rockfish (loading=-0.35) show strong correlation with the negative site of axis two and therefore they are more associated with southern latitudes which was correlated with high surface salinities and low temperature conditions (upwelling conditions).

On the other site of the spectrum, longspine thornyhead (loading=-0.92), giant grenadier (loading=-0.84), pacific grenadier (loading=-0.79), shortspine thornyhead (loading=-0.63) and sablefish (loading=-0.48) correlated very strongly with the negative site of axis 2. These are deep-water species, which are primarily associated with deeper, salty and cold habitats. This group of species shows less variation in term of species composition and environmental conditions (Figure 4.64 the ordination points are more uniform and closer together). However, still some of the species show correlations with canonical axes 2. Shortspine thornyhead (loading=-0.33) and sablefish (loading=-0.24) showed a fair correlation with the deep southern region, which is associated with low temperatures and high variability in chlorophyll-a field at the surface (this turns out to be the deep upwelling region offshore of Cape Blanco. Pacidic grenadier (loading= 0.18), Giant grenadier (loading= 0.15) and longspine thornyhead (loading=0.01) are the only species that correlated strongly with the negative site of canonical axis 1 and correlated very weakly with canonical axes.

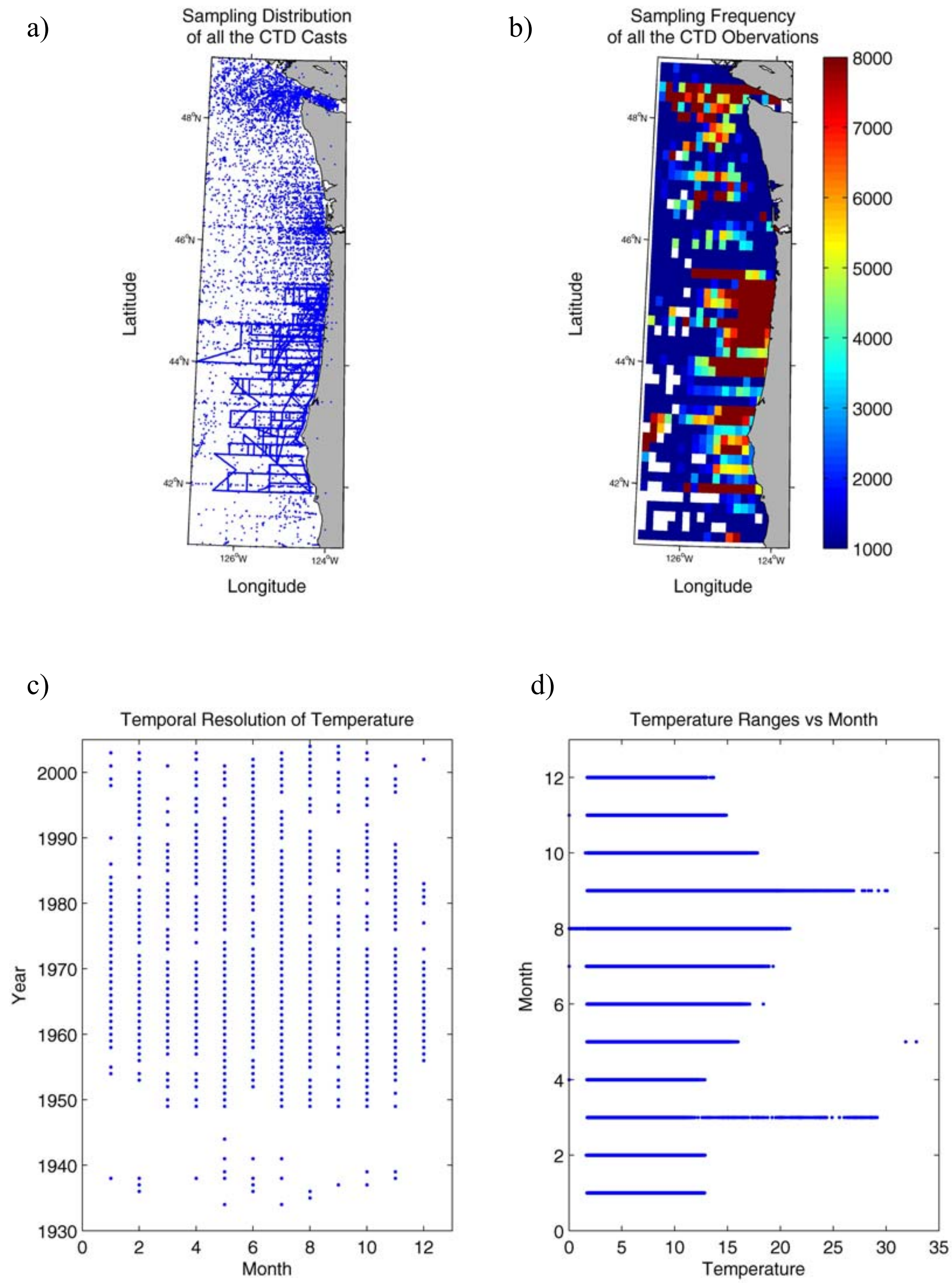


Figure 4-1 This group of figures explore the temperature field acquired by CTD casts. a) Sampling distribution of all the CTD casts deployed off the Washington and Oregon coasts from 1930s to the year 2004. b) Sampling frequency distributions. The map displays the number of observations in each of the grids (~18 km spatial resolution grids). c) Temporal resolution. d) Temperature (in degrees Celsius) range in each of month.

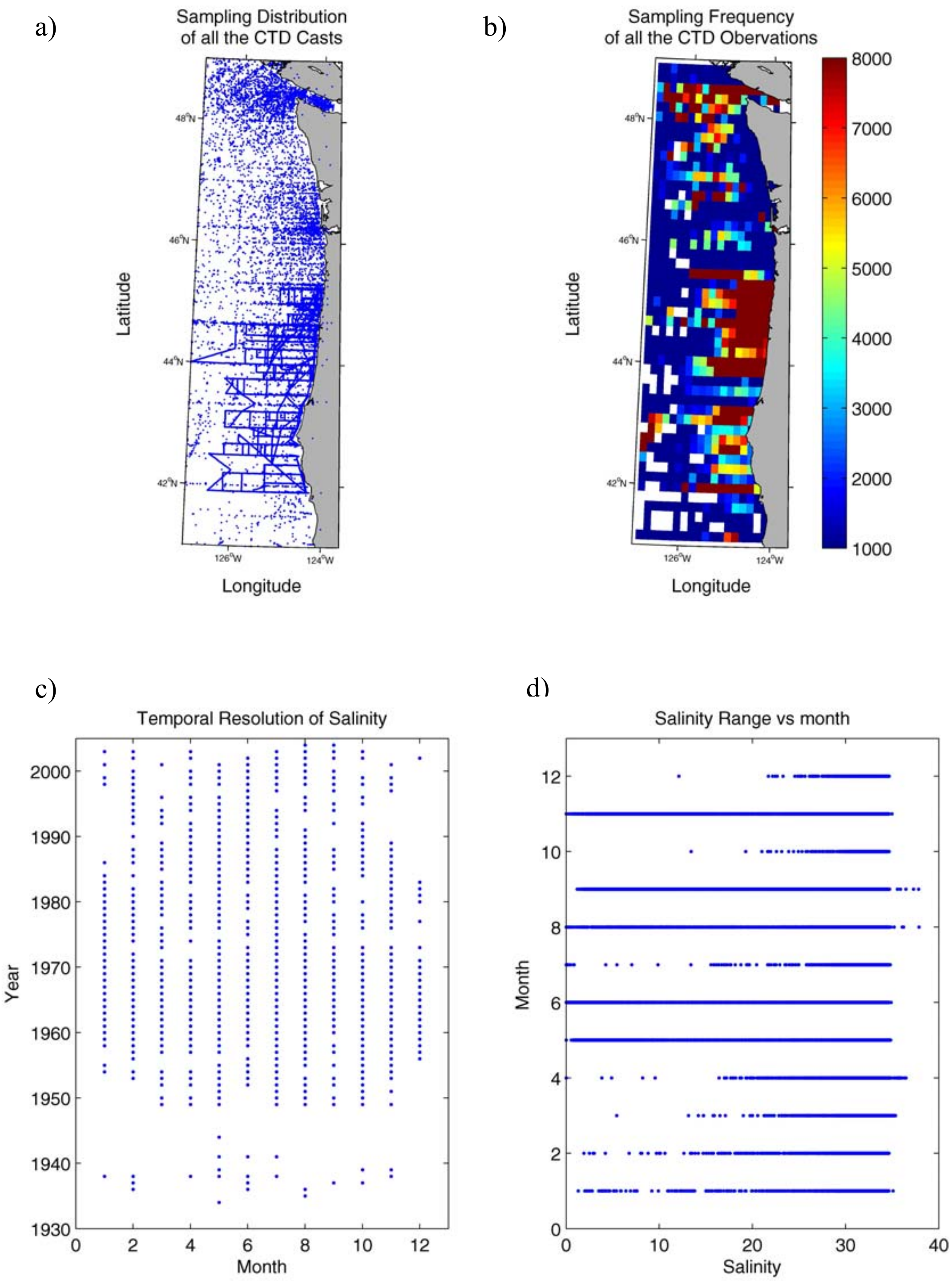


Figure 4-2 This group of figures explore the salinity field acquired by CTD casts. a) Sampling distribution of all the CTD casts deployed off the Washington and Oregon coasts from 1930s to the year 2004. b) Sampling frequency distributions. The map displays the number of observations in each of the grids (~ 18 km spatial resolution grids). c) Temporal resolution. d) Salinity range in each of month.

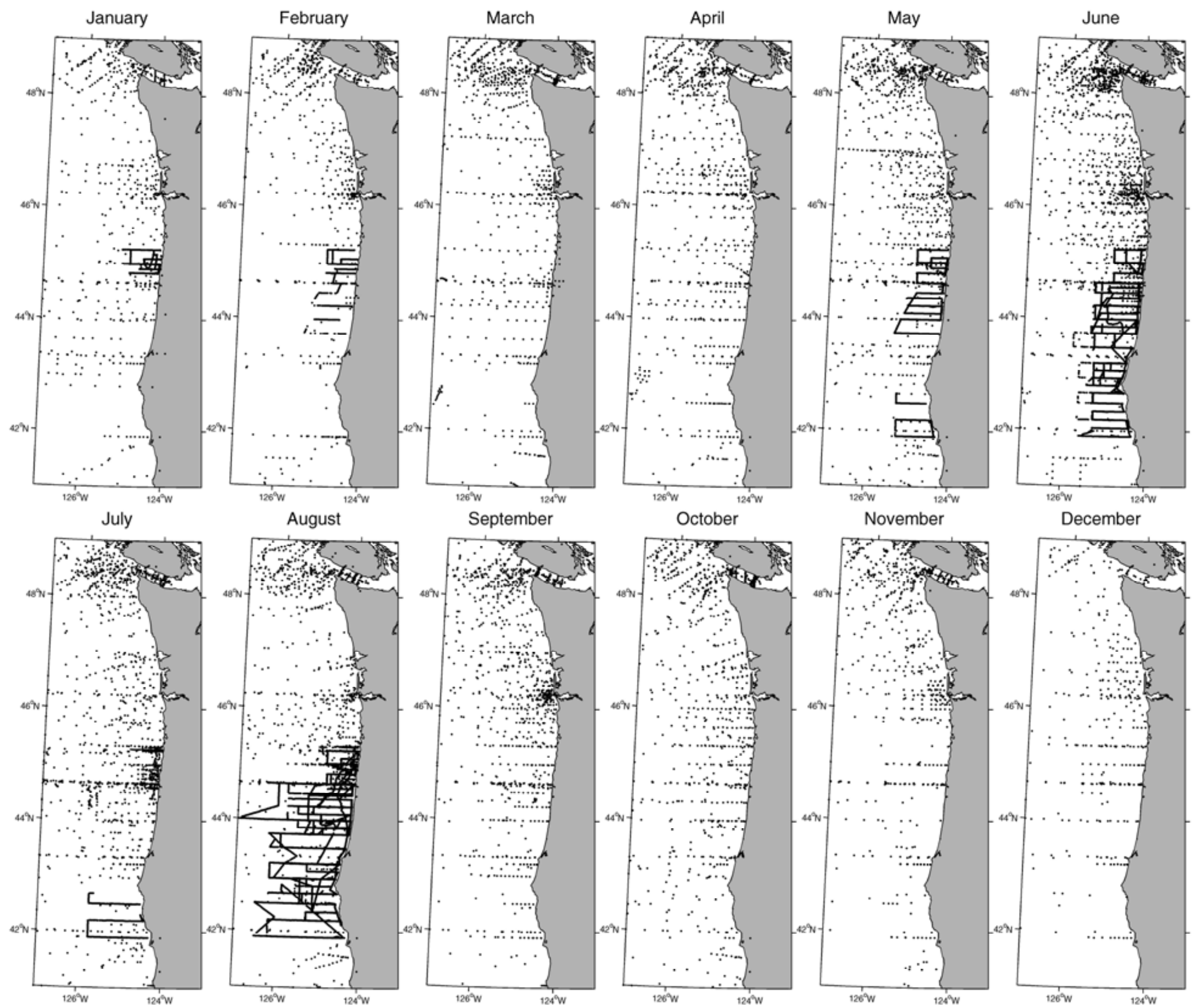


Figure 4-3 Monthly spatial distributions for CTD casts collected from the 1930s to the year 2004.

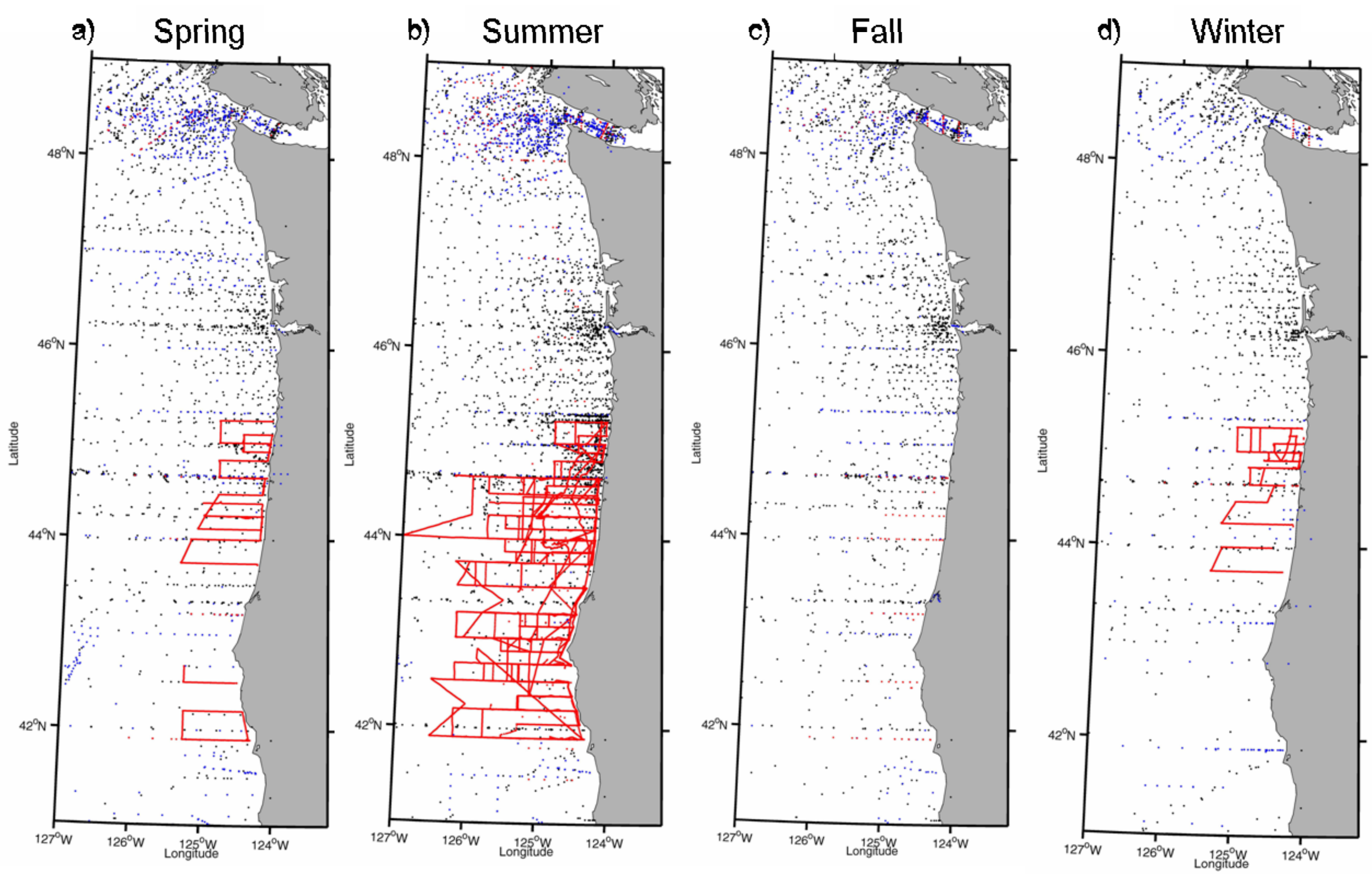


Figure 4-4 Seasonal sampling distribution of CTD casts. CTD casts in black cover the time period from 1930s to 1976. CTD casts in blue cover the time period from 1997 to 1997 and CTD casts in red cover the time period from 1998 to 2004.

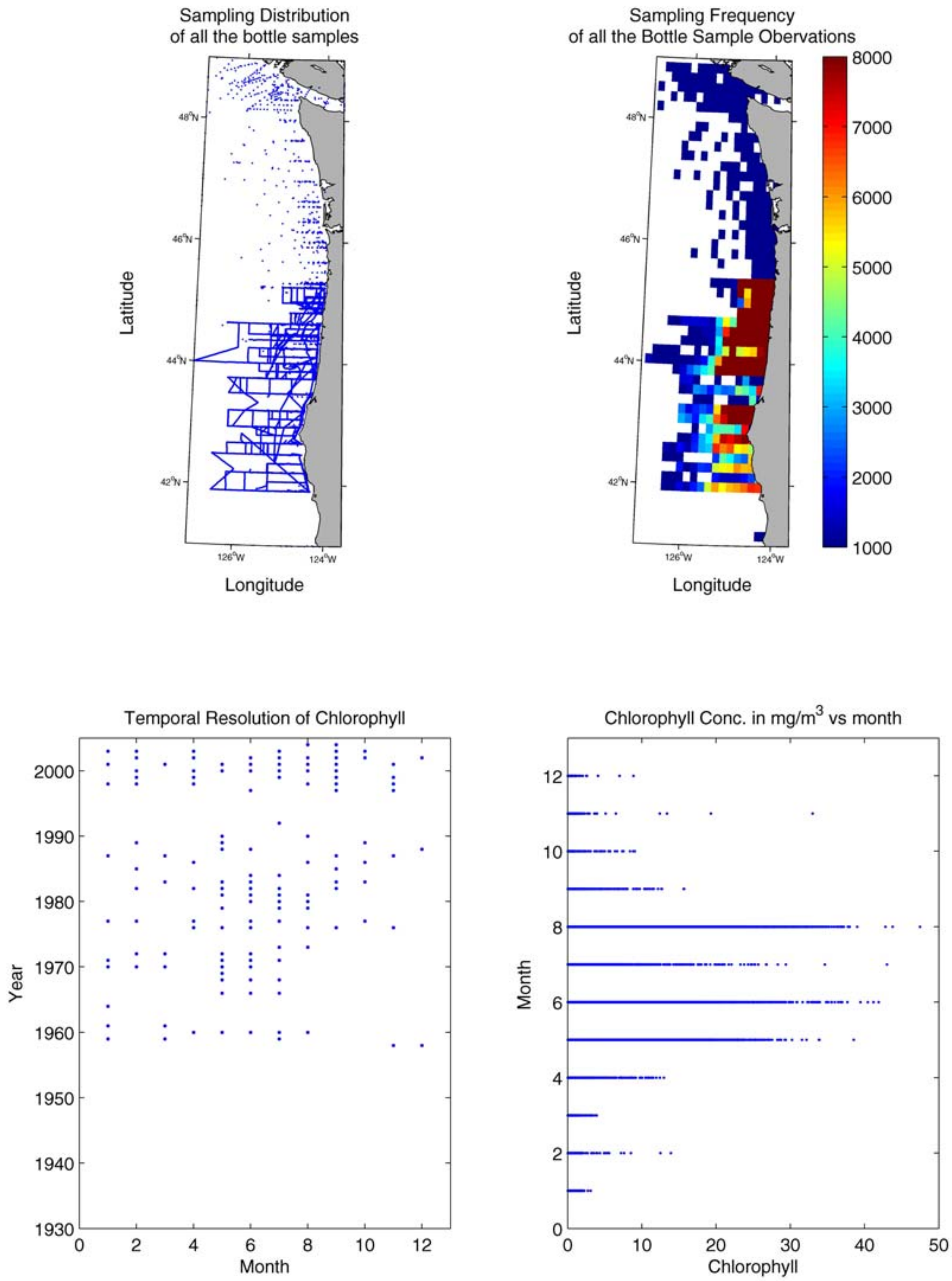


Figure 4-5 This group of figures explore the chlorophyll-a field sampled with fluorometers and Niskin bottle samples. a) Sampling distribution of chlorophyll-a observations off the Washington and Oregon coasts from 1958 to the year 2004. b) Sampling frequency distributions. The map displays the number of observations in each of the grids (~ 18 km spatial resolution). c) Temporal resolution. d) Chlorophyll-a concentration ranges for each month.

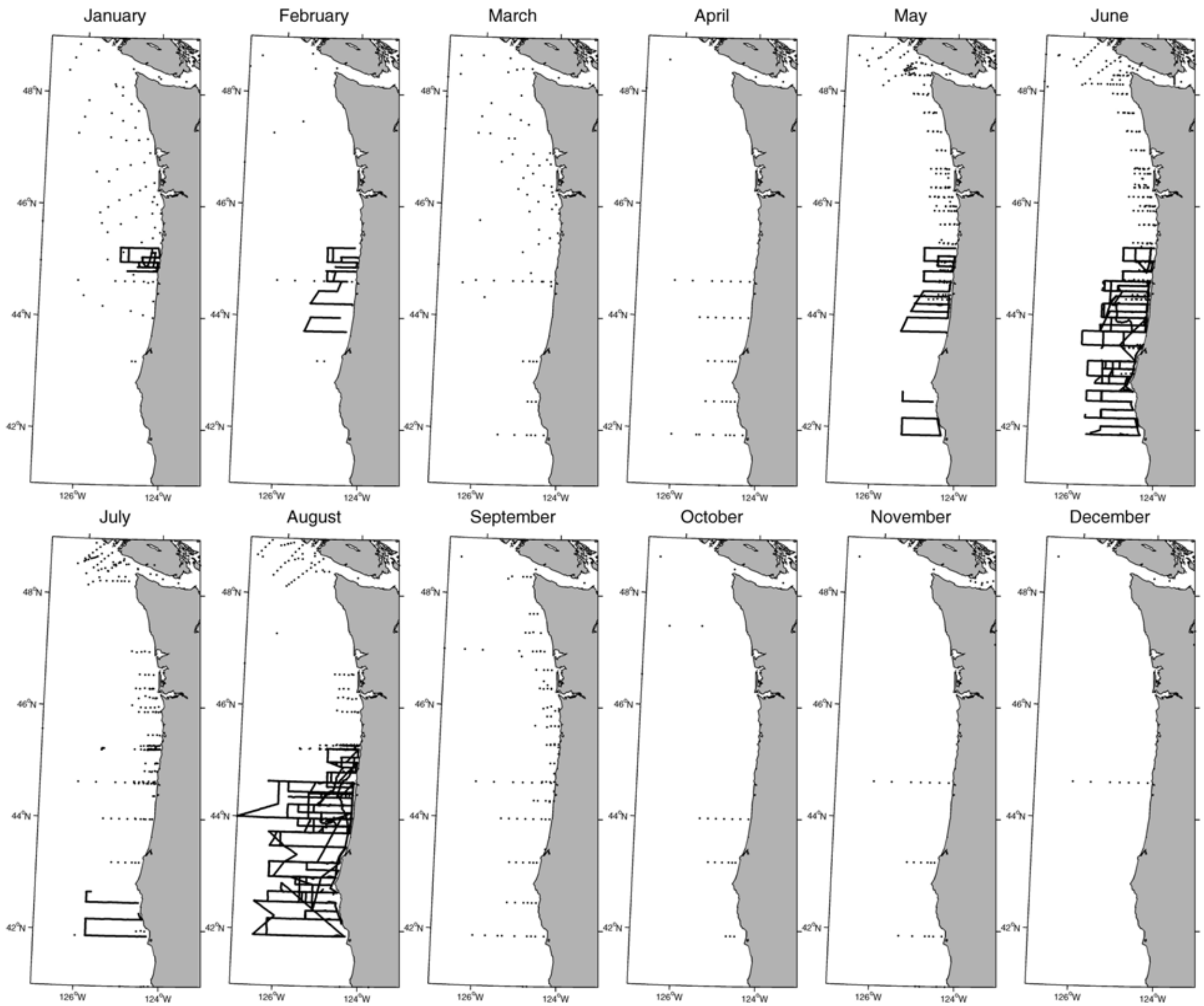


Figure 4-6 Monthly spatial distributions of chlorophyll-a samples from fluorometers and Niskin bottles collected from 1959 to the year 2004.

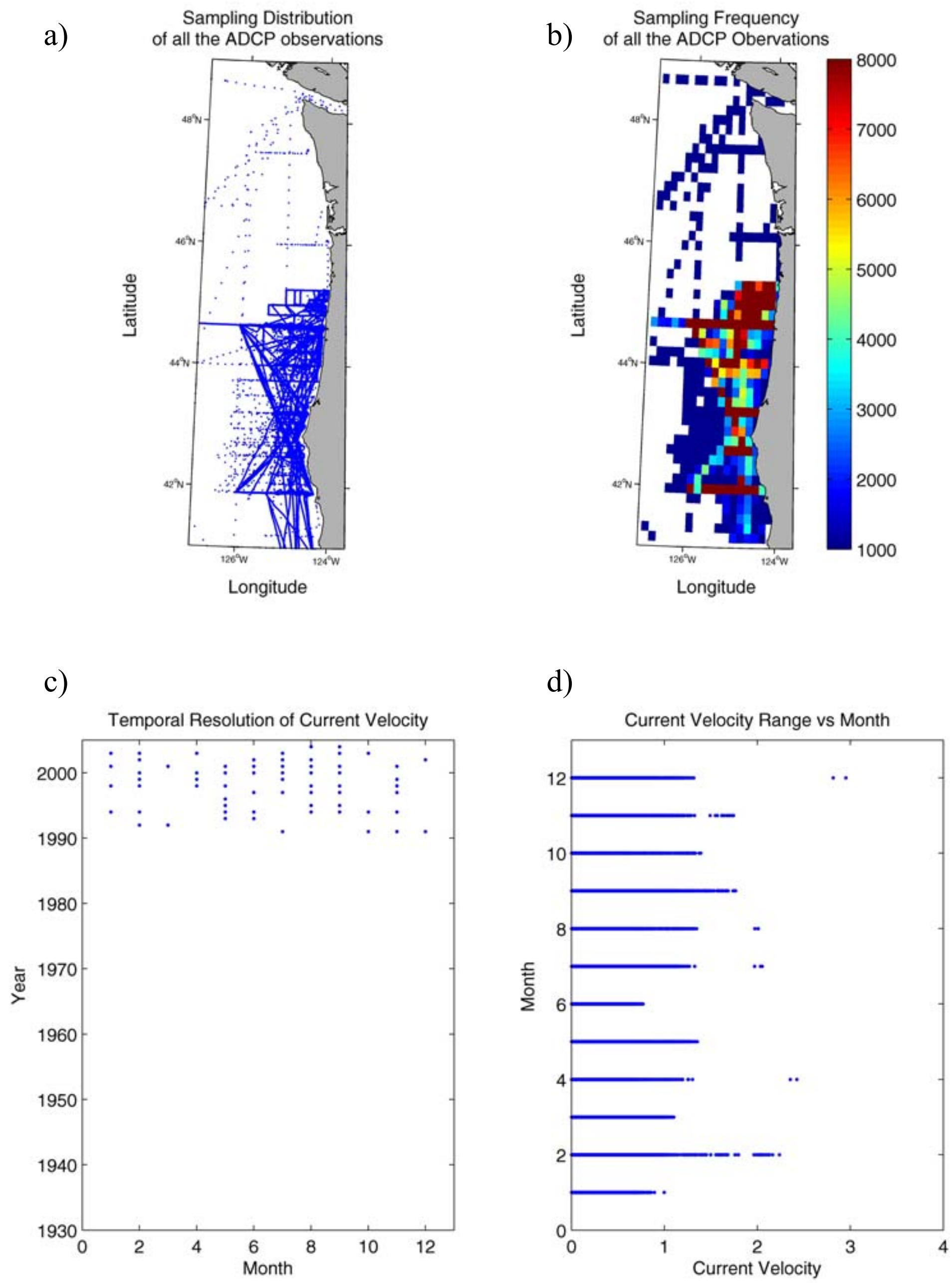


Figure 4-7 This group of figures explore the current velocity filed acquired by shipboard ADCPs. a) Sampling distribution of all the ADCP observations off the Washington and Oregon coasts from 1991 to the year 2004. b) Sampling frequency distributions. The map displays the number of observations in each of the grid boxes (~18 km spatial resolution). c) Temporal resolution. d) Current velocity (m s^{-1}) ranges in each month.

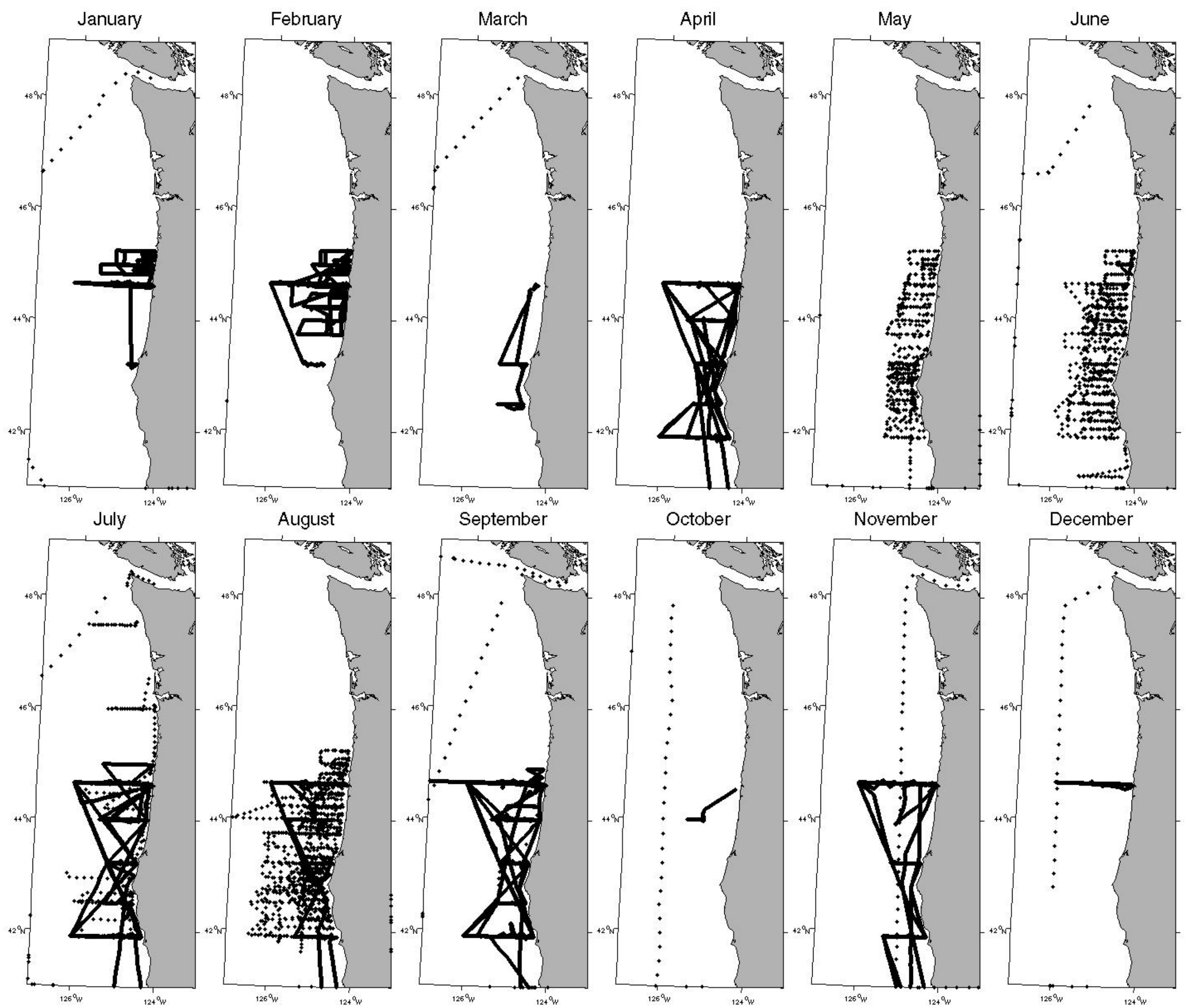


Figure 4-8 Monthly spatial distributions of shipboard ADCP observations collected in the study from 1991 to the year 2004.

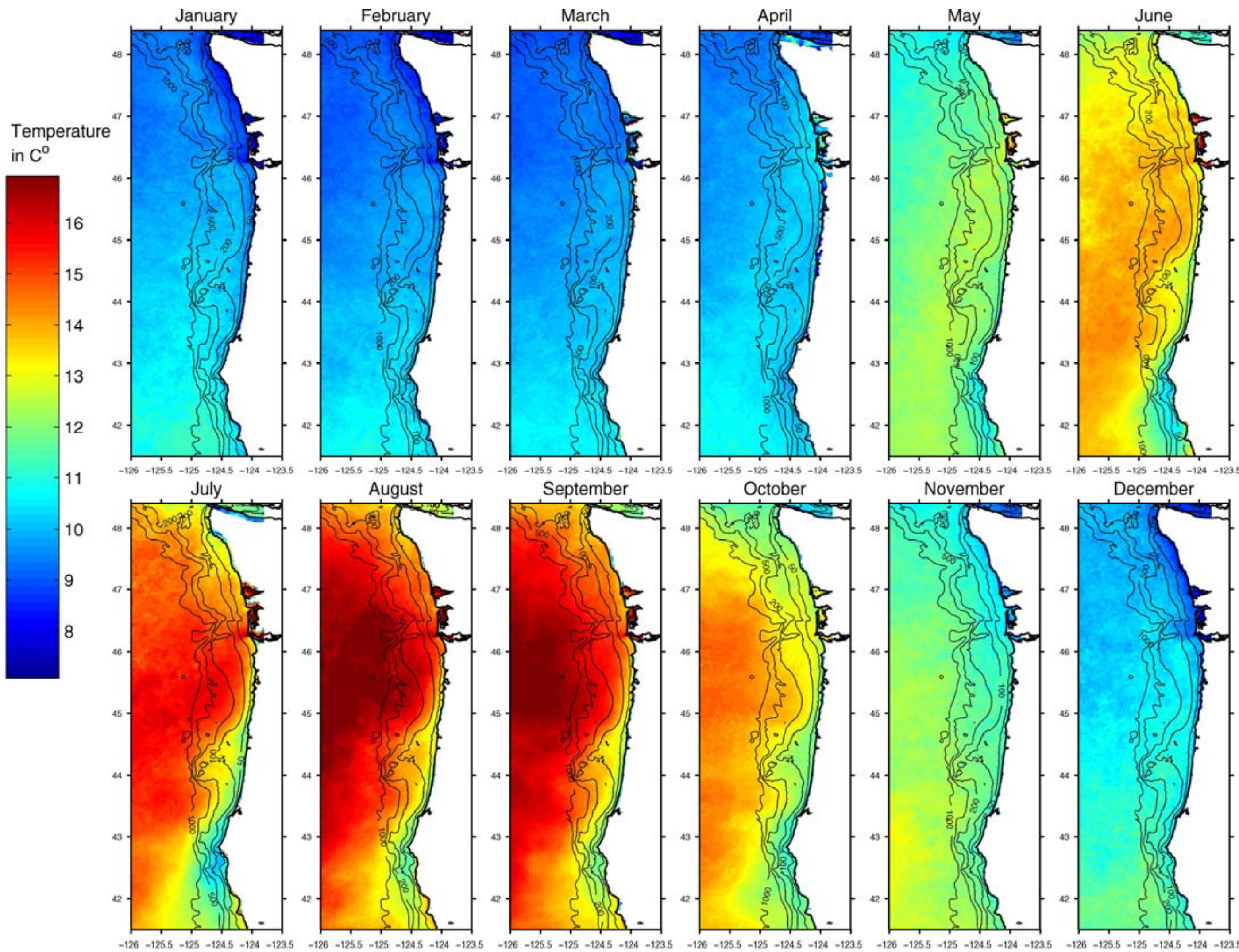


Figure 4-9 Climatological monthly means for sea surface temperature off the Washington and Oregon coasts from the Advance Very High Resolution Radiometer (AVHRR).

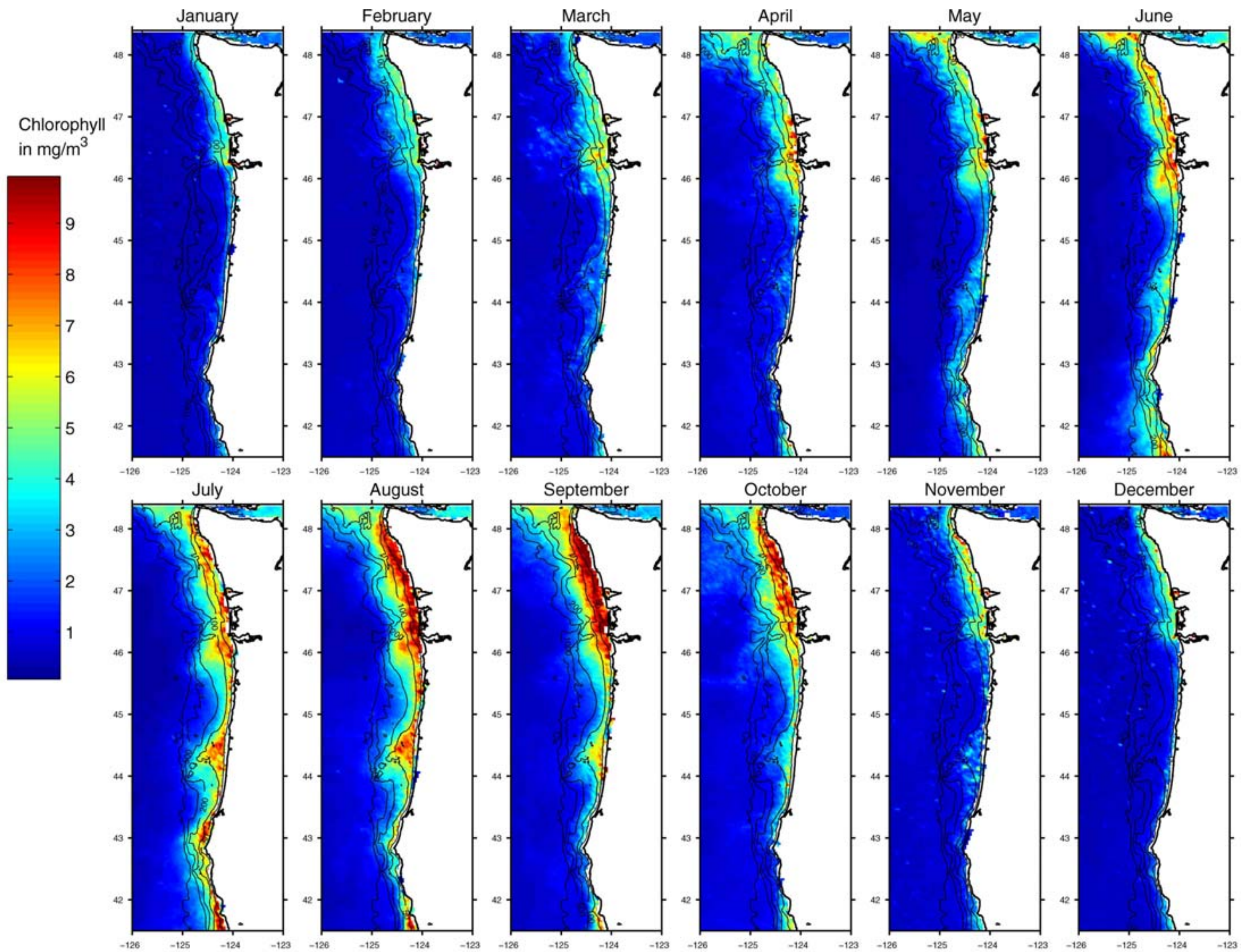


Figure 4-10 Climatological monthly means for chlorophyll-a concentrations off the Washington and Oregon coasts from the Sea-viewing Wide Filed-of-view Sensor (SeaWiFS).

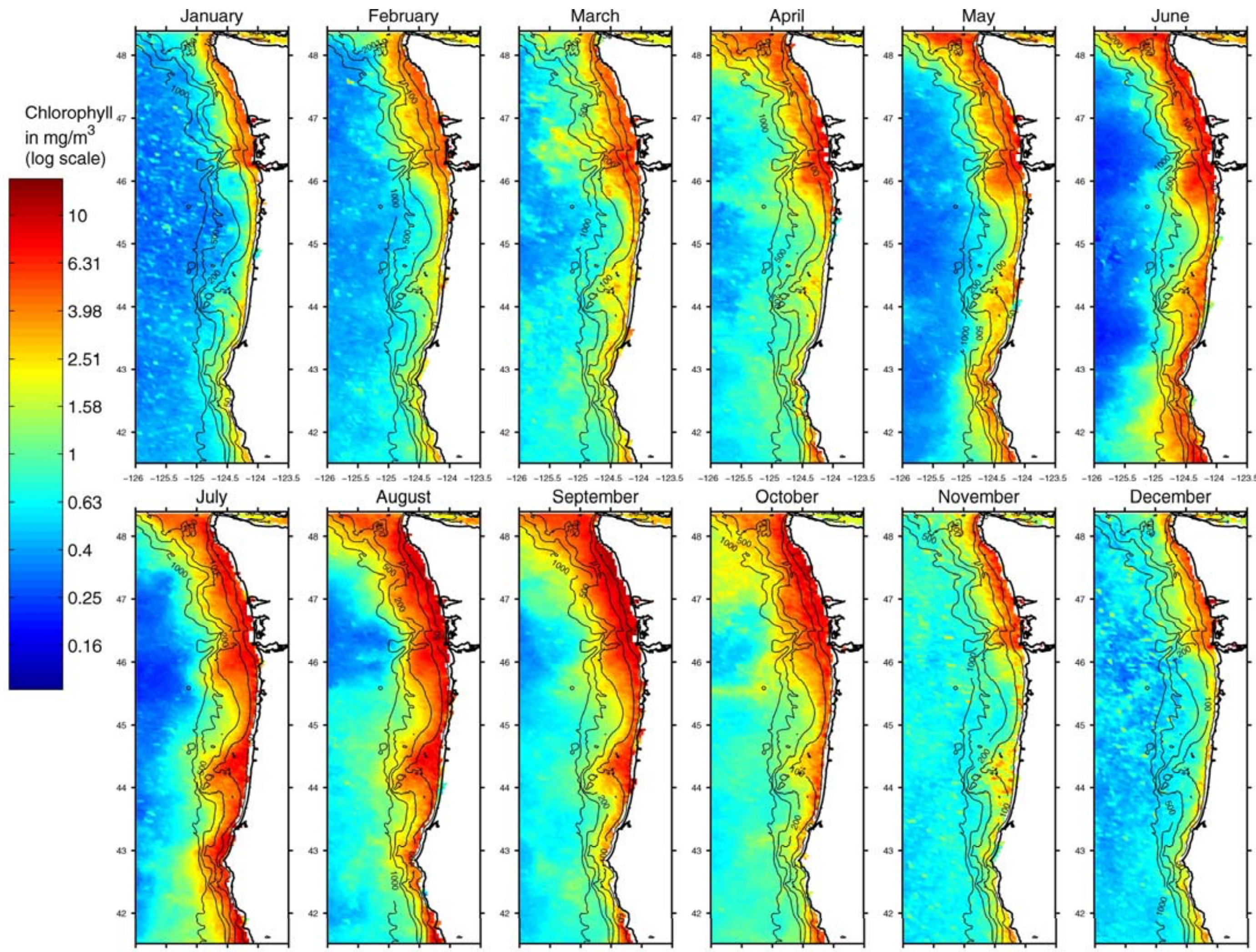


Figure 4-11 Climatological monthly means for chlorophyll-a concentrations (log scale) off the Washington and Oregon coasts from the Sea-viewing Wide Filed-of-view Sensor (SeaWiFS).

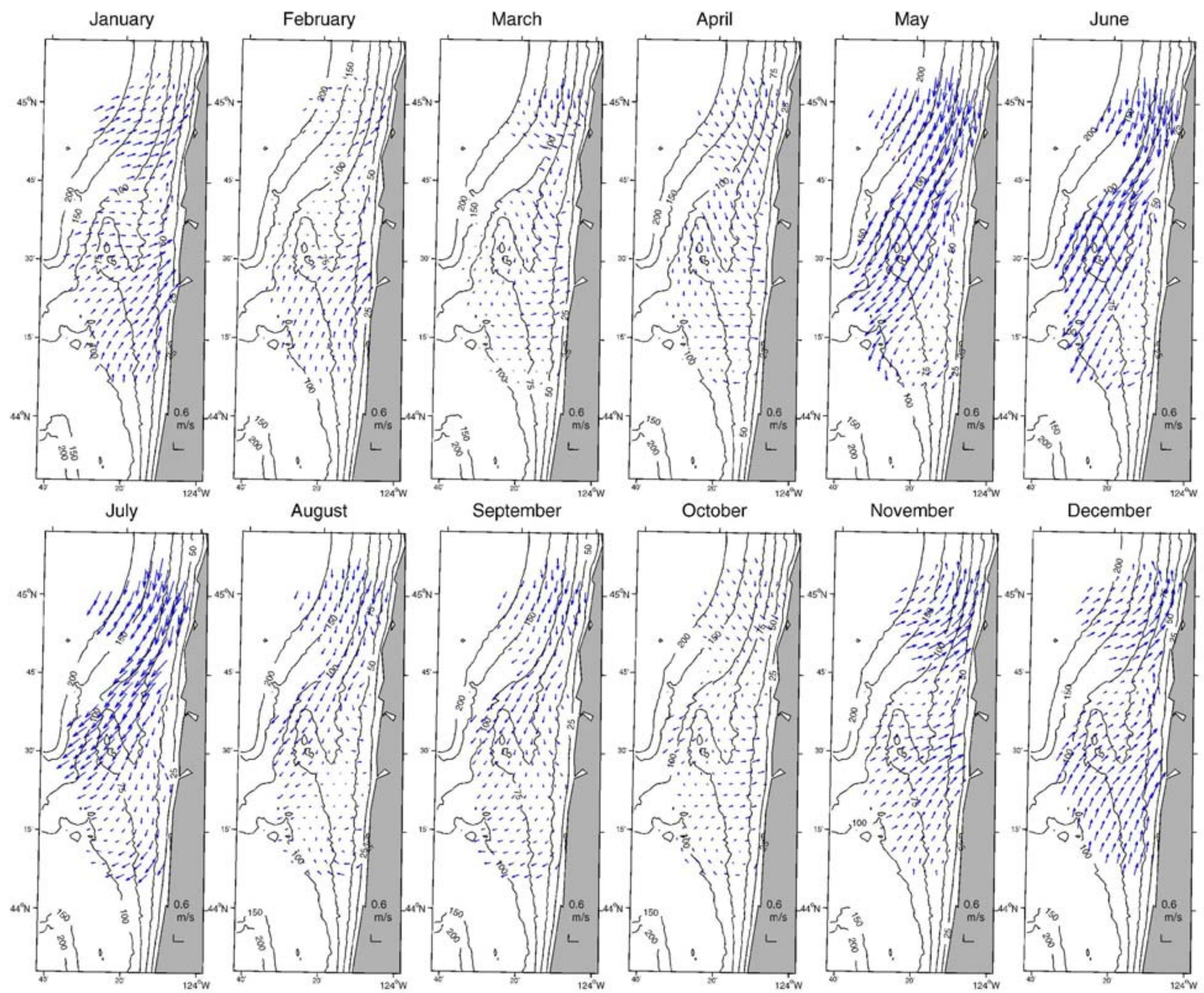


Figure 4-12 Monthly means for surface currents from May 2001 to April 2003 from HF coastal radar stations located on the central Oregon coast.

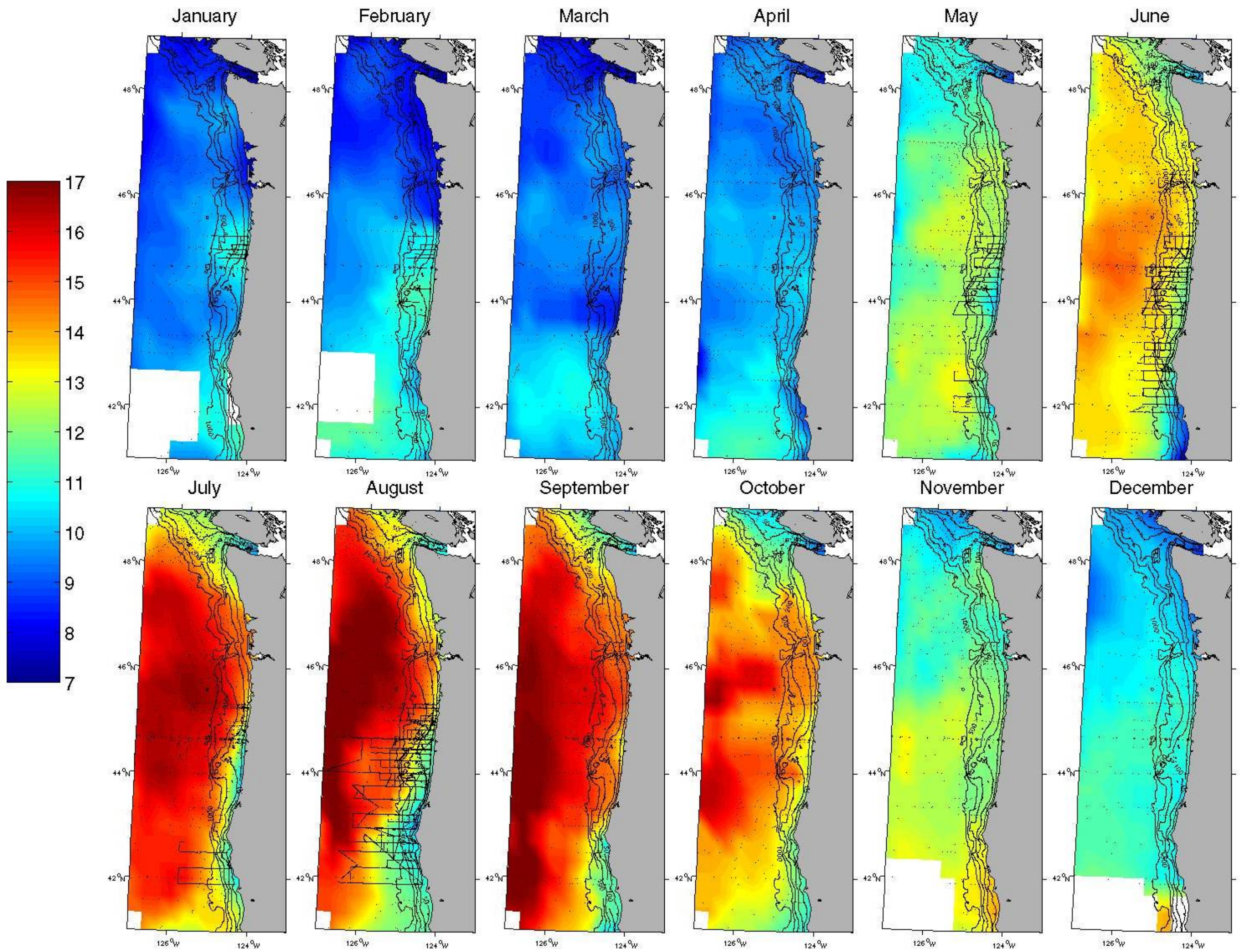


Figure 4-13 Climatological monthly means for temperature at the surface off the Washington and Oregon coasts from CTD cast observations (1930-2004).

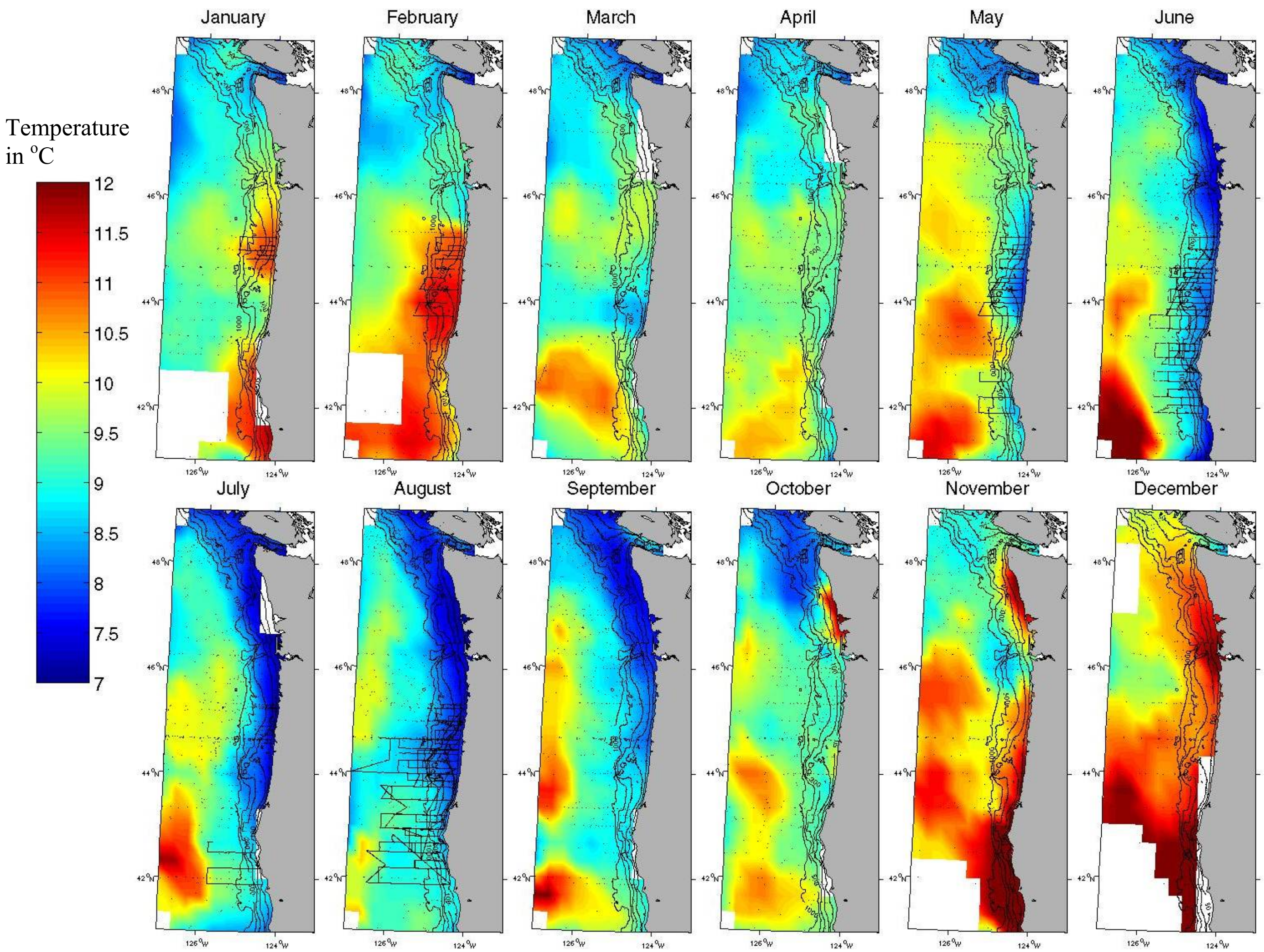


Figure 4-14 Climatological monthly means for temperature at 50 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

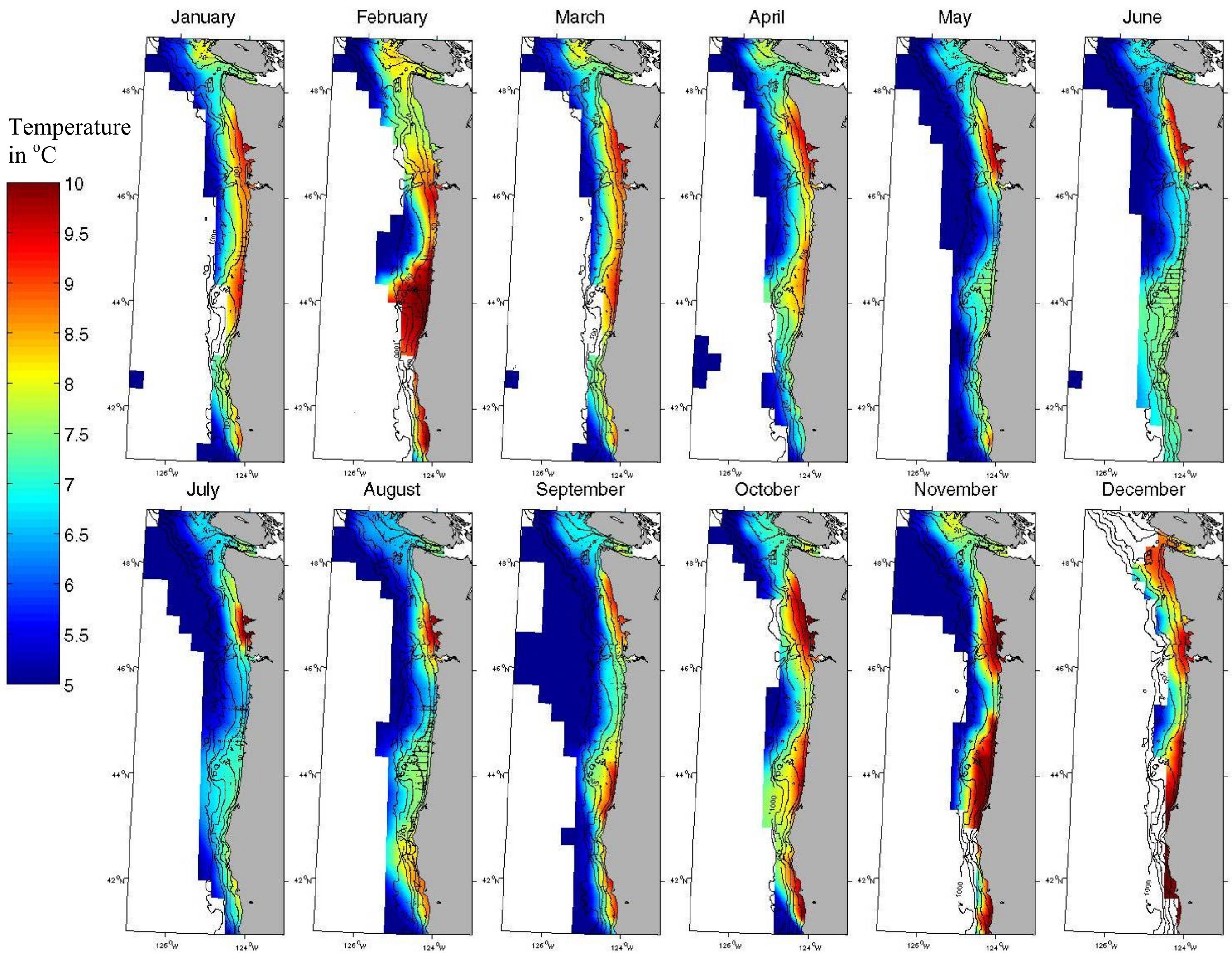


Figure 4-15 Maps of climatological monthly means for temperature at the bottom of the seafloor (10 m above the seafloor) off the Washington and Oregon coasts from CTD cast observations (1930-2004).

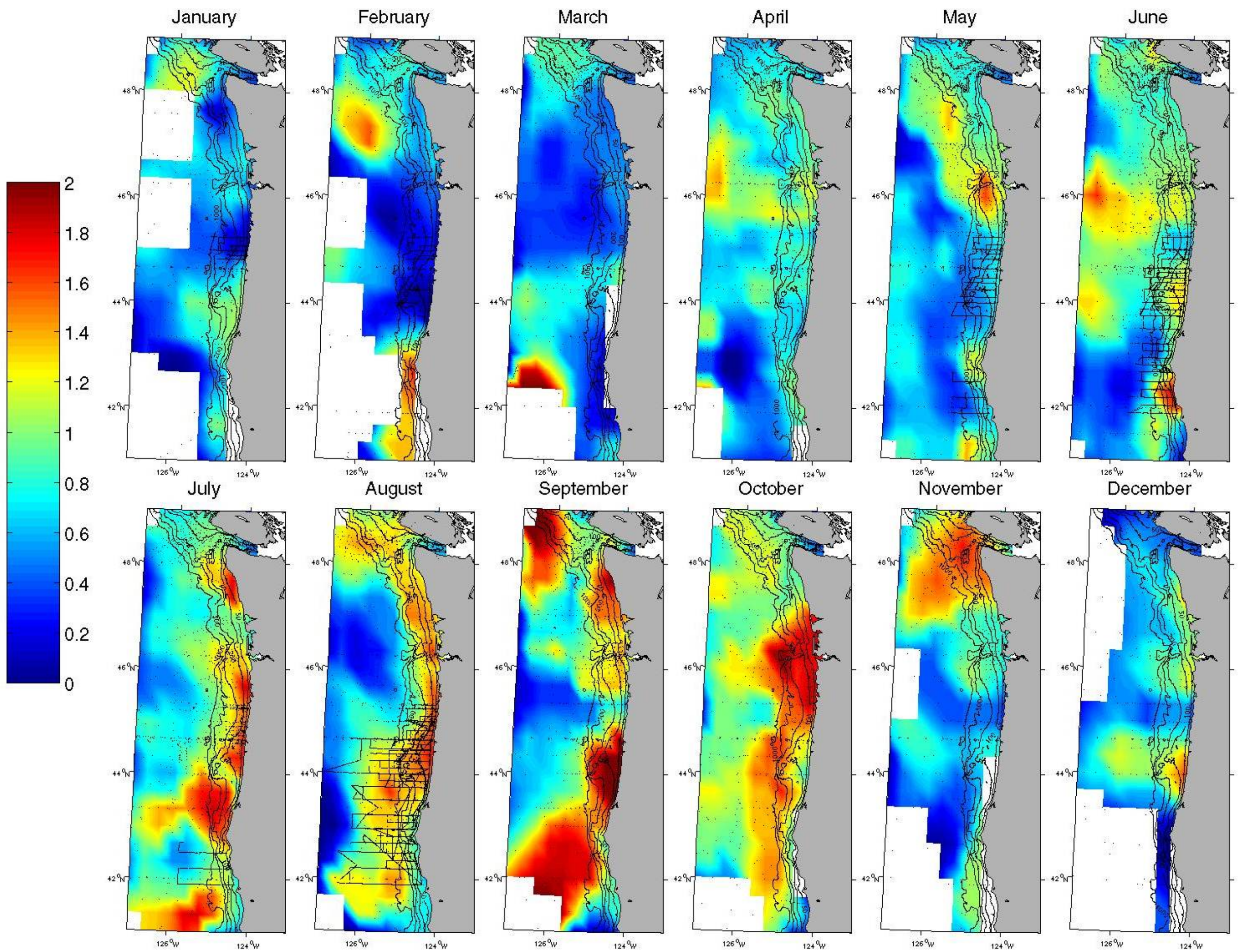


Figure 4-16 Climatological monthly standard deviations for temperature at the surface off the Washington and Oregon coasts from CTD cast observations (1930-2004).

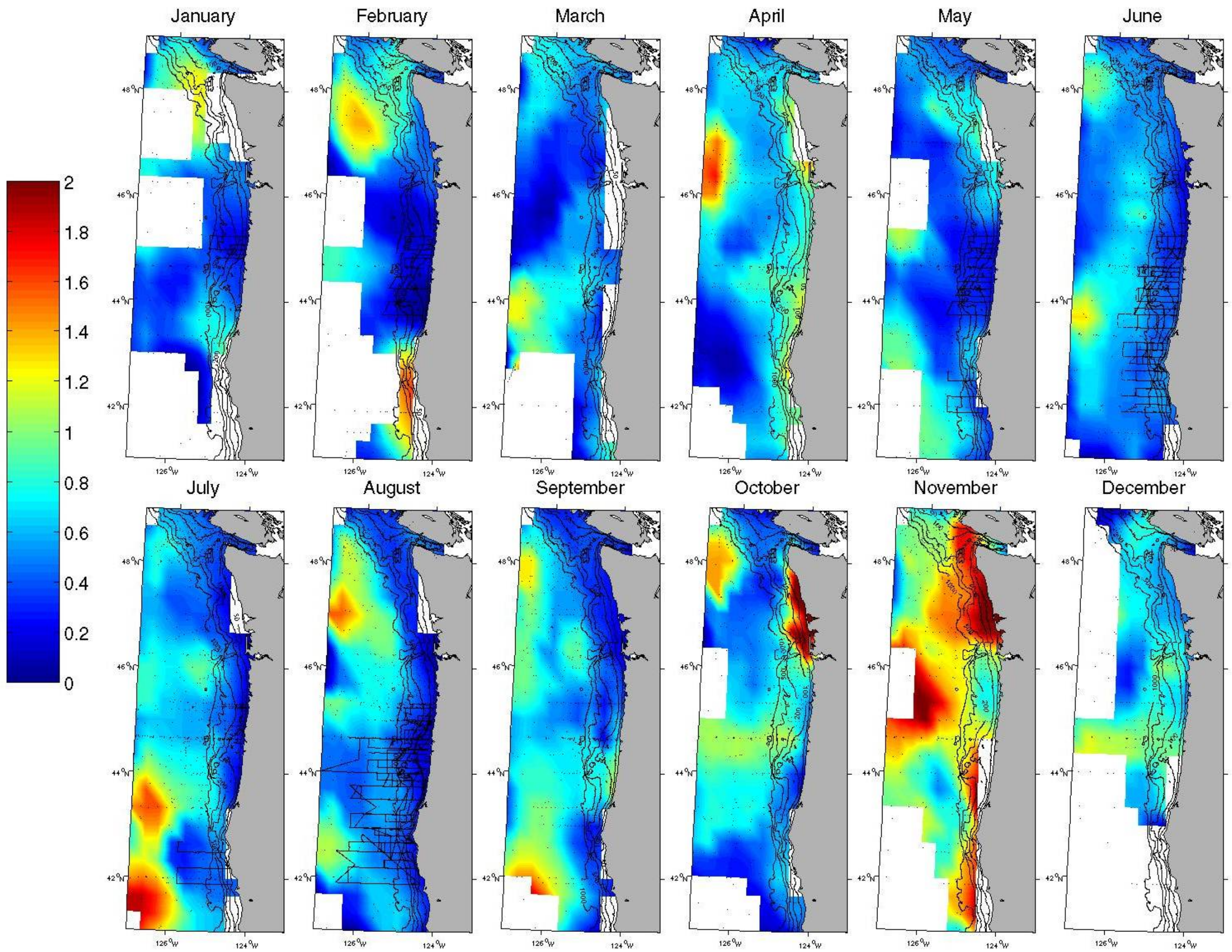


Figure 4-17 Climatological monthly standard deviations for temperature at 50 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

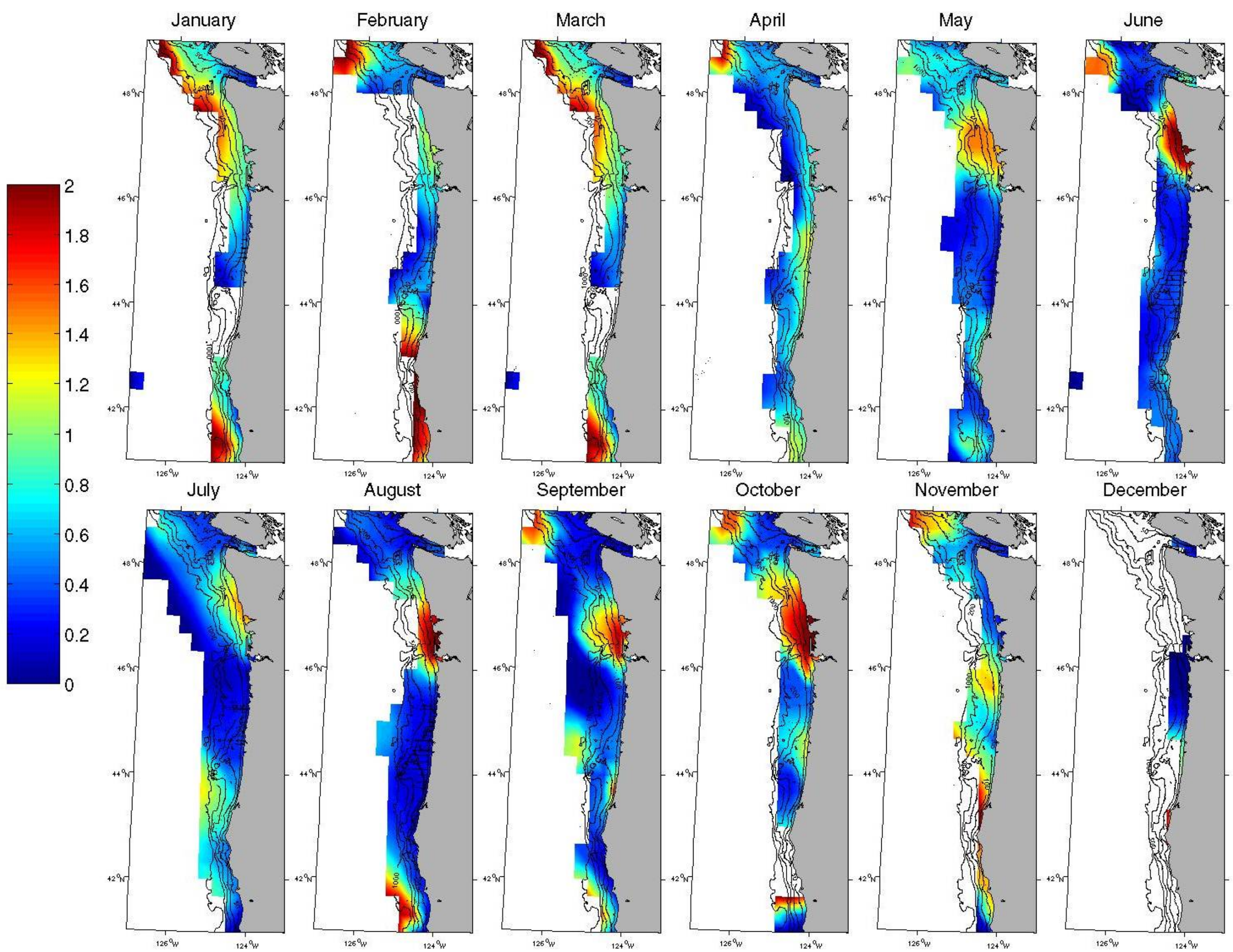


Figure 4-18 Climatological monthly standard deviations for temperature at the bottom (10 m above the bottom) off the Washington and Oregon coasts from CTD cast observations (1930-2004).

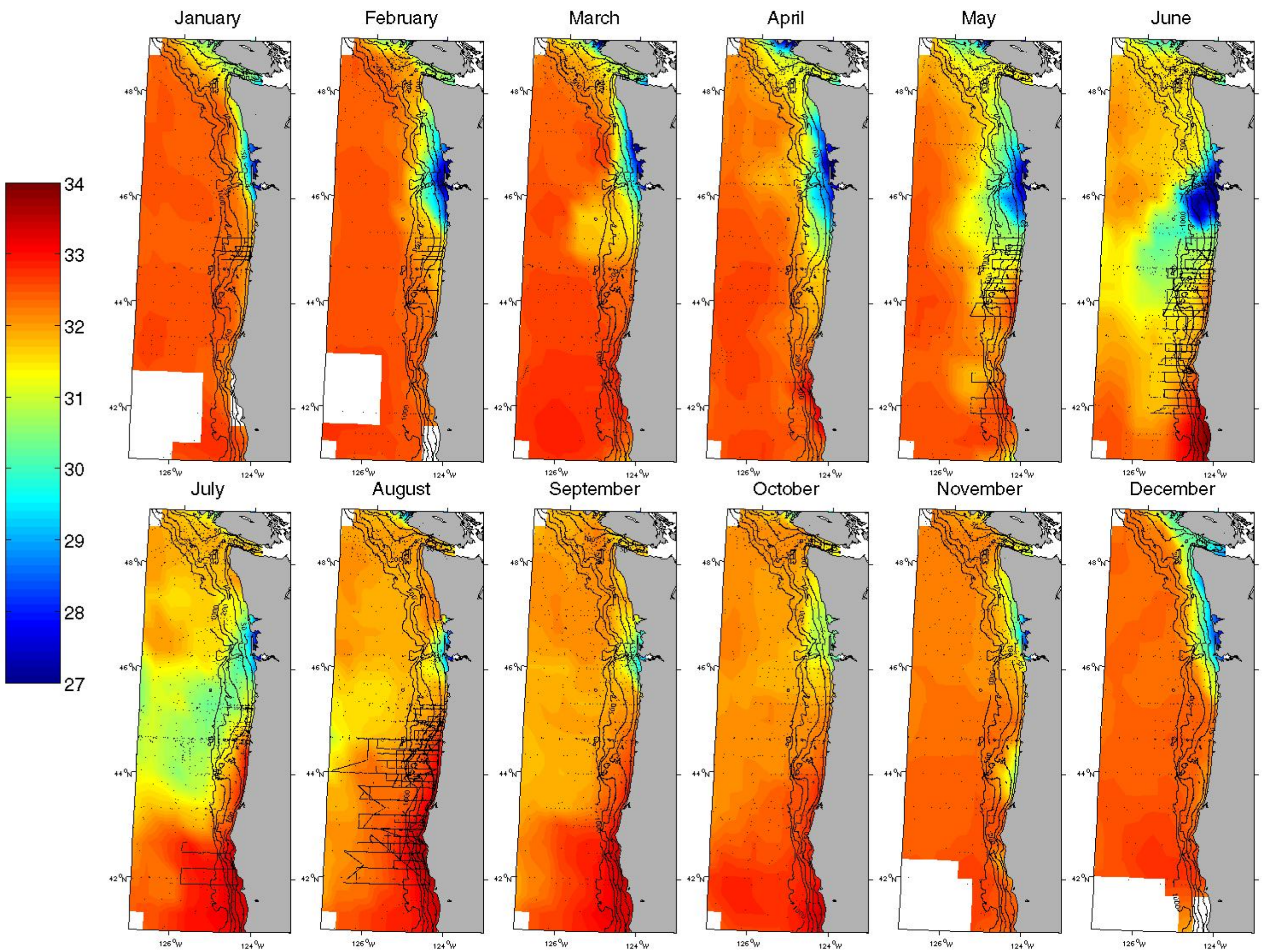


Figure 4-19 Climatological monthly means for salinity at the surface off the Washington and Oregon coasts from CTD cast observations (1930-2004).

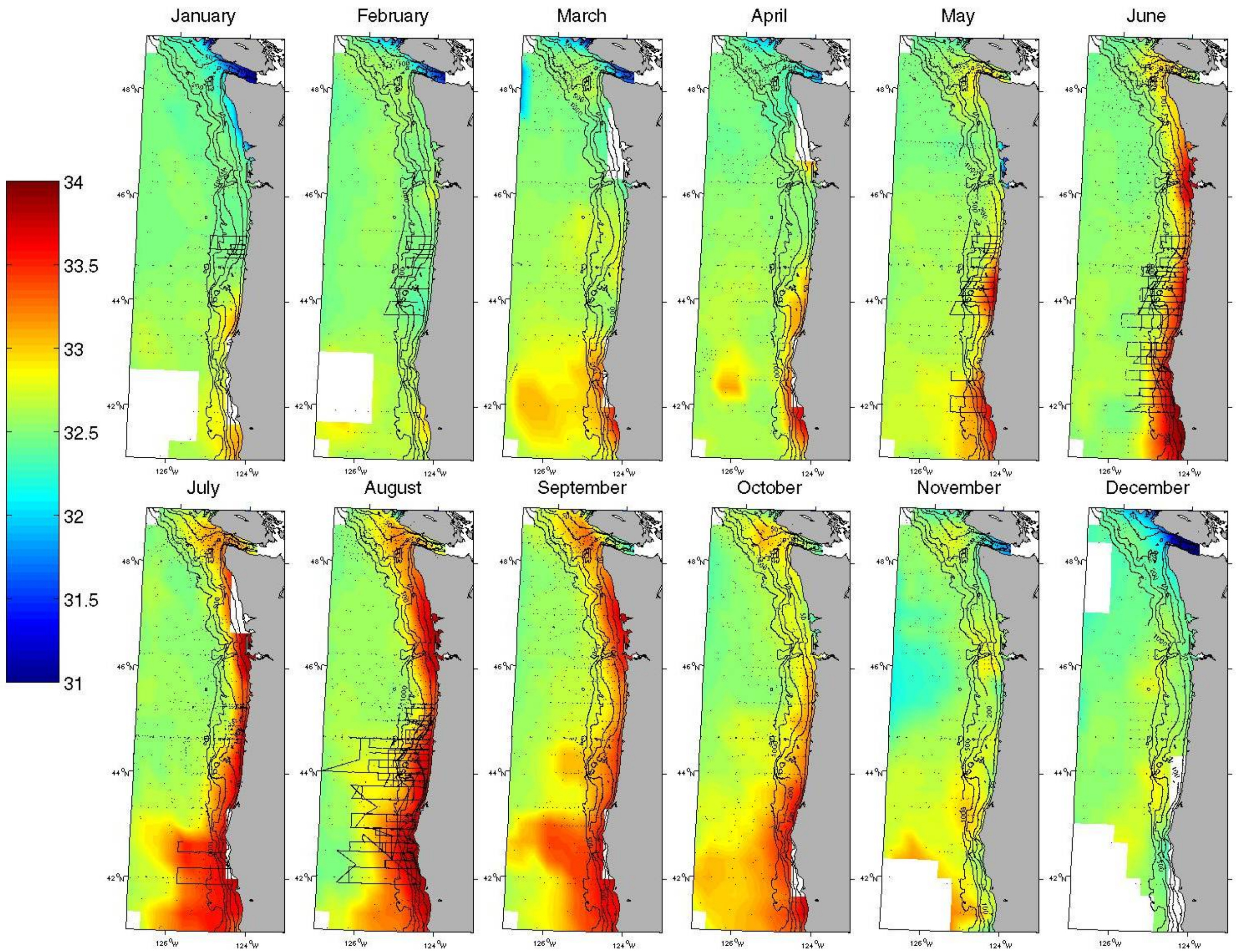


Figure 4-20 Climatological monthly means for salinity at 50 m off the Washington and Oregon coasts from CTD cast observations (1930-2004).

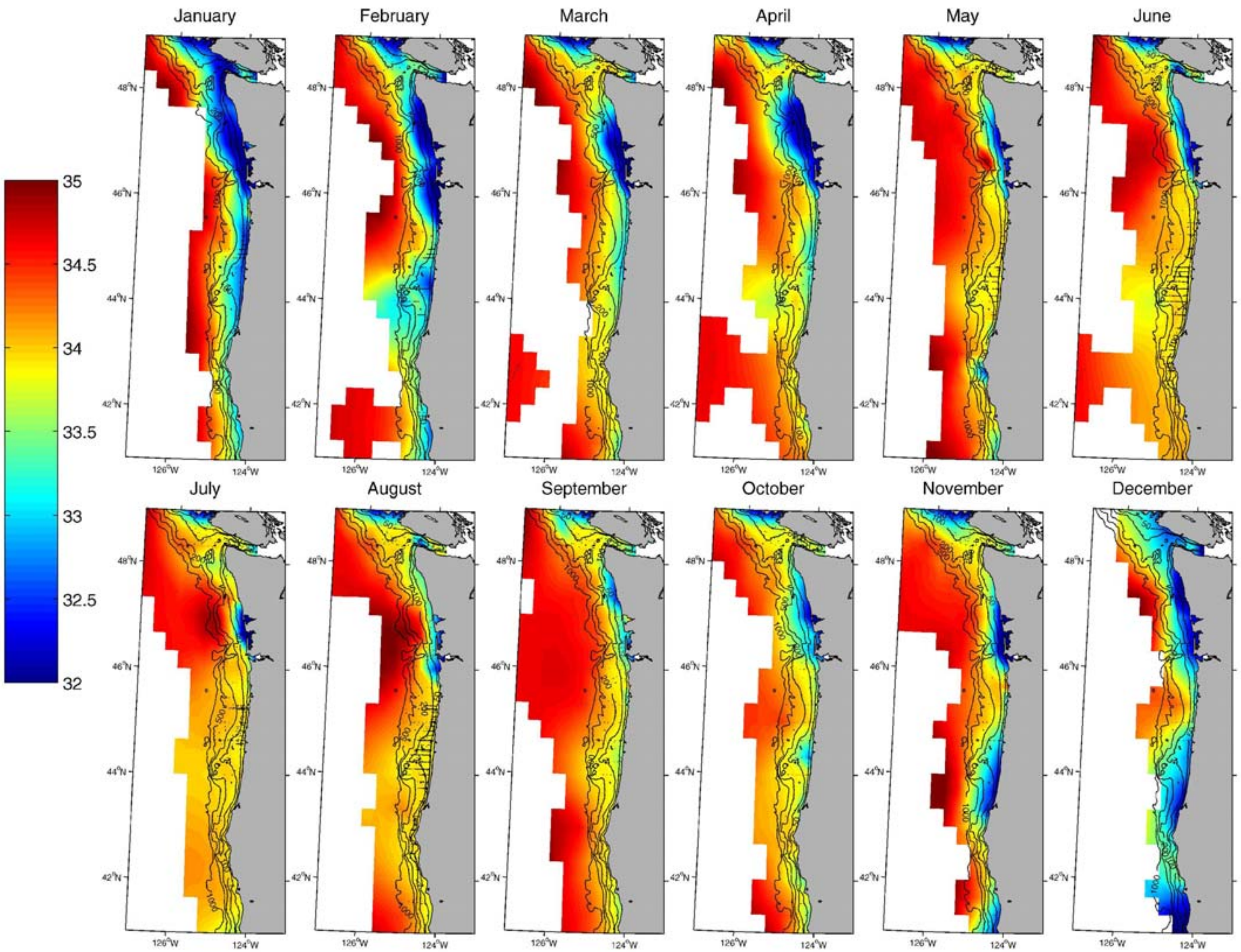


Figure 4-21 Climatological monthly means for salinity at the bottom (10 m above the bottom) off the Washington and Oregon coasts from CTD cast observations (1930-2004).

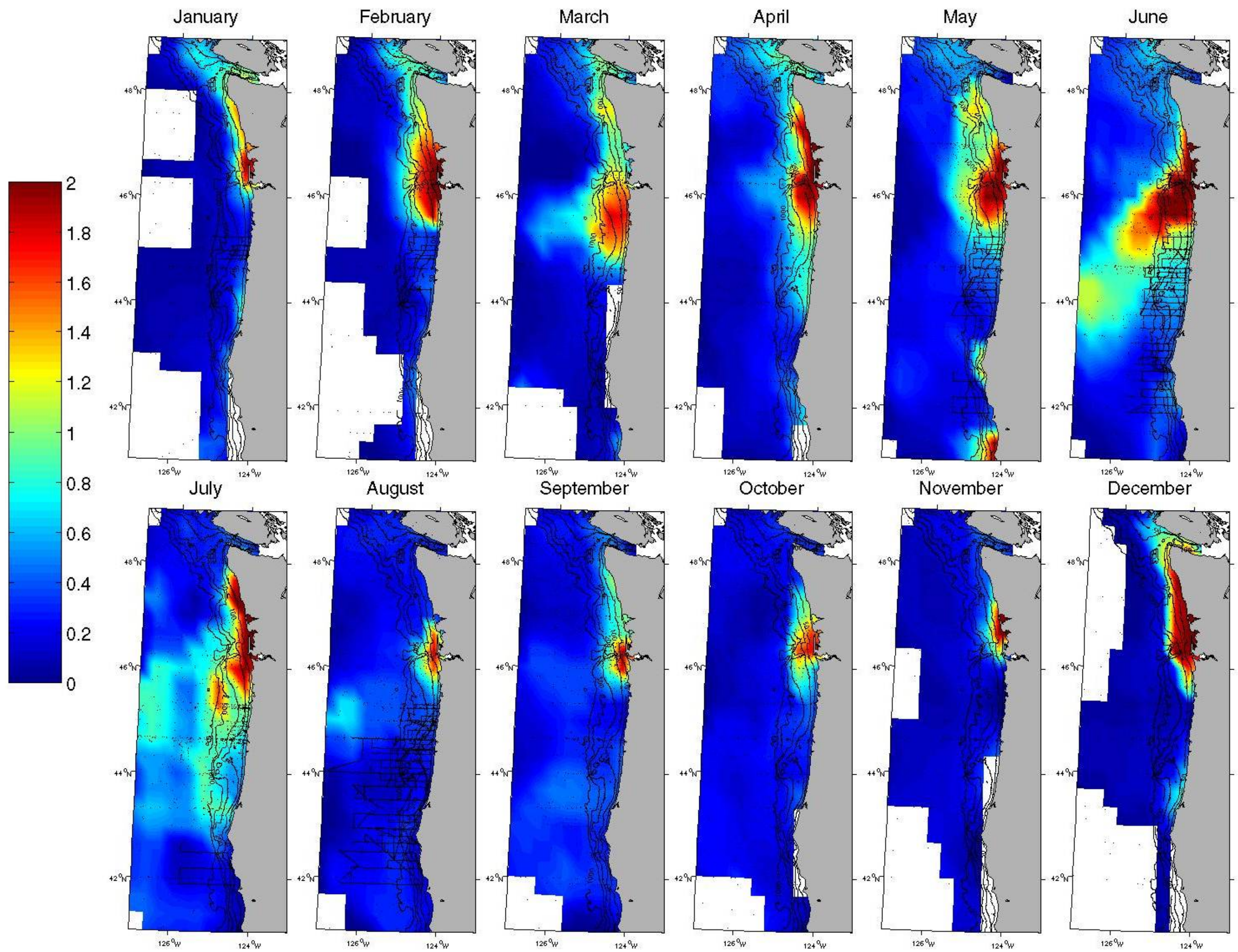


Figure 4-22 Climatological monthly standard deviations for salinity at the surface off the Washington and Oregon coasts from CTD cast observations (1930-2004).

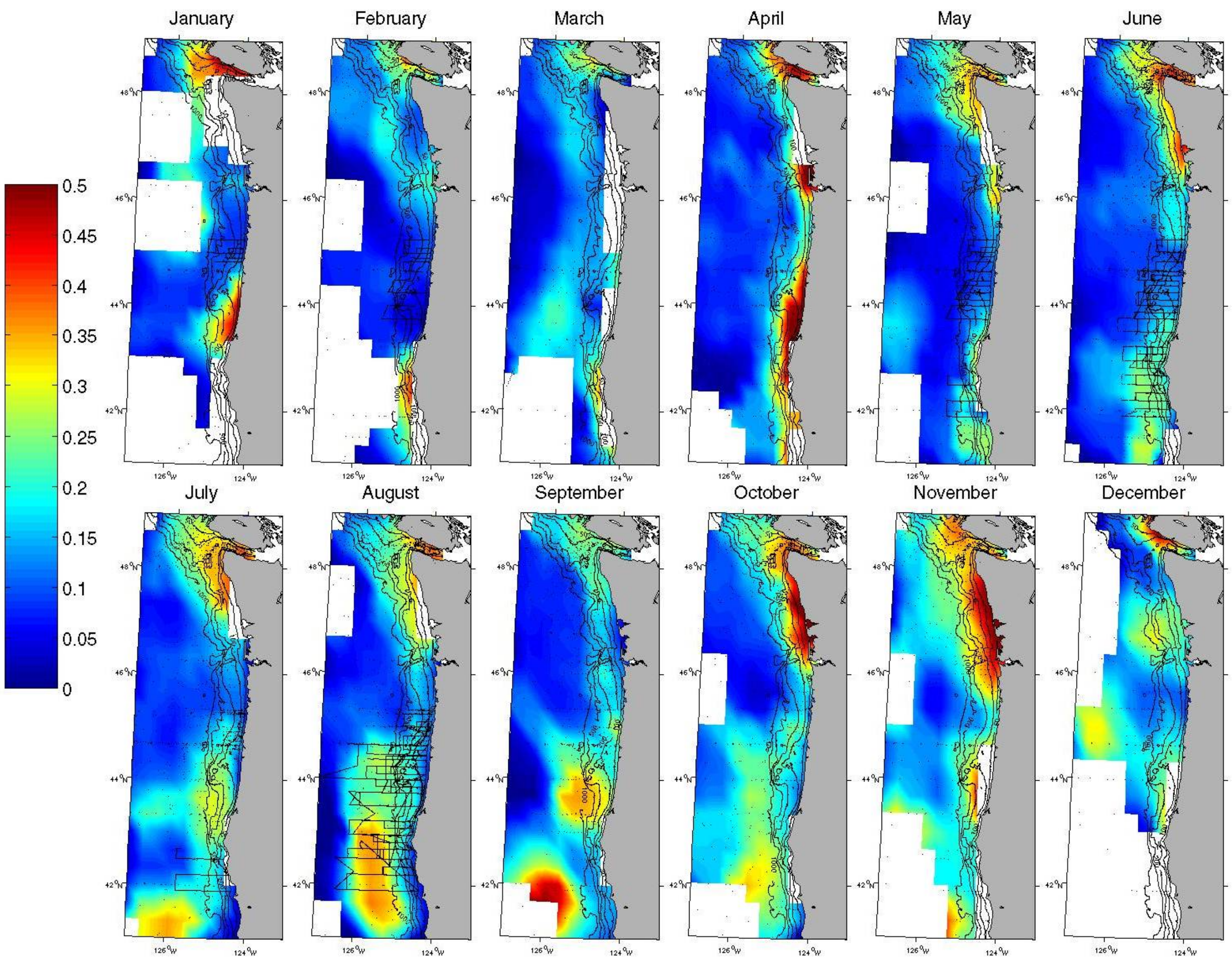


Figure 4-23 Climatological monthly standard deviation for salinity at 50 m off the Washington and Oregon coasts from CTD cast observations (1930-2004).

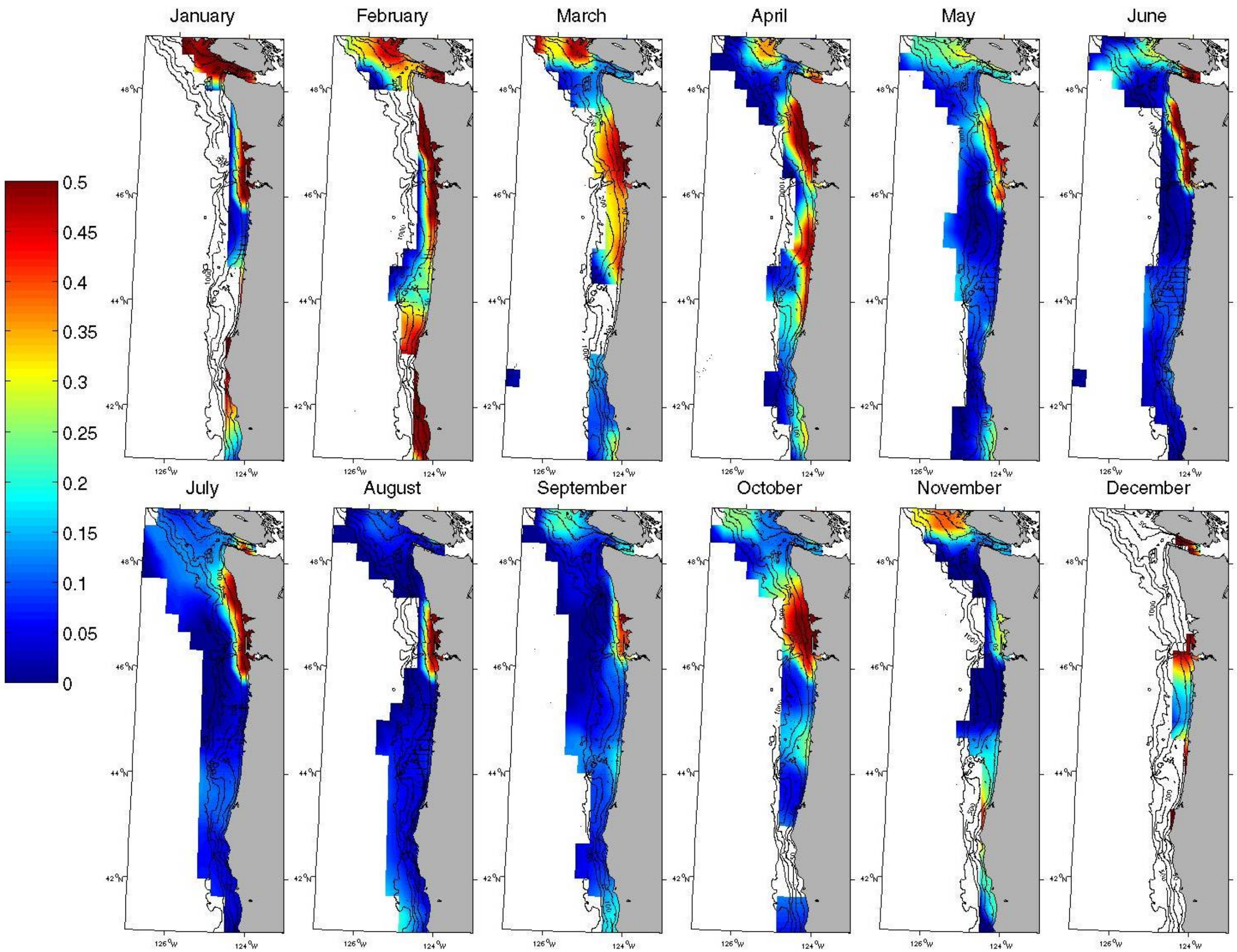


Figure 4-24 Climatological monthly standard deviations for salinity at the bottom (10 m above the bottom) off the Washington and Oregon coasts from CTD cast observations (1930-2004).

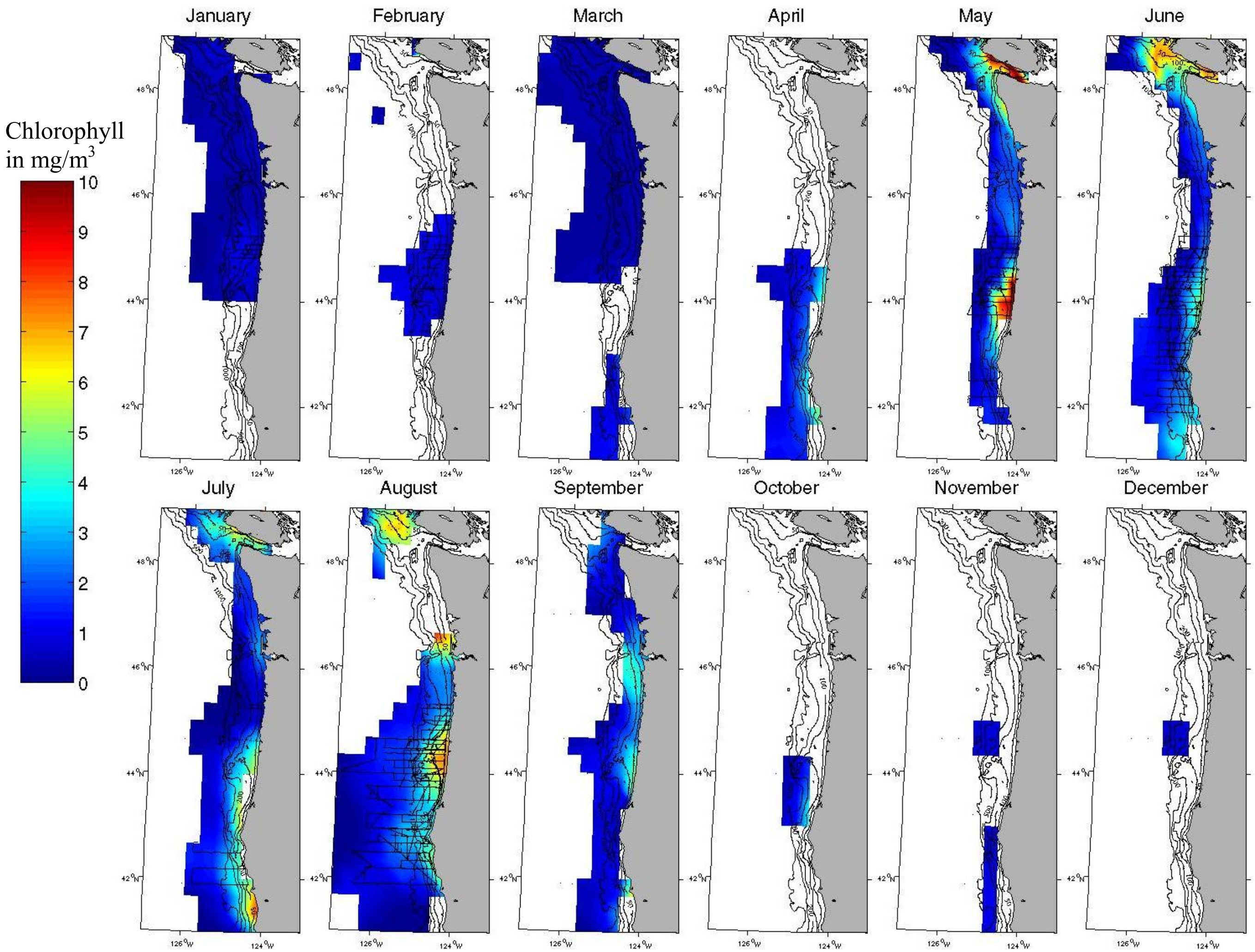


Figure 4-25 Climatological monthly means for chlorophyll-a concentrations at 0-10 m depth (natural scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

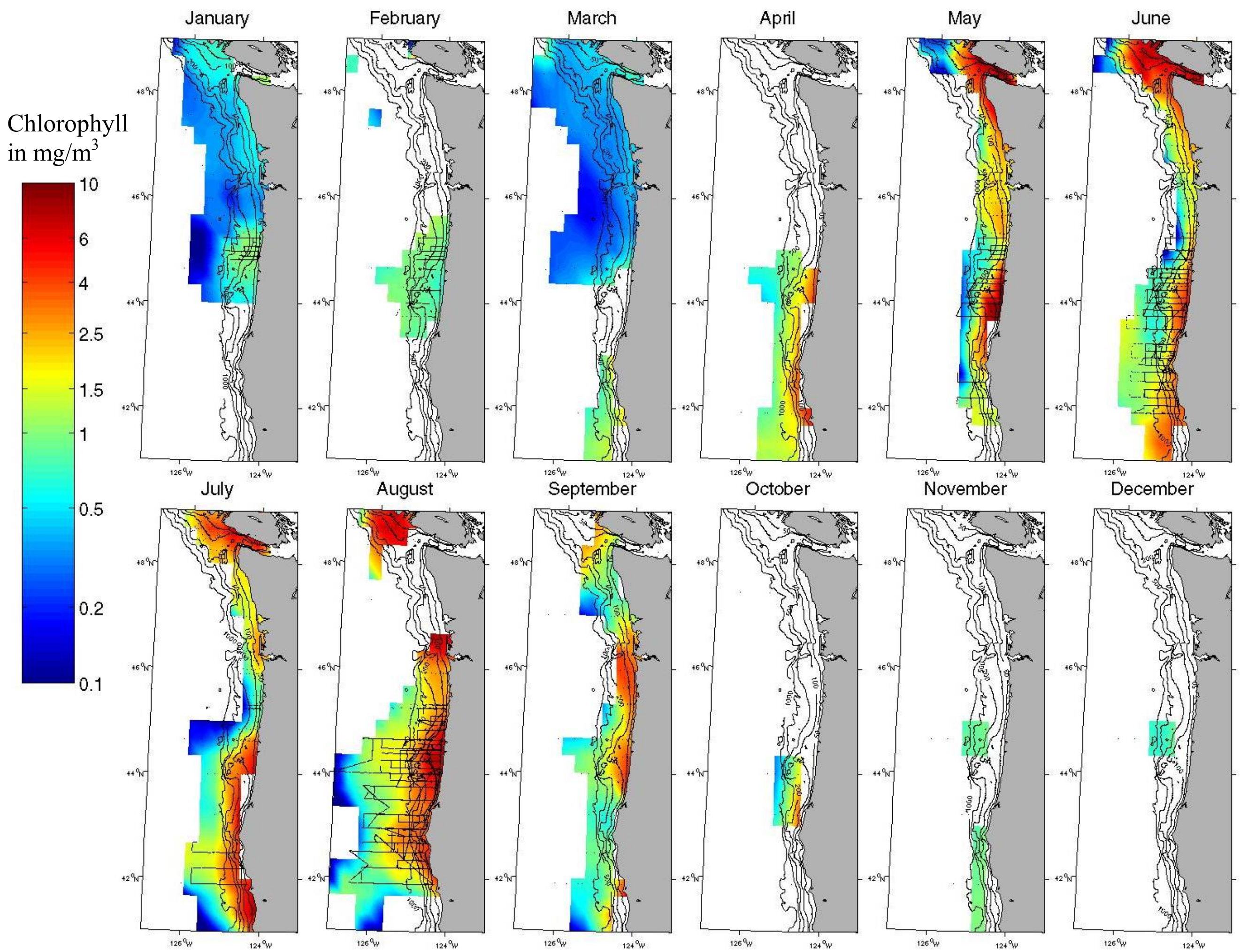


Figure 4-26 Climatological monthly means for chlorophyll-a concentrations at 0-10 m depth (log scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

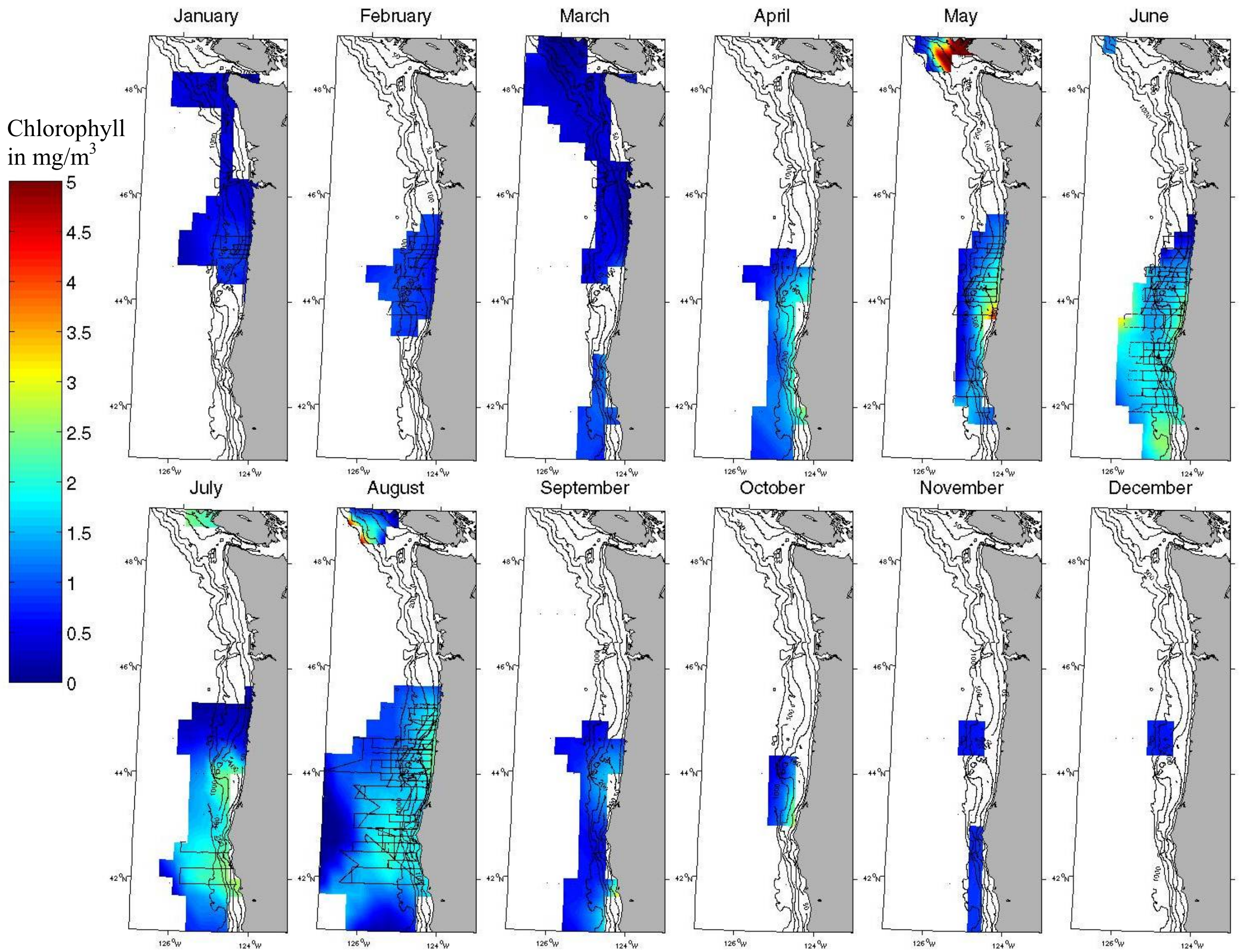


Figure 4-27 Climatological monthly means for chlorophyll-a concentrations at 20-30 m depth (natural scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

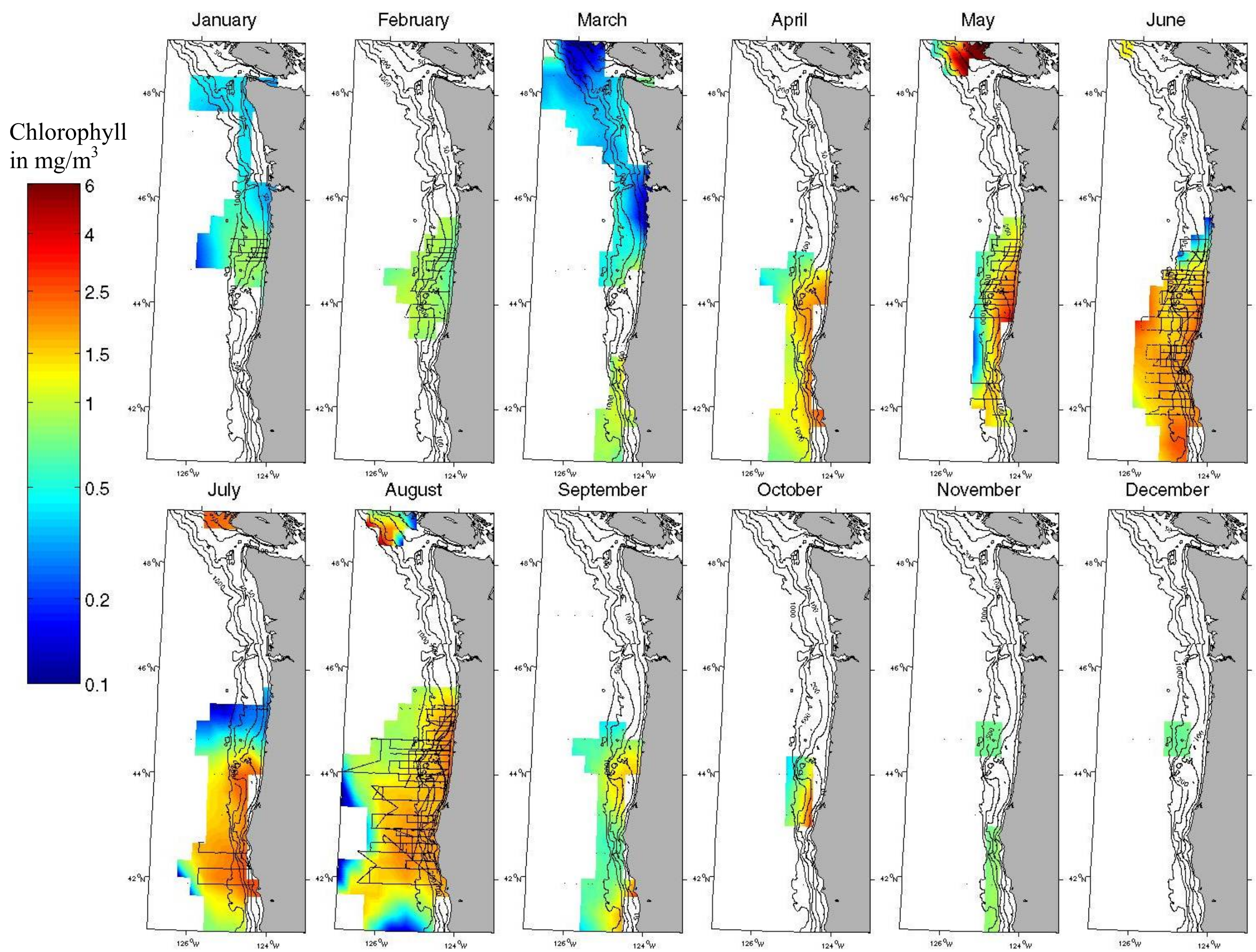


Figure 4-28 Climatological monthly means for chlorophyll-a concentrations at 20-30 m depth (log scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

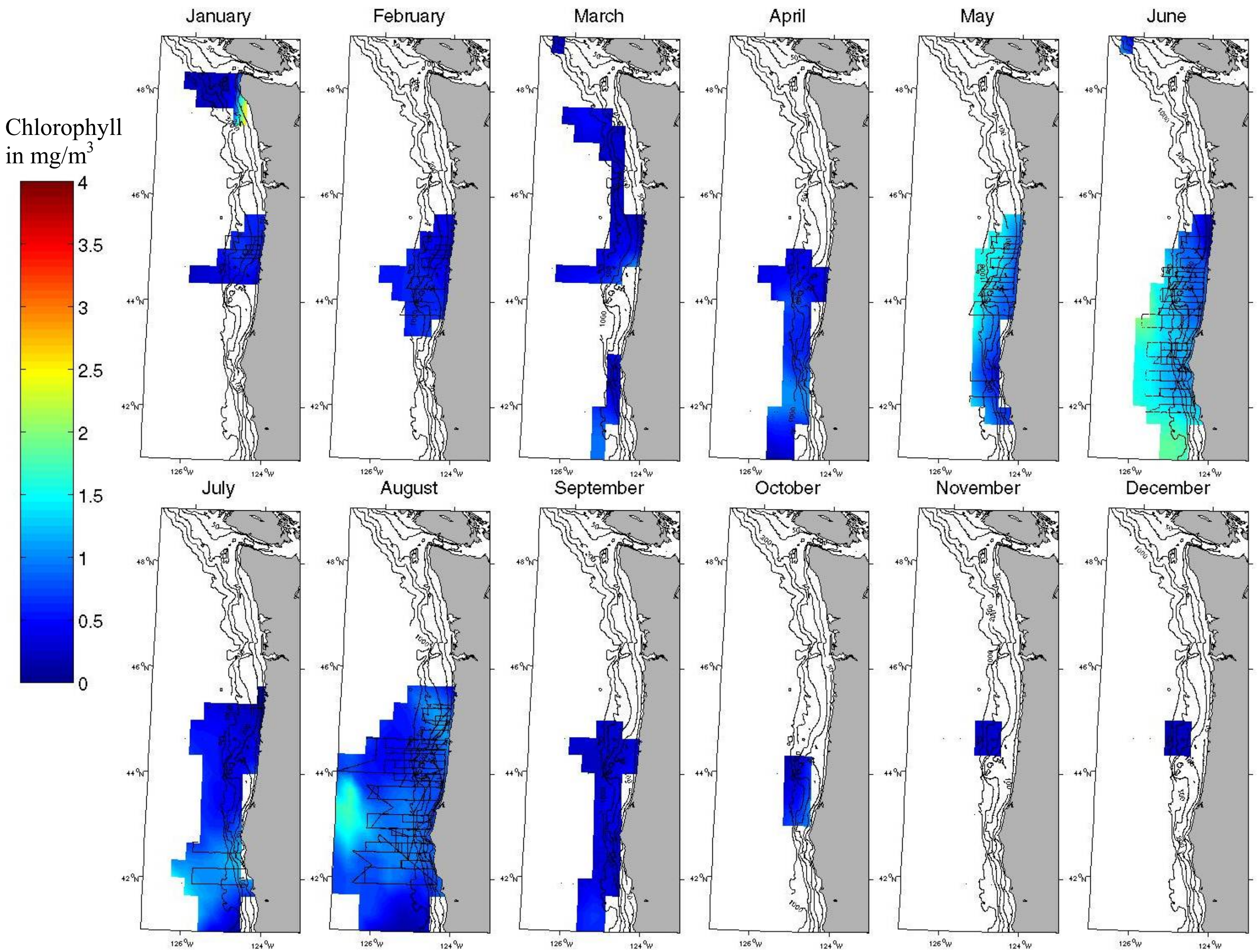


Figure 4-29 Climatological monthly means for chlorophyll-a concentrations at 40-50 m (natural scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

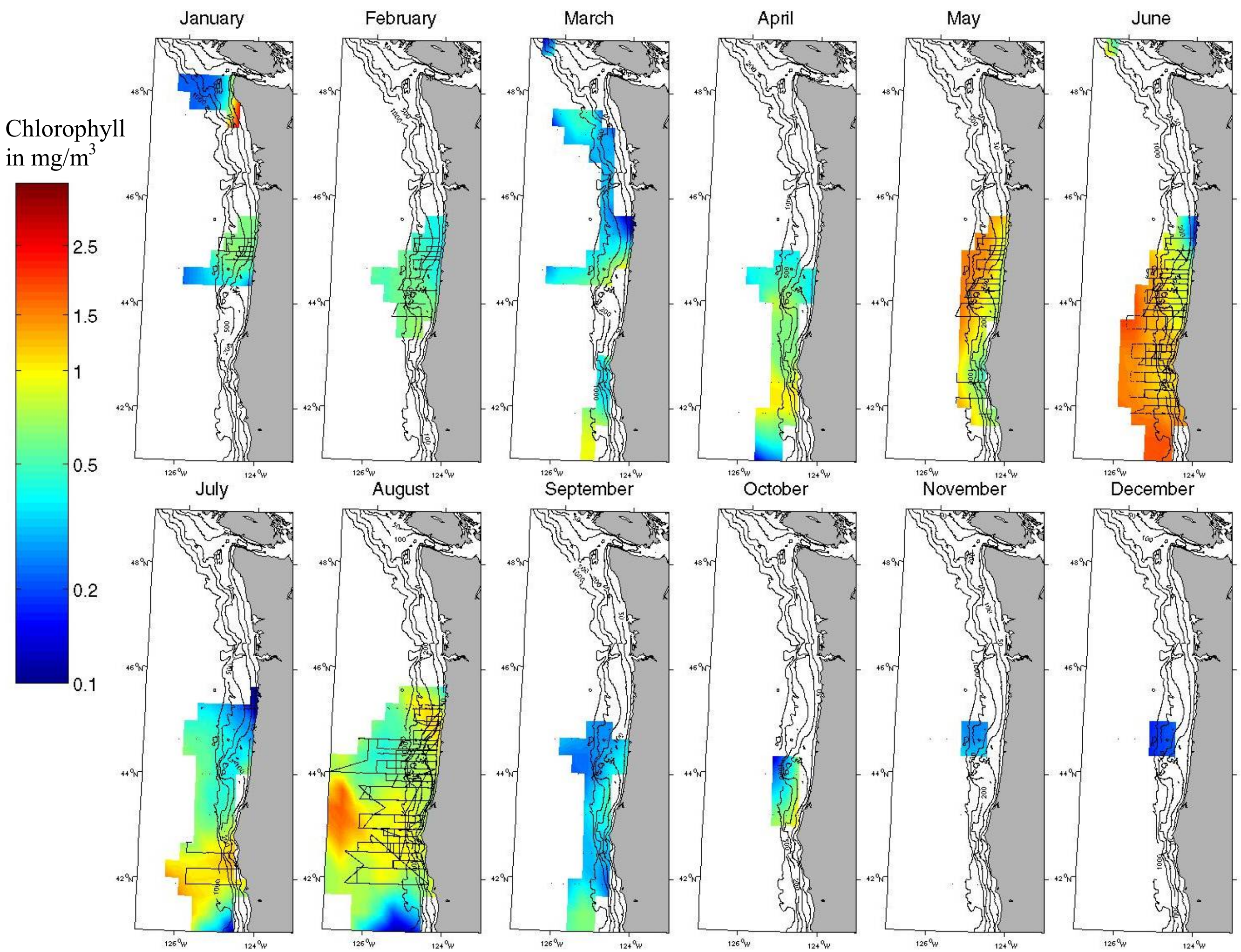


Figure 4-30 Climatological monthly means for chlorophyll-a concentrations at 40-50 m (log scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

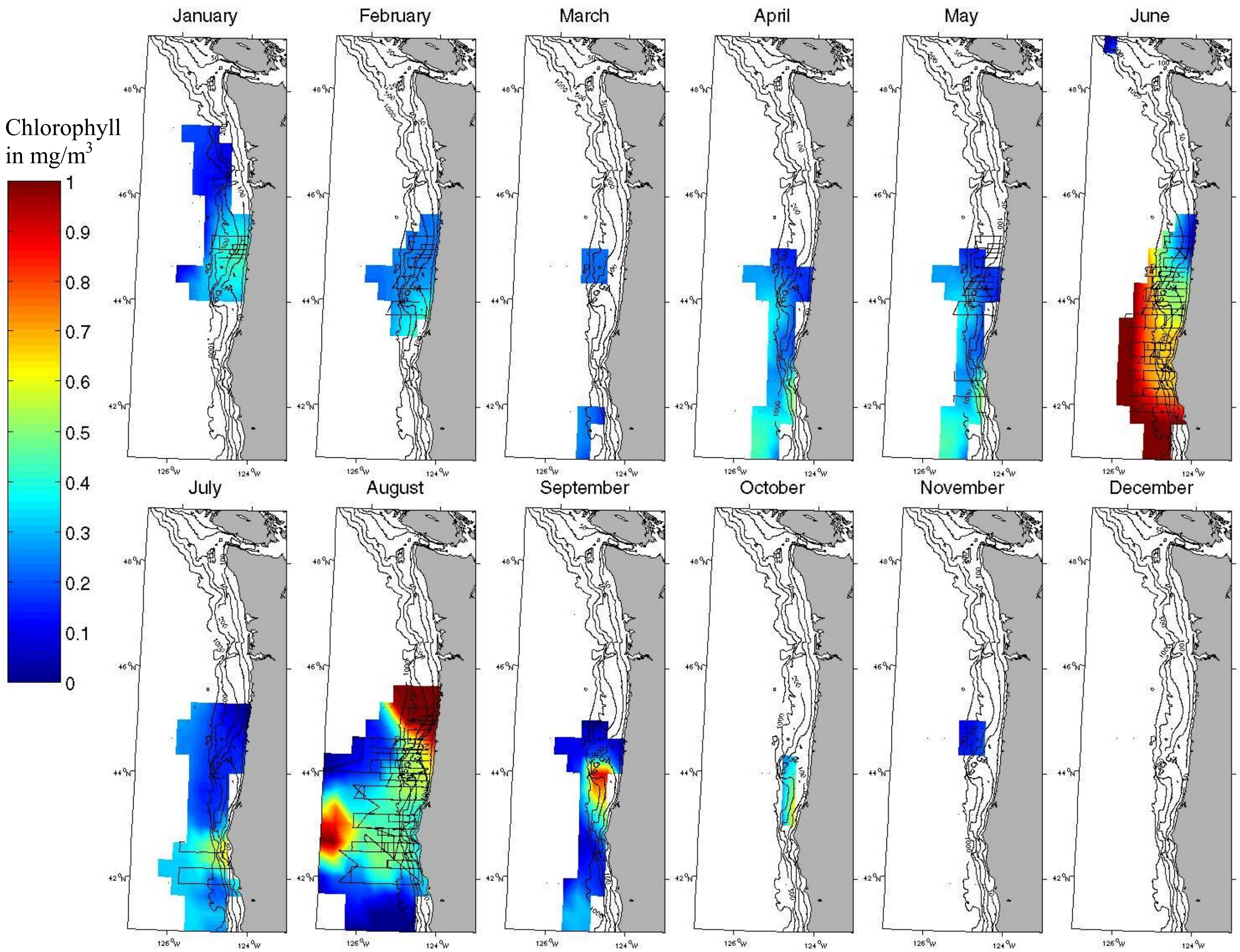


Figure 4-31 Climatological monthly means for chlorophyll-a concentrations at 60-70 m (natural scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

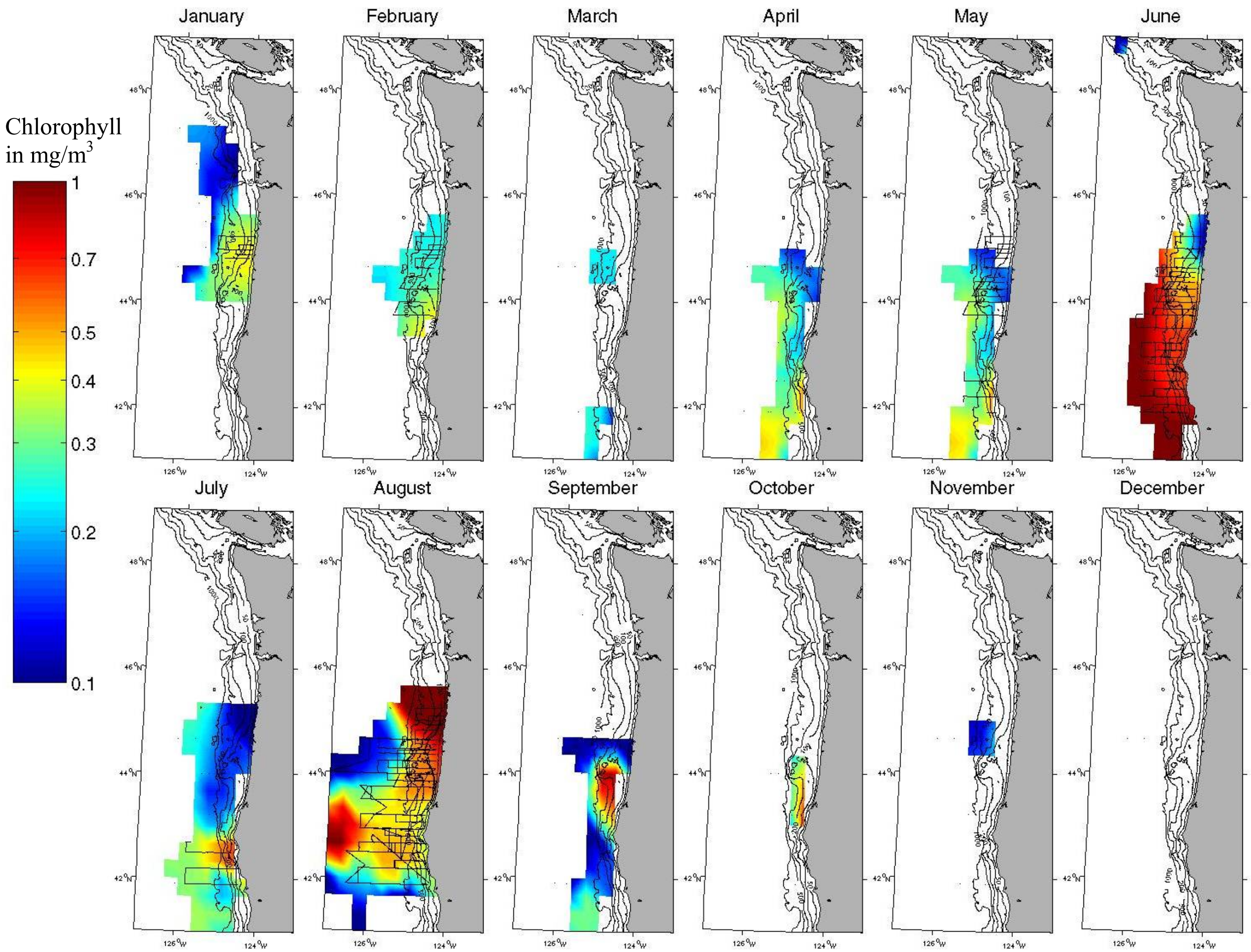


Figure 4-32 Climatological monthly means for chlorophyll-a concentrations at 60-70 m (log scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

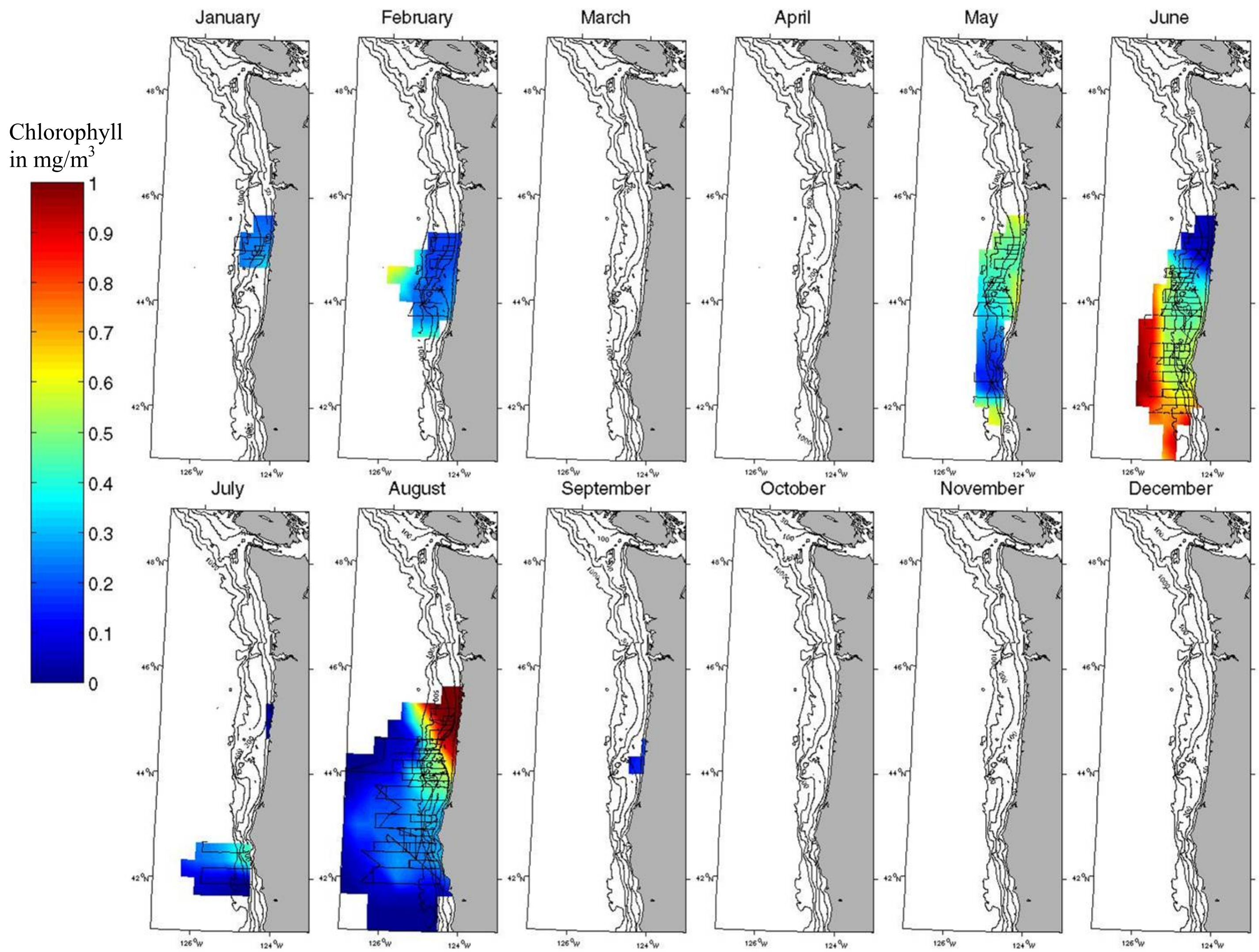


Figure 4-33 Climatological monthly means for chlorophyll-a concentrations at 80-90 m (natural scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

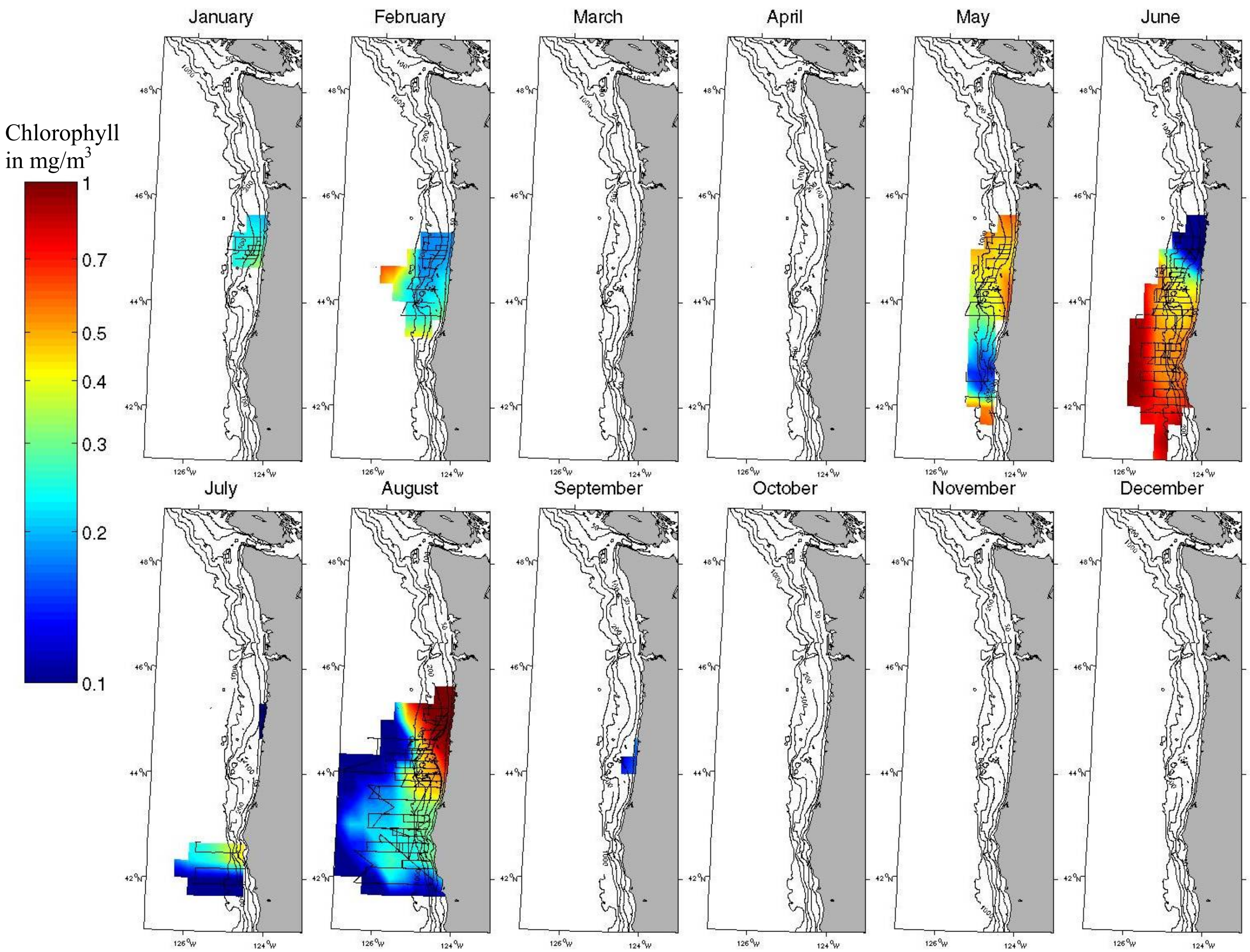


Figure 4-34 Climatological monthly means for chlorophyll-a concentrations at 80-90 m (log scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

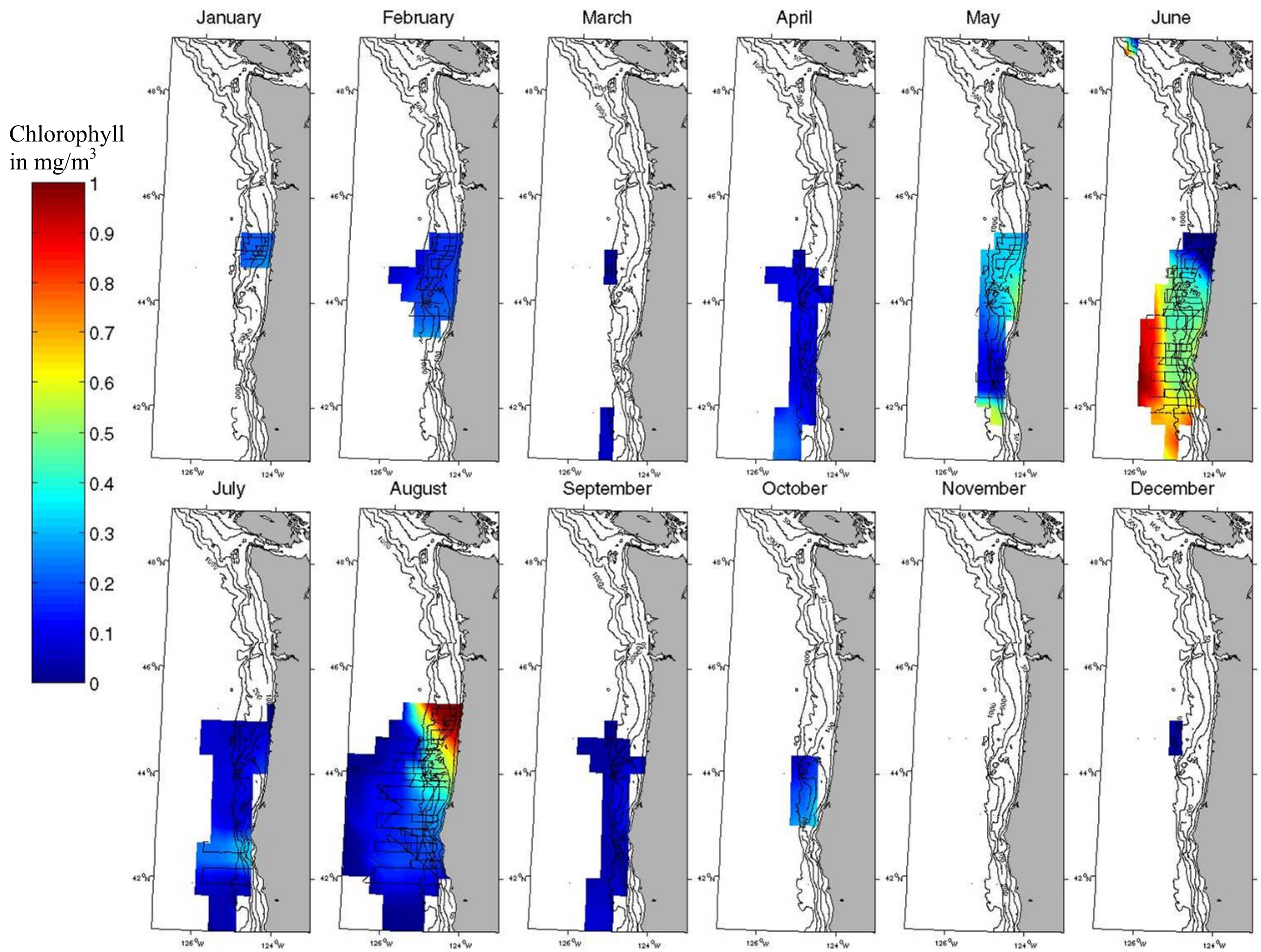


Figure 4-35 Climatological monthly means for chlorophyll-a concentrations at 100-110 m (natural scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

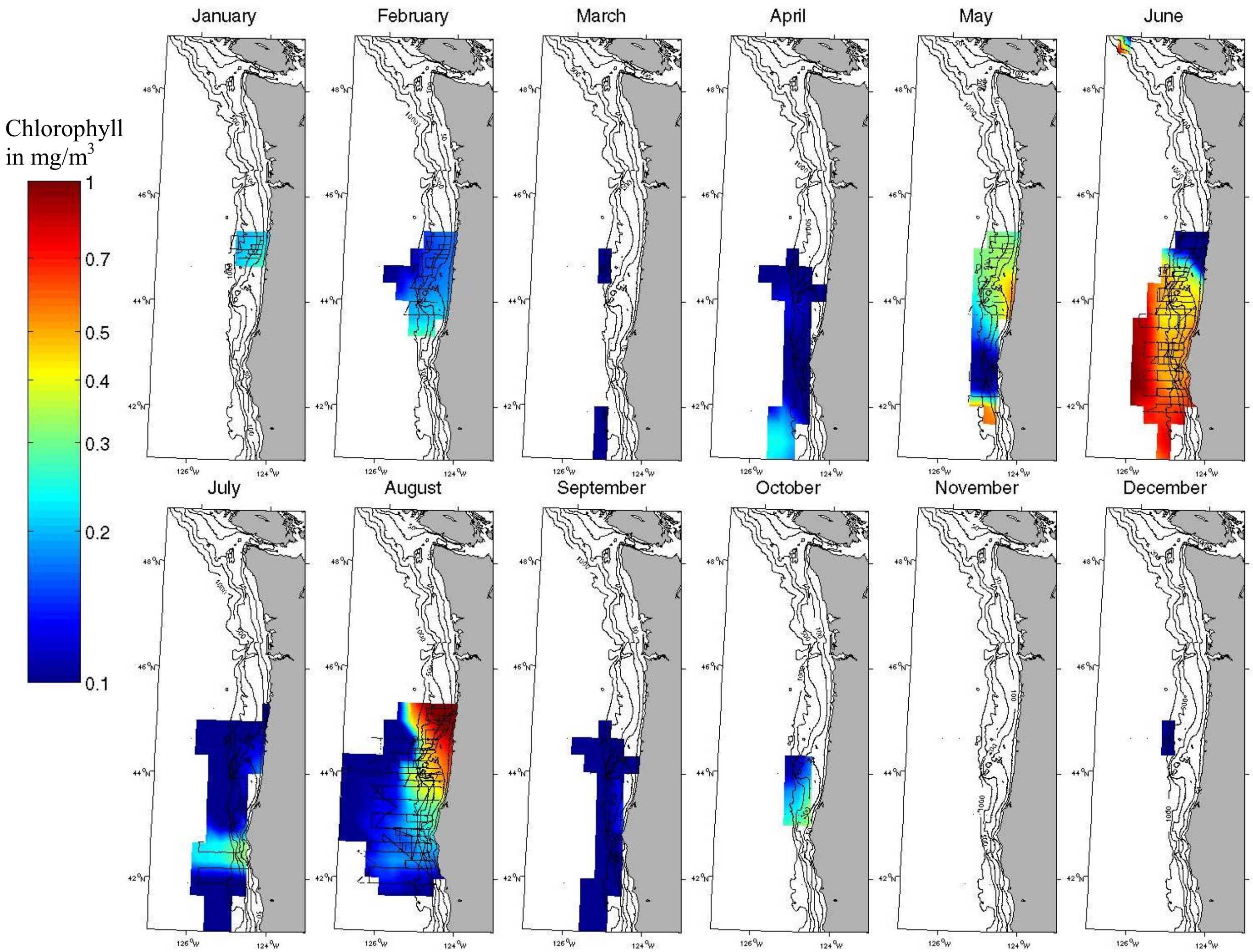


Figure 4-36 Climatological monthly means for chlorophyll-a concentrations at 100-110 m (log scale) off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

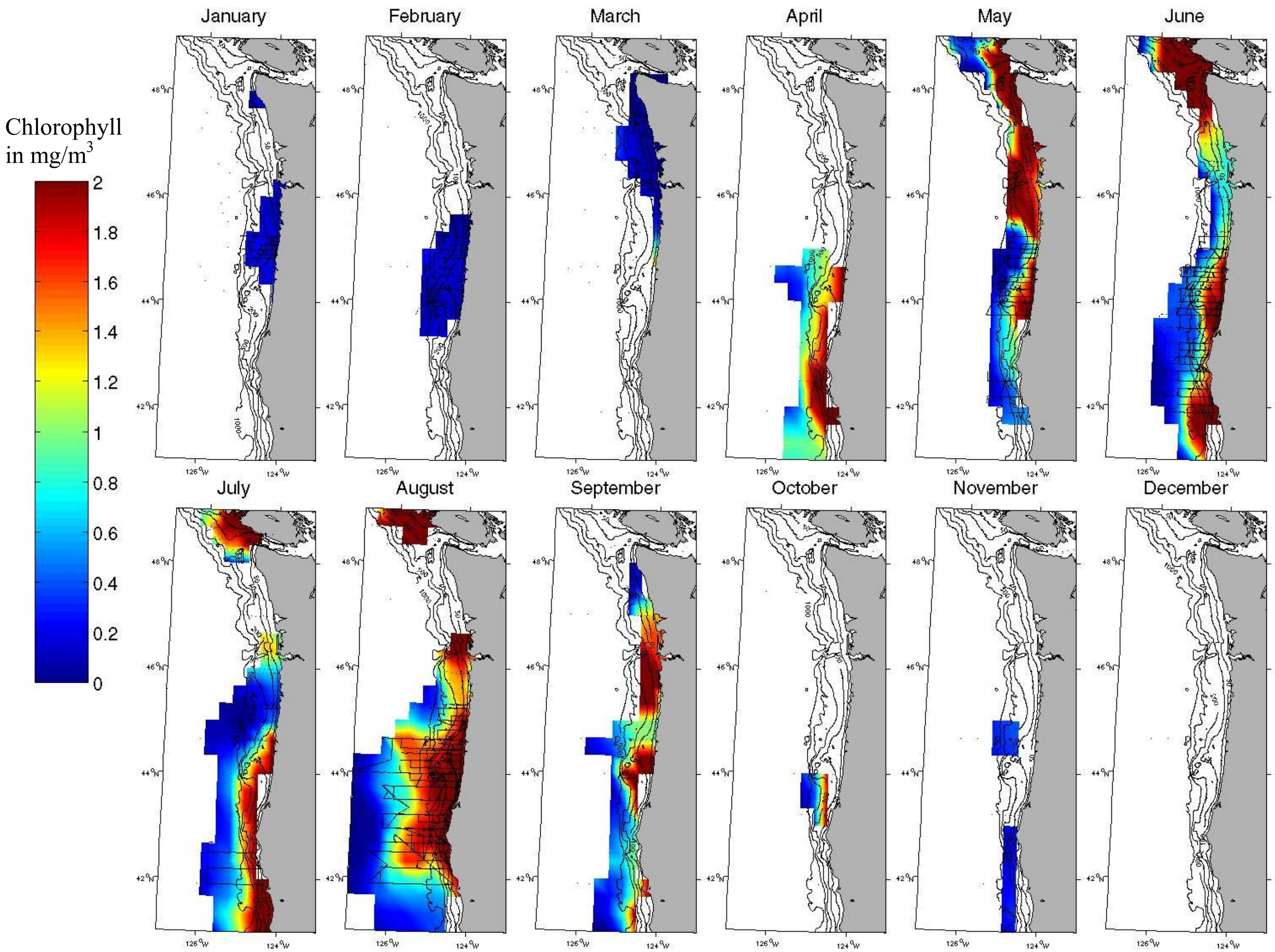


Figure 4-37 Climatological monthly standard deviations for chlorophyll-a at the surface off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

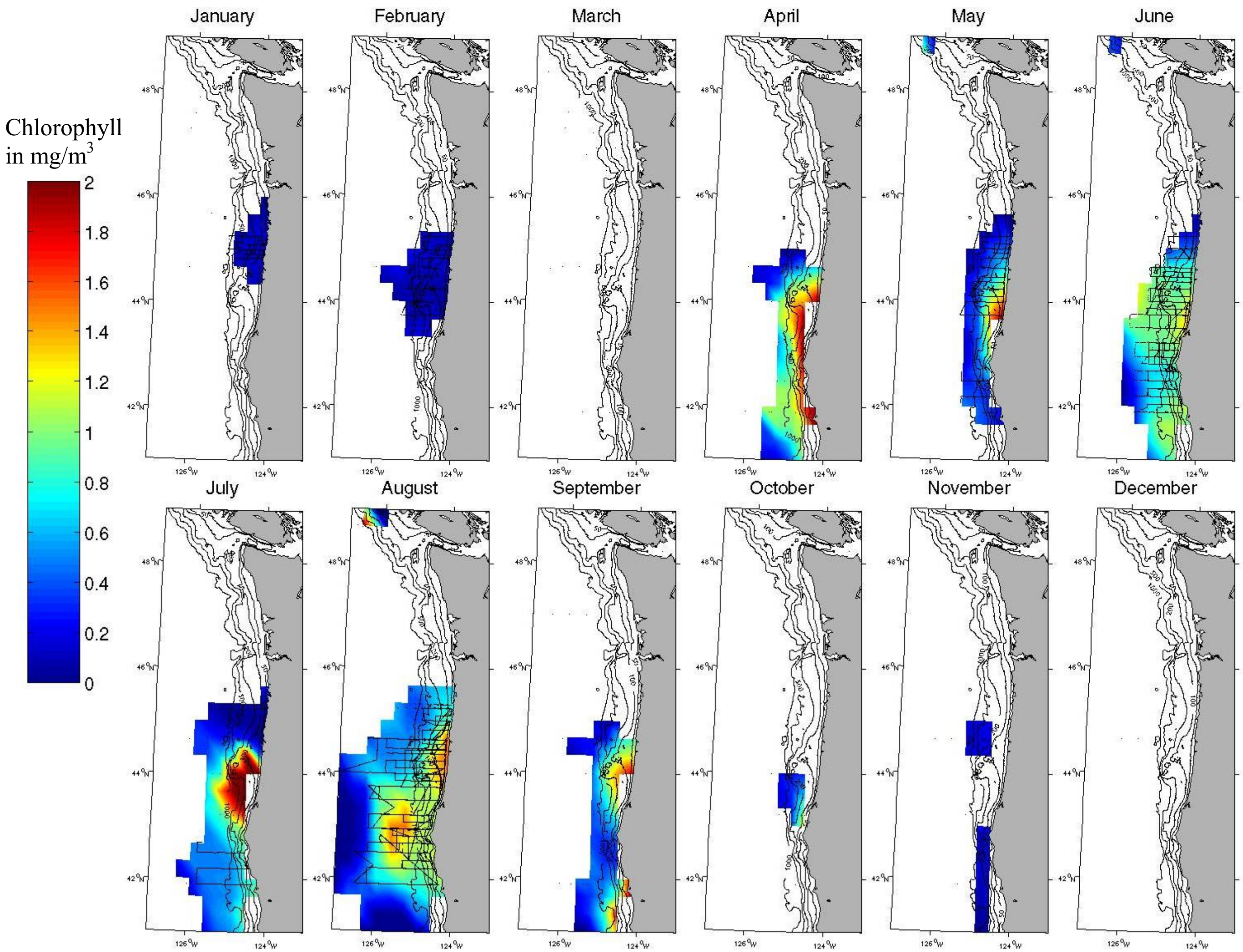


Figure 4-38 Climatological monthly standard deviations for chlorophyll-a at 20-30 m off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

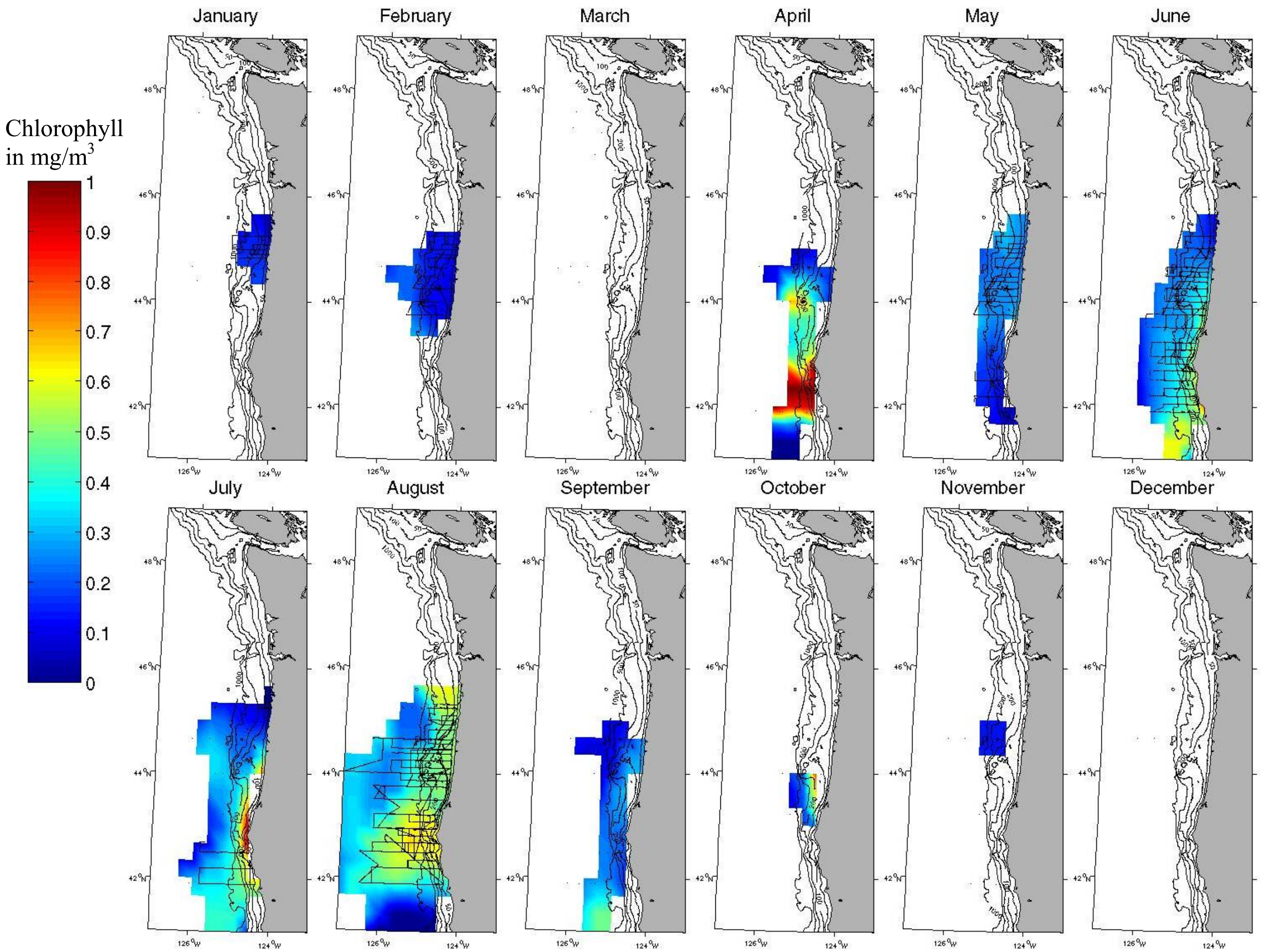


Figure 4-39 Climatological monthly standard deviations for chlorophyll-a at 40-50 m off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

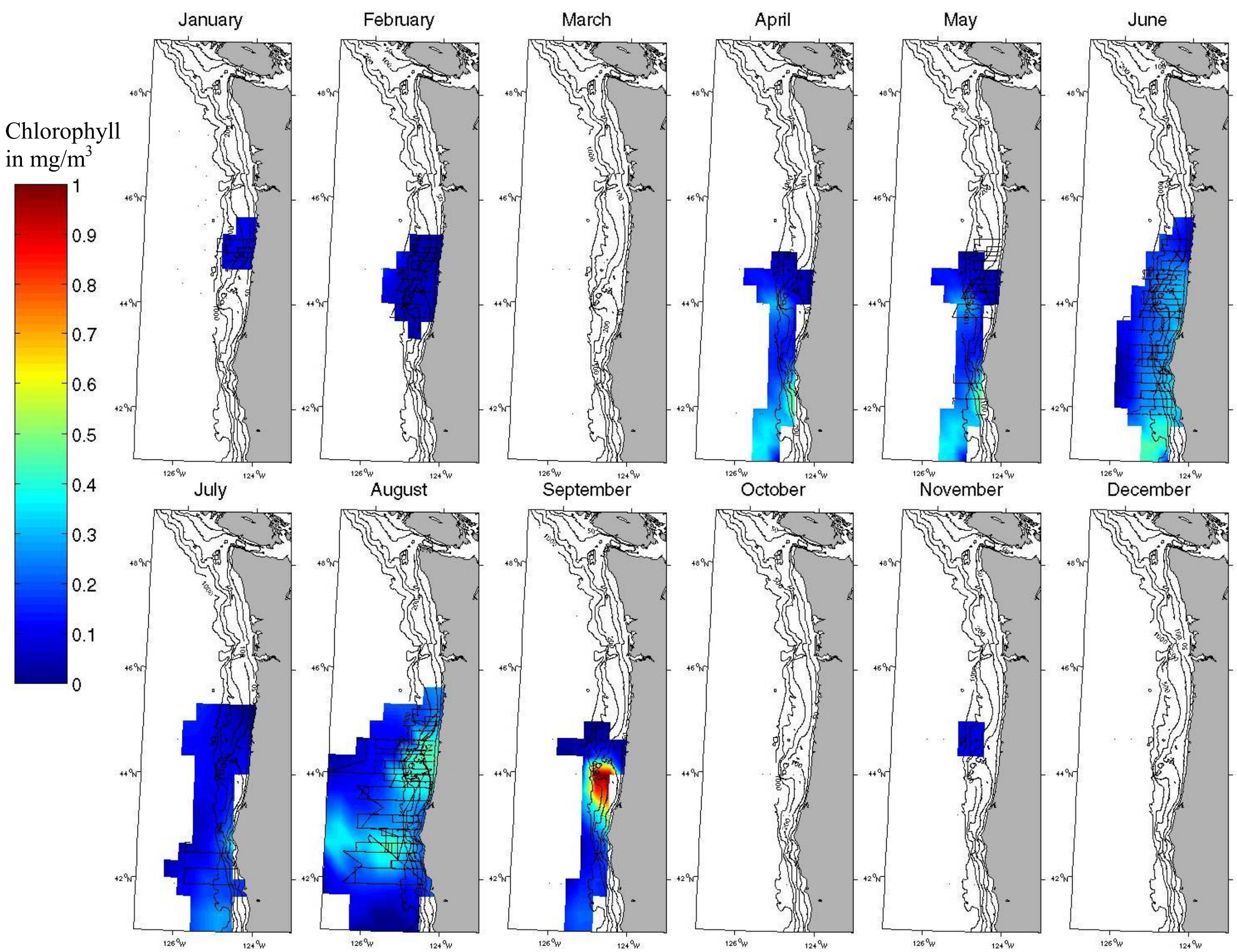


Figure 4-40 Climatological monthly standard deviations for chlorophyll-a at 60-70 m off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

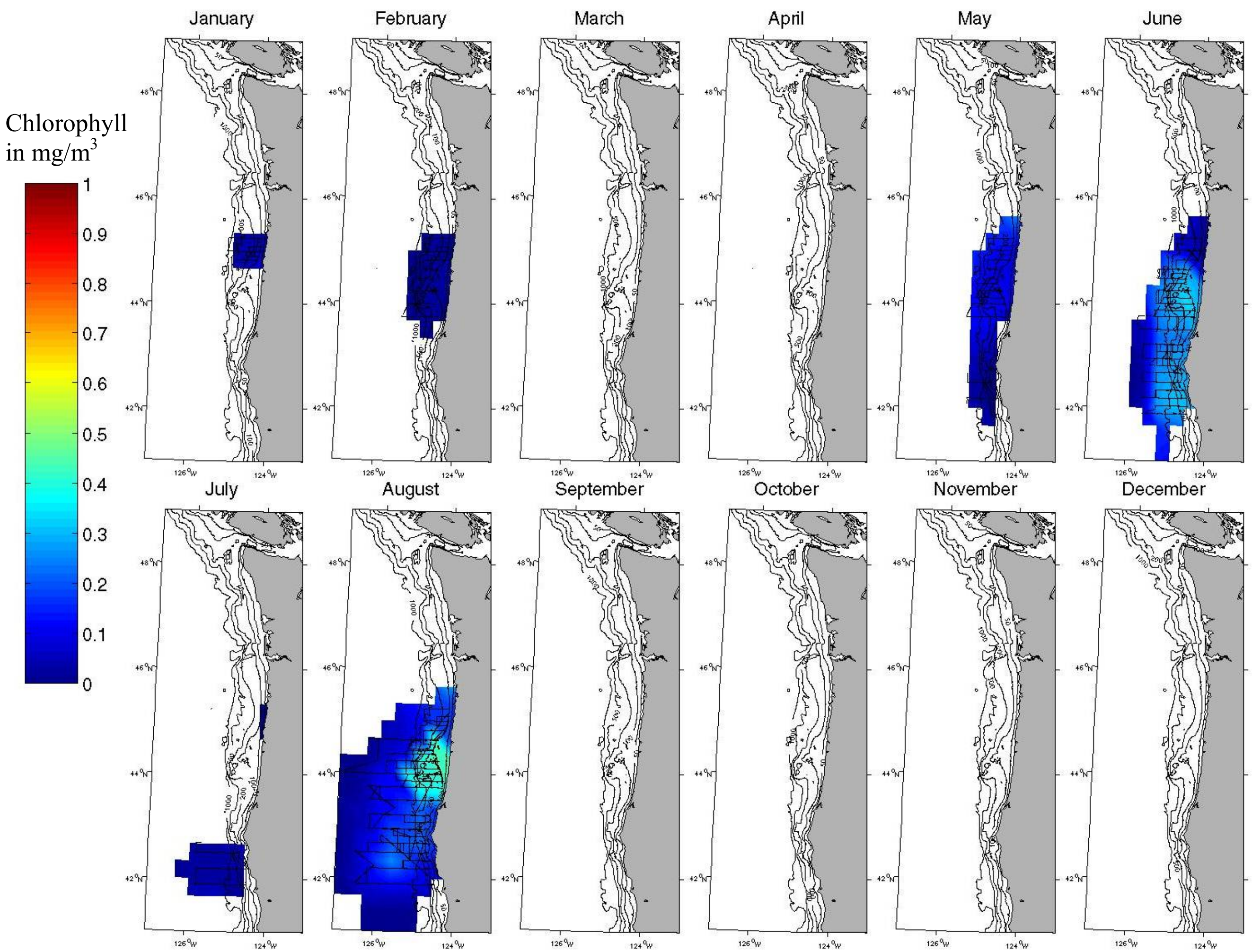


Figure 4-41 Climatological monthly standard deviations for chlorophyll-a at 80-90 m off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

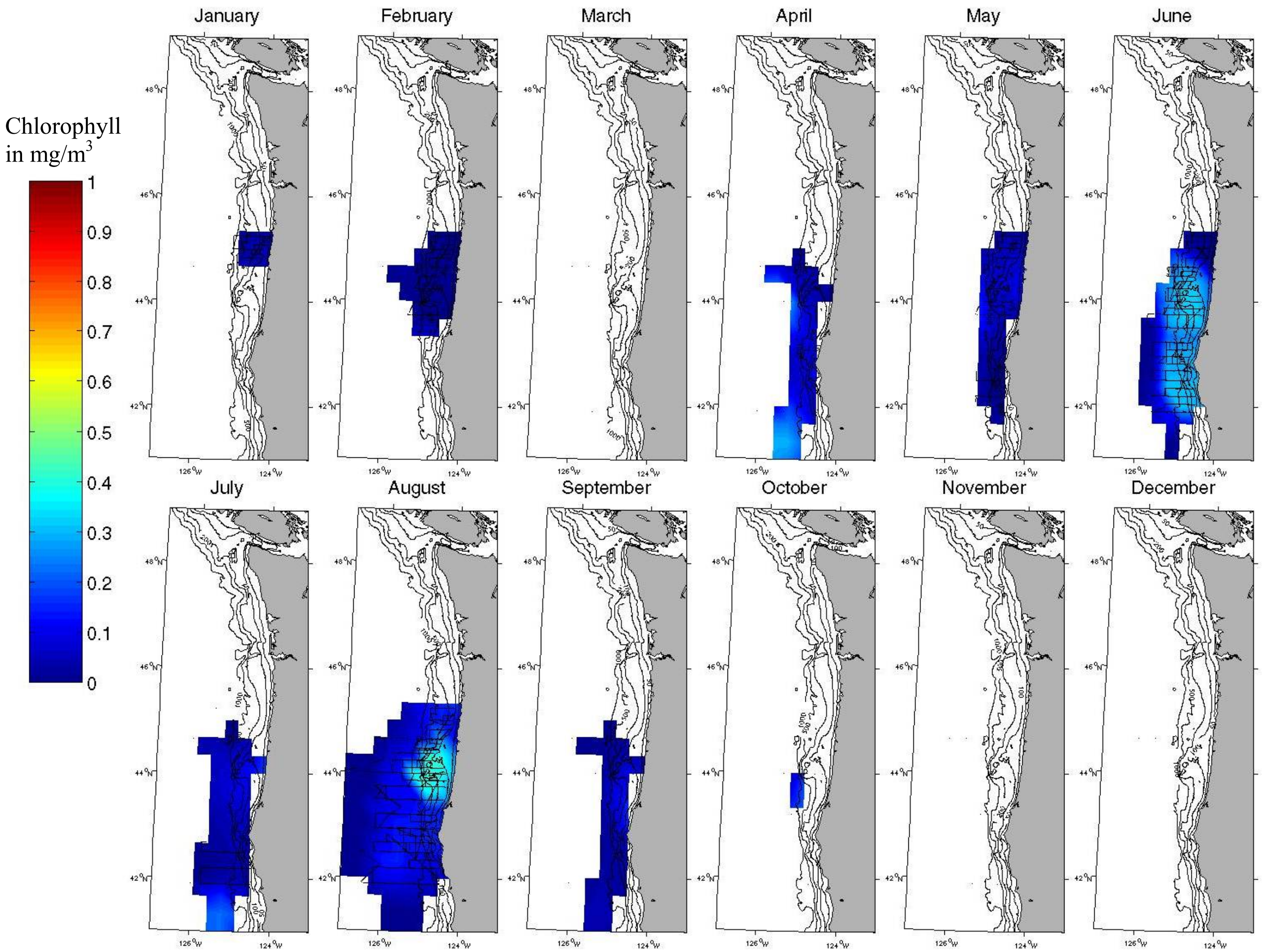


Figure 4-42 Climatological monthly standard deviations for chlorophyll-a at 100-110 off the Washington and Oregon coasts from fluorometers and Niskin bottle samples (1950-2004).

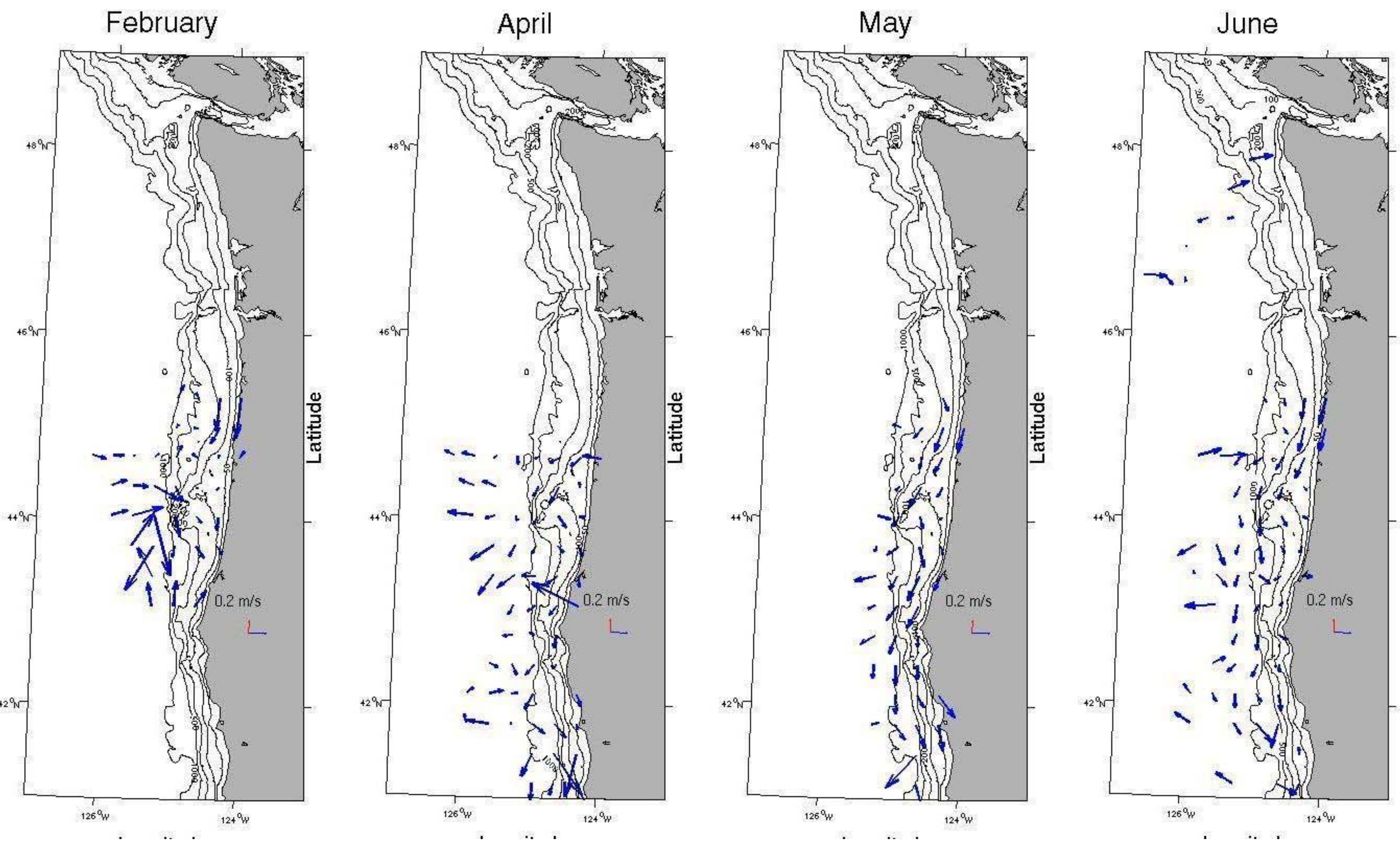


Figure 4-43 Climatological monthly means for current velocity at 30 m depth off the Washington and Oregon coasts from shipboard ADCP observations (1991-2004).

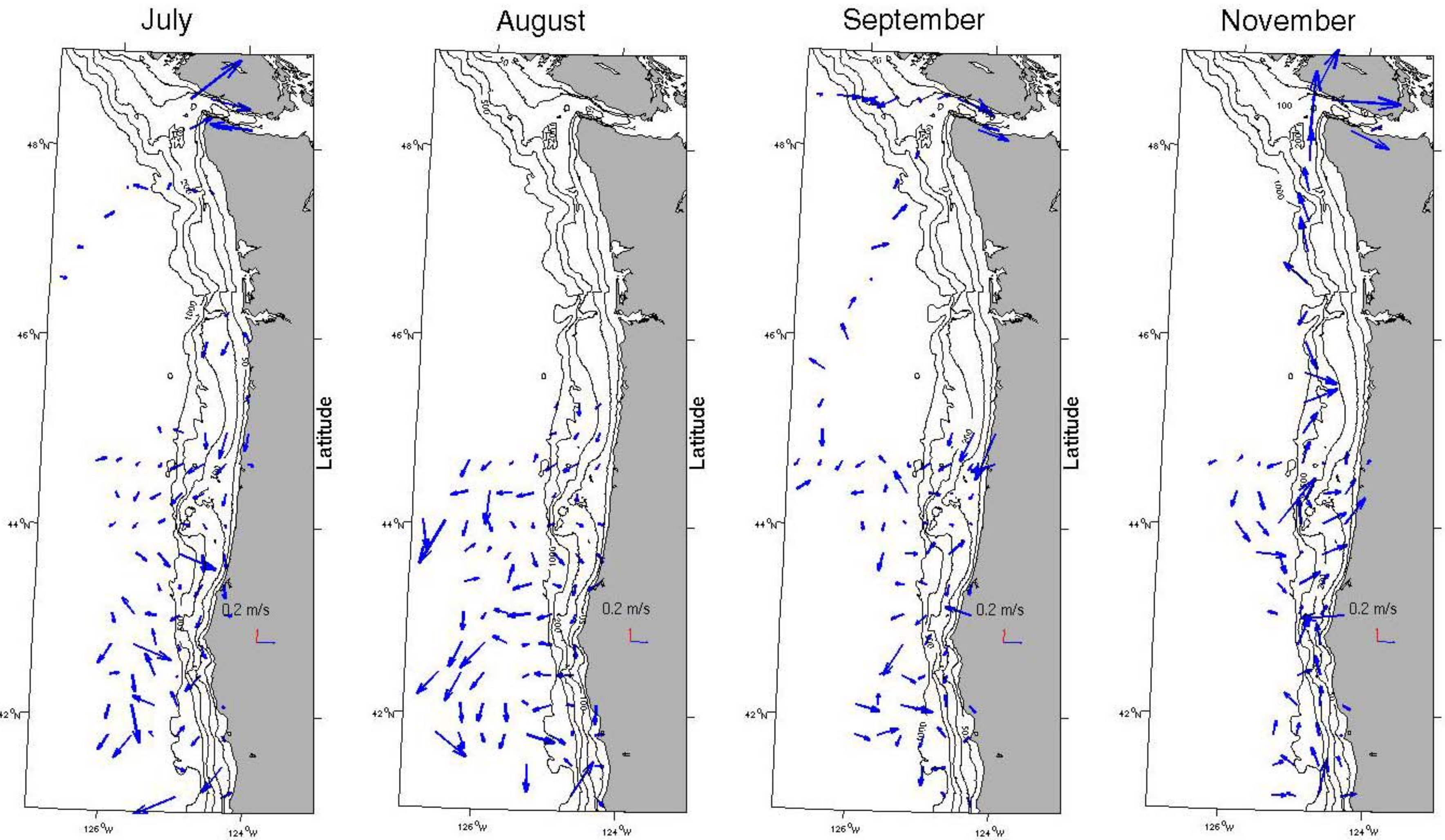


Figure 4-44 Climatological monthly means for current velocity at 30 m depth off the Washington and Oregon coasts from shipboard ADCP observations (1991-2004).

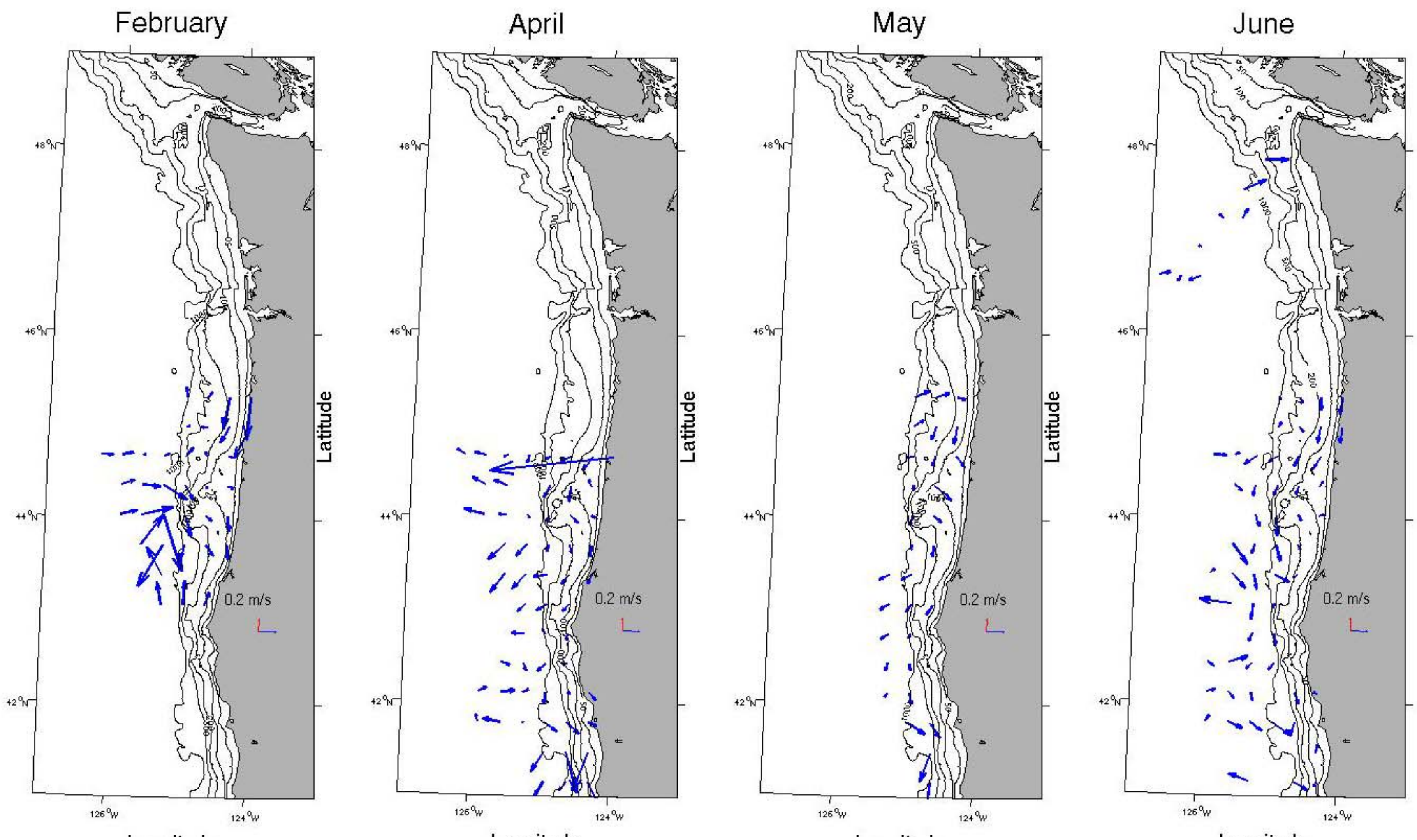


Figure 4-45 Climatological monthly means for current velocity at 50 m depth off the Washington and Oregon coasts from shipboard ADCP obserbations (1991-2004).

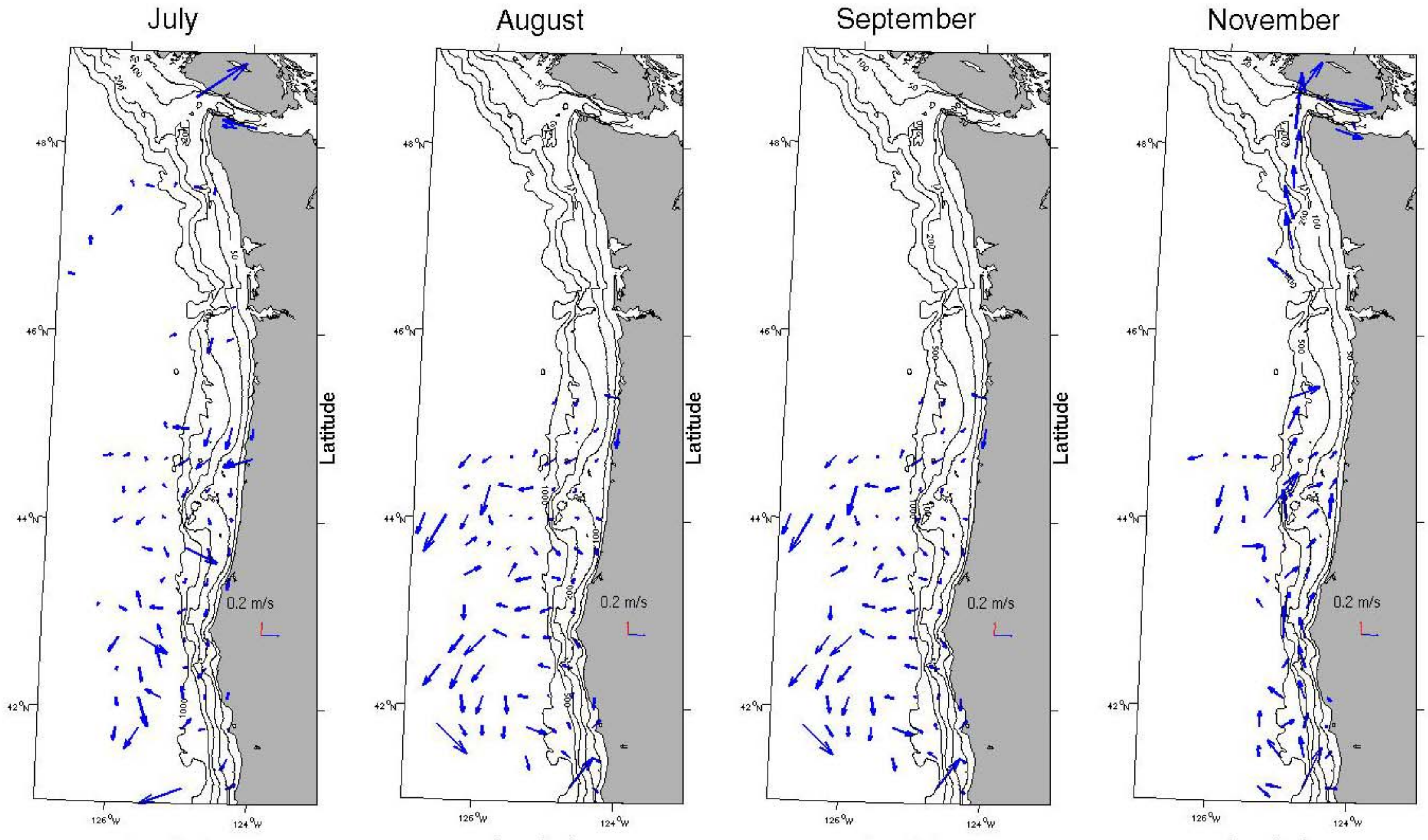


Figure 4-46 Climatological monthly means for current velocity at 50 m depth off the Washington and Oregon coasts from shipboard ADCP observations (1991-2004).

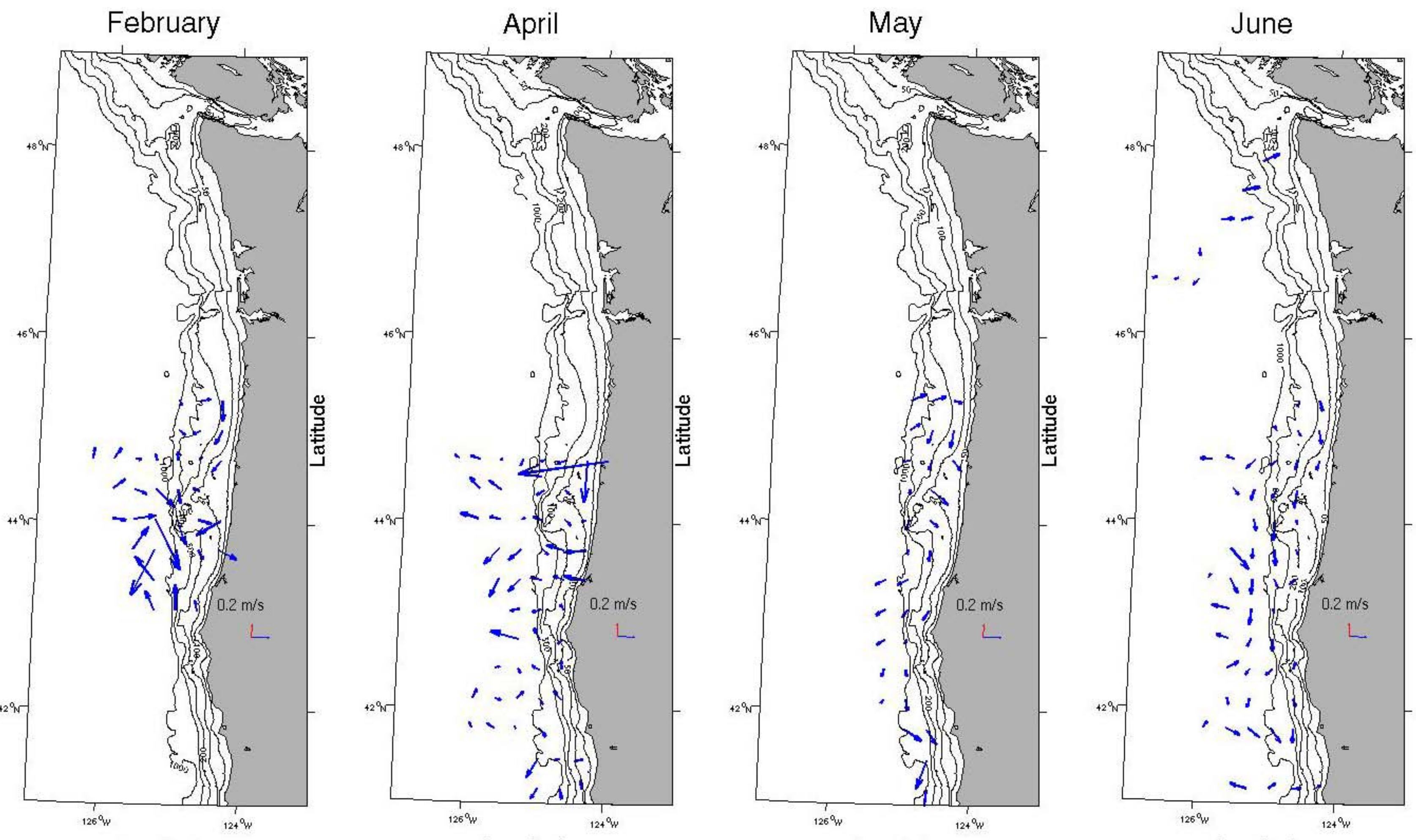


Figure 4-47 Climatological monthly means for current velocity at 100 m depth off the Washington and Oregon coasts from shipboard ADCP observations (1991-2004).

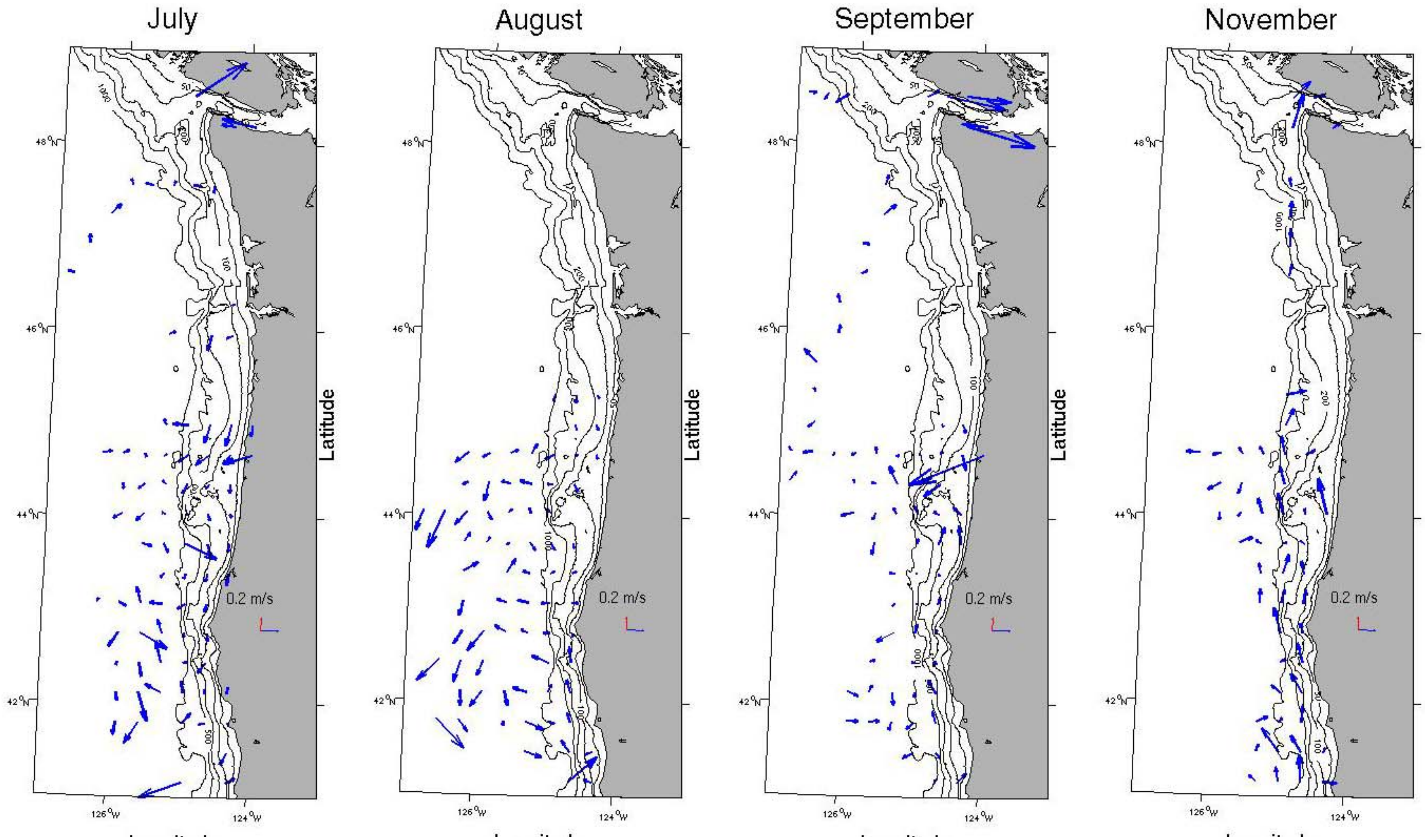


Figure 4-48 Climatological monthly means for current velocity at 100 m depth off the Washington and Oregon coasts from shipboard ADCP obserbations (1991-2004).

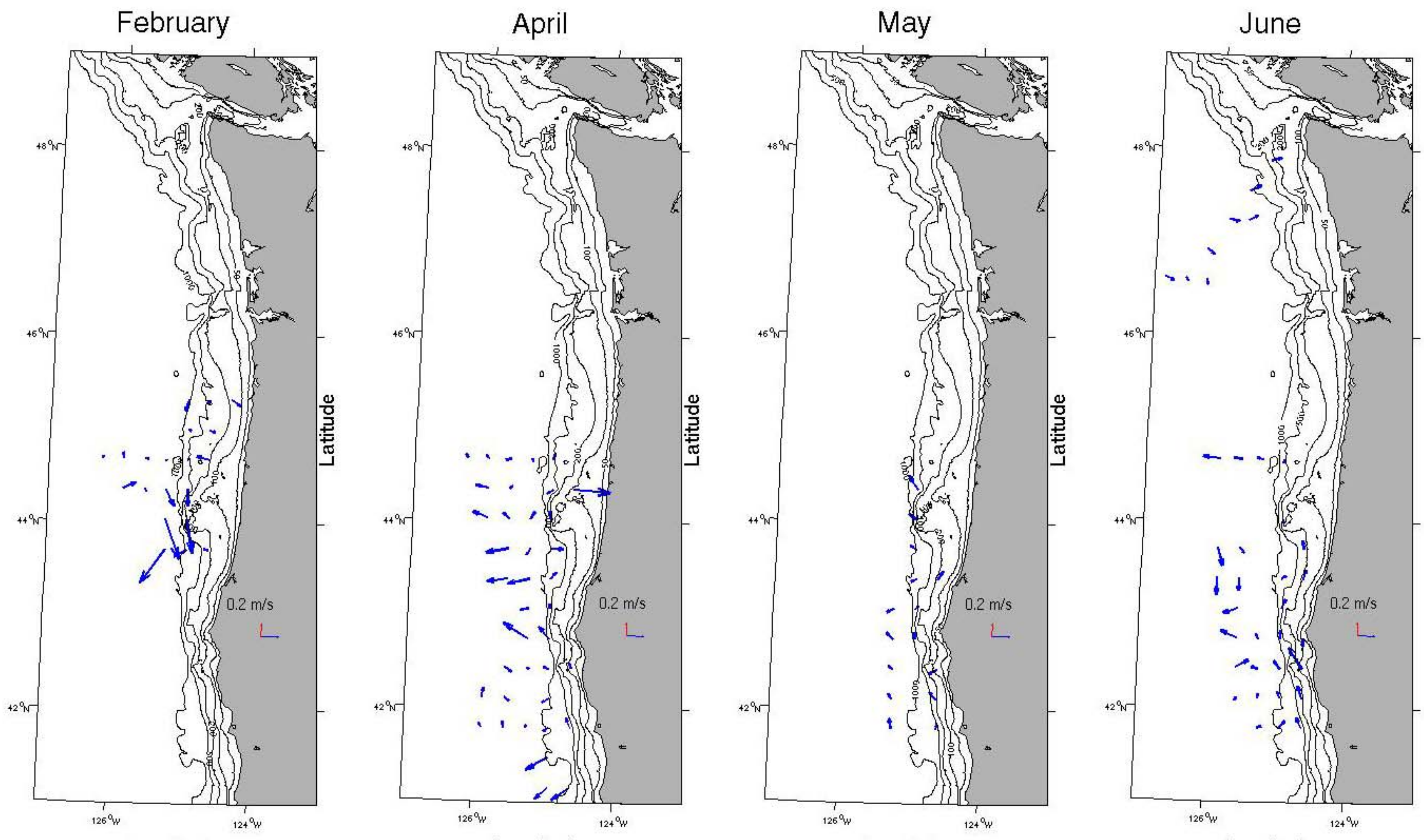


Figure 4-49 Climatological monthly means for current velocity at 300 m depth off the Washington and Oregon coasts from shipboard ADCP observations (1991-2004).

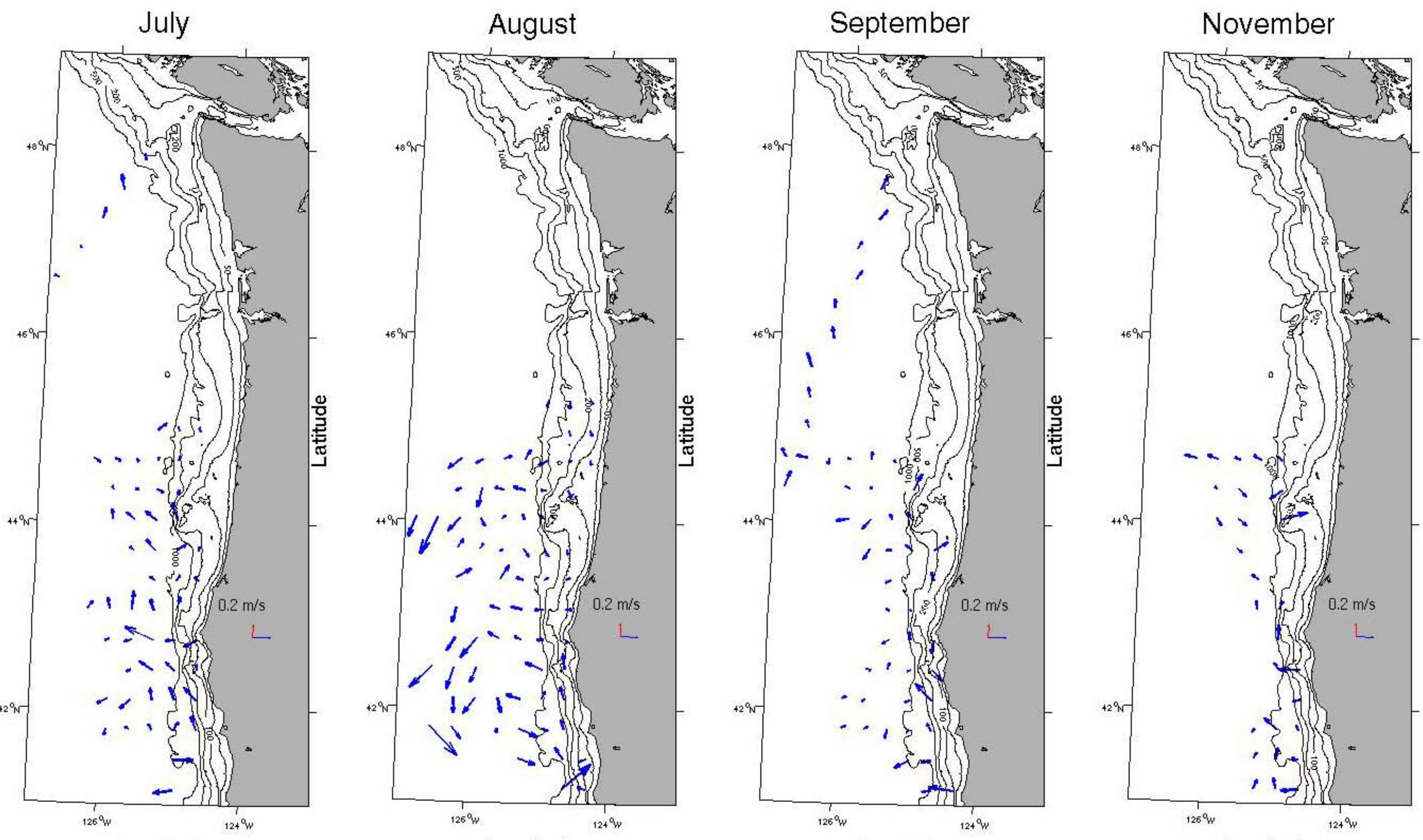


Figure 4-50 Climatological monthly means for current velocity at 300 m depth off the Washington and Oregon coasts from shipboard ADCP observations (1991-2004).

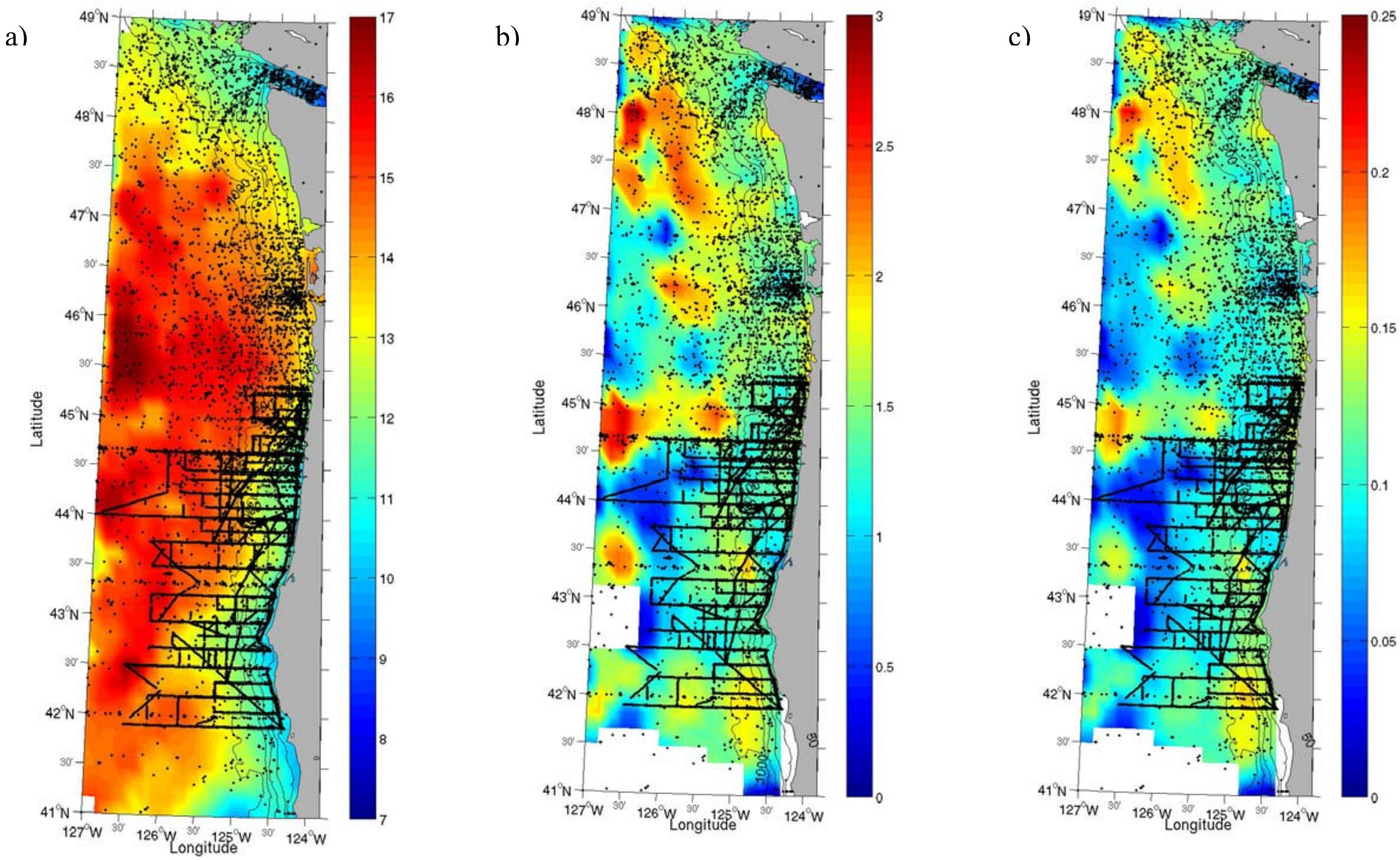


Figure 4-51 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for temperature at the surface including the months from May-October.

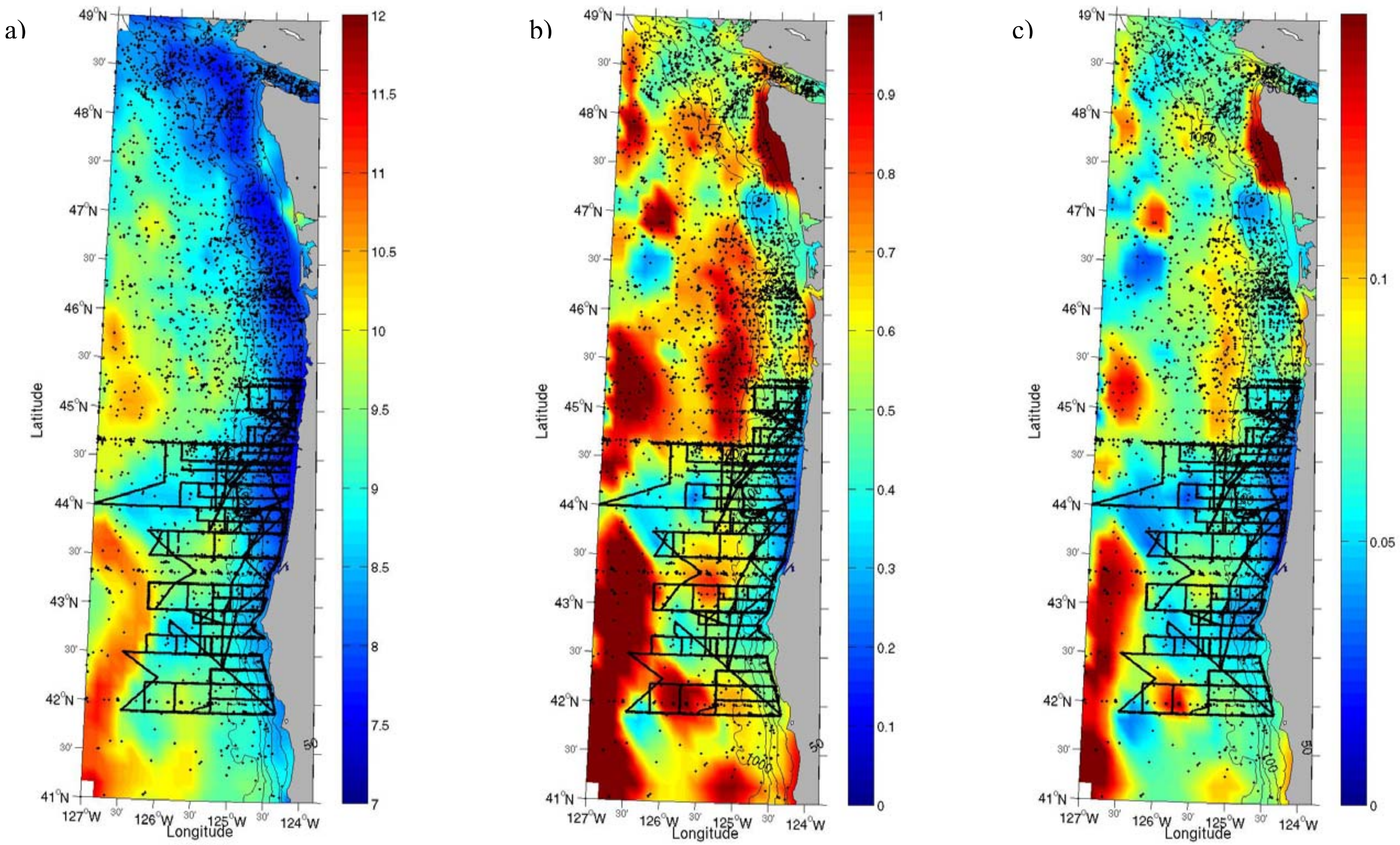


Figure 4-52 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for temperature at 50 m depth including the months from May-October.

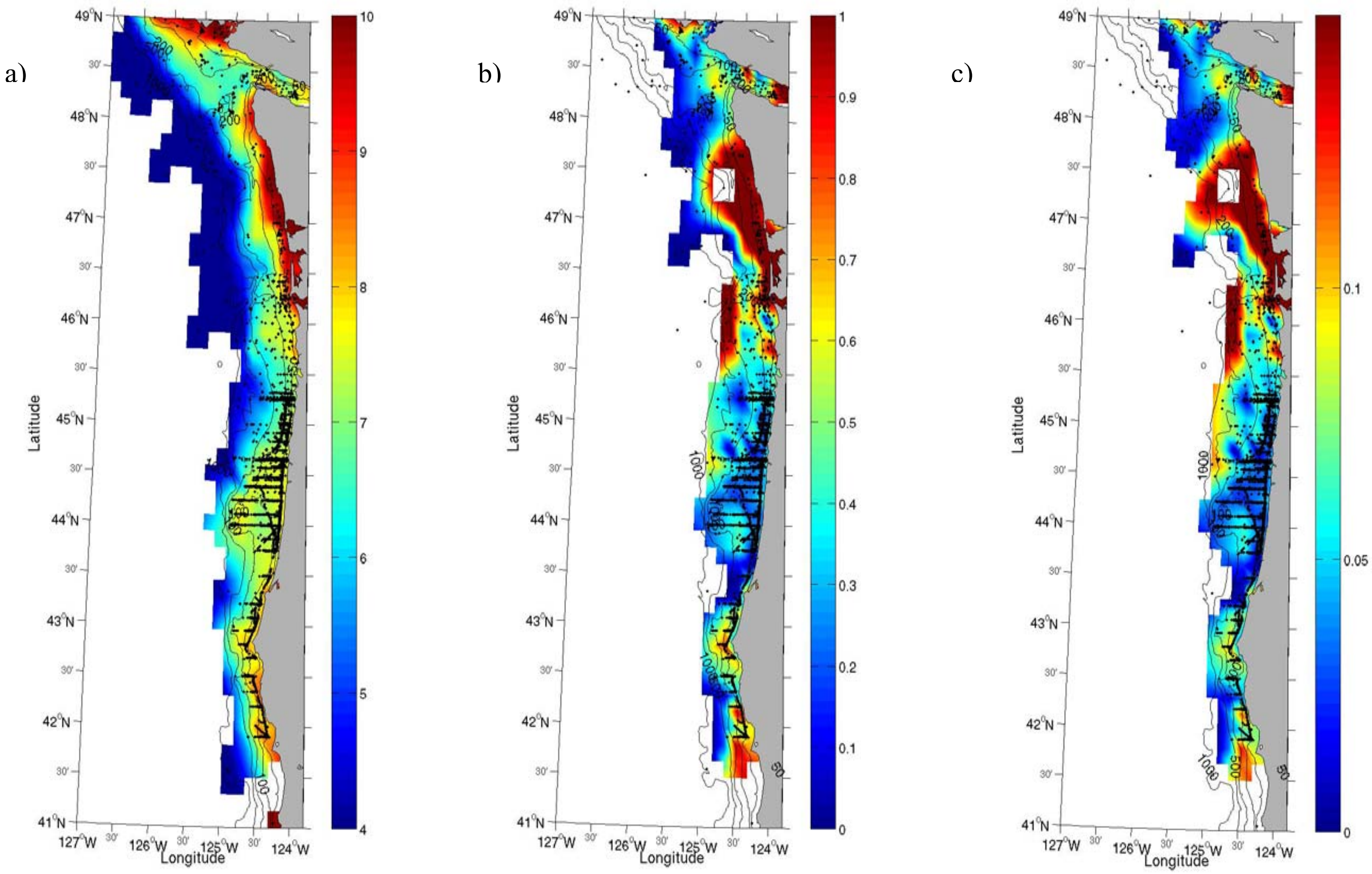


Figure 4-53 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for temperature at the bottom including the months from May-October.

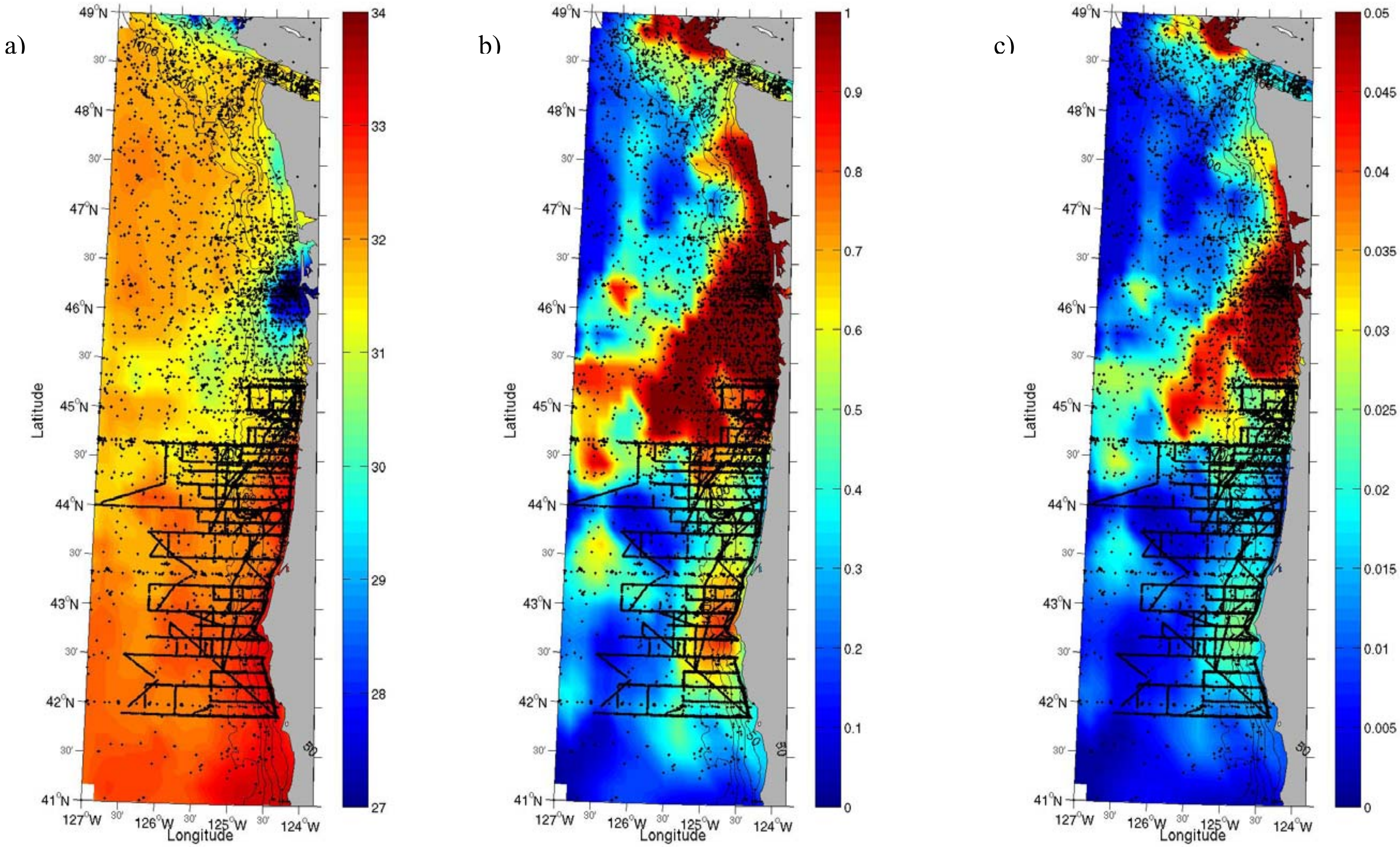


Figure 4-54 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for salinity at the surface including the months from May-October.

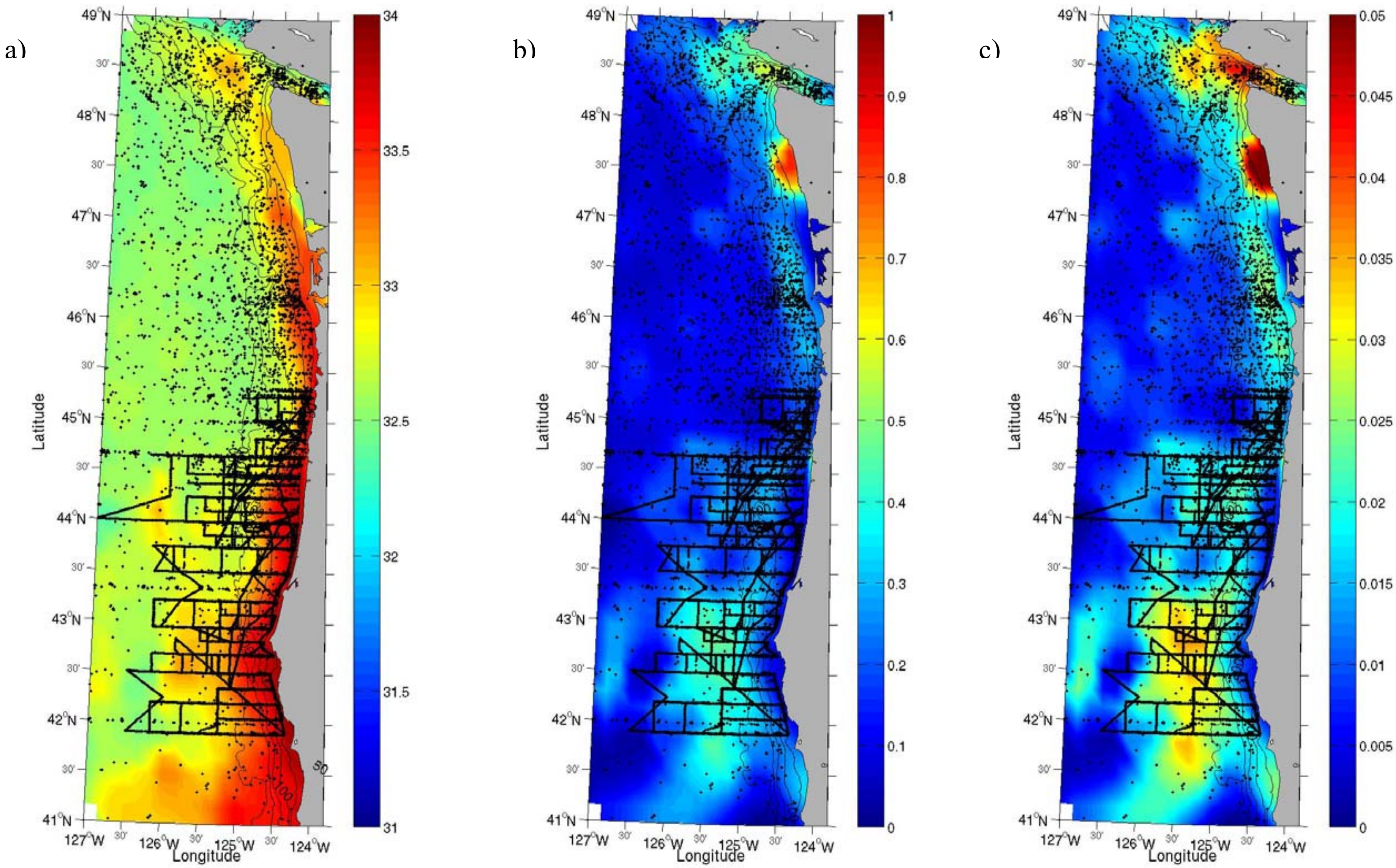


Figure 4-55 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for salinity at 50 m including the months from May-October.

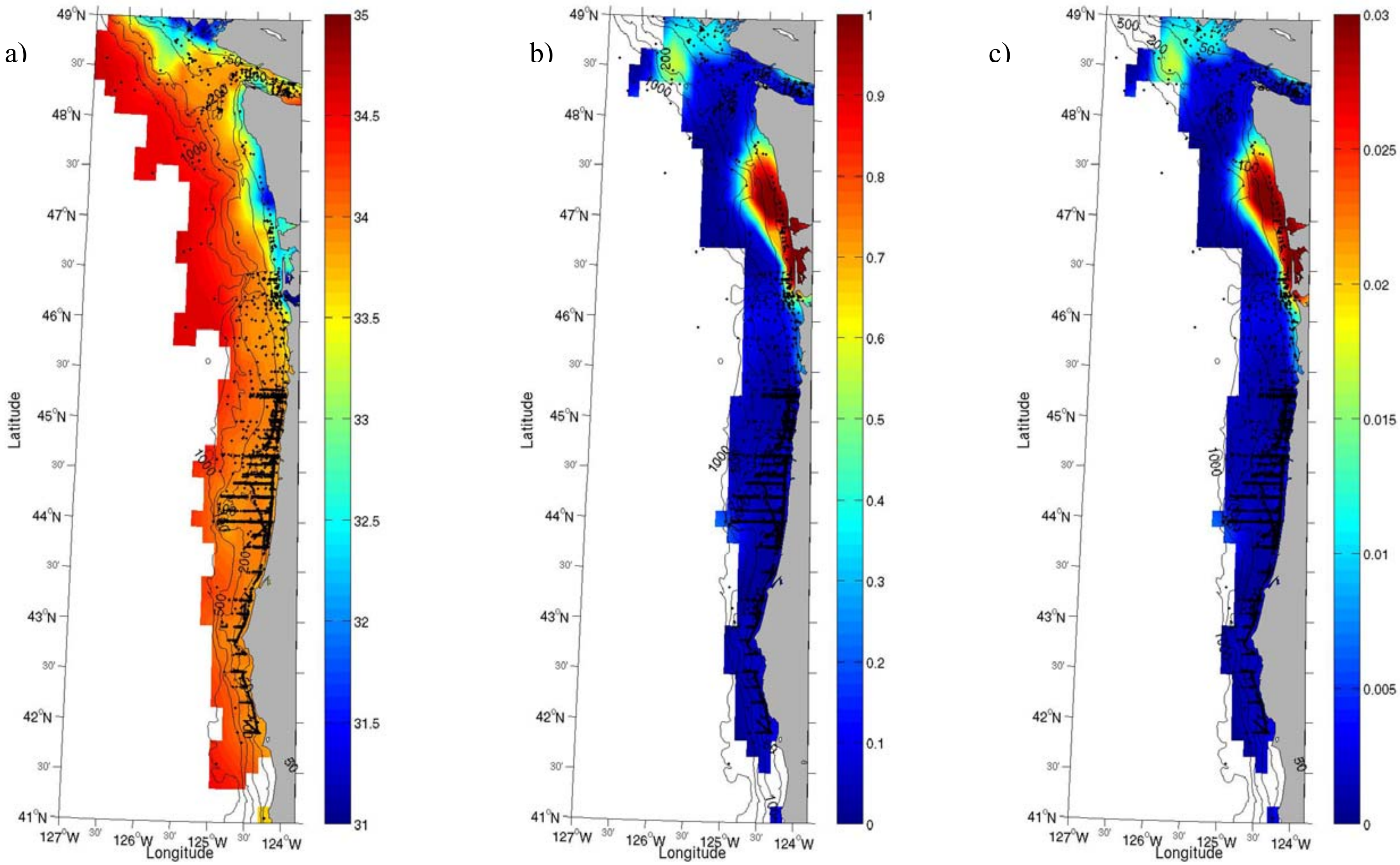


Figure 4-56 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for salinity at the bottom including the months from May-October.

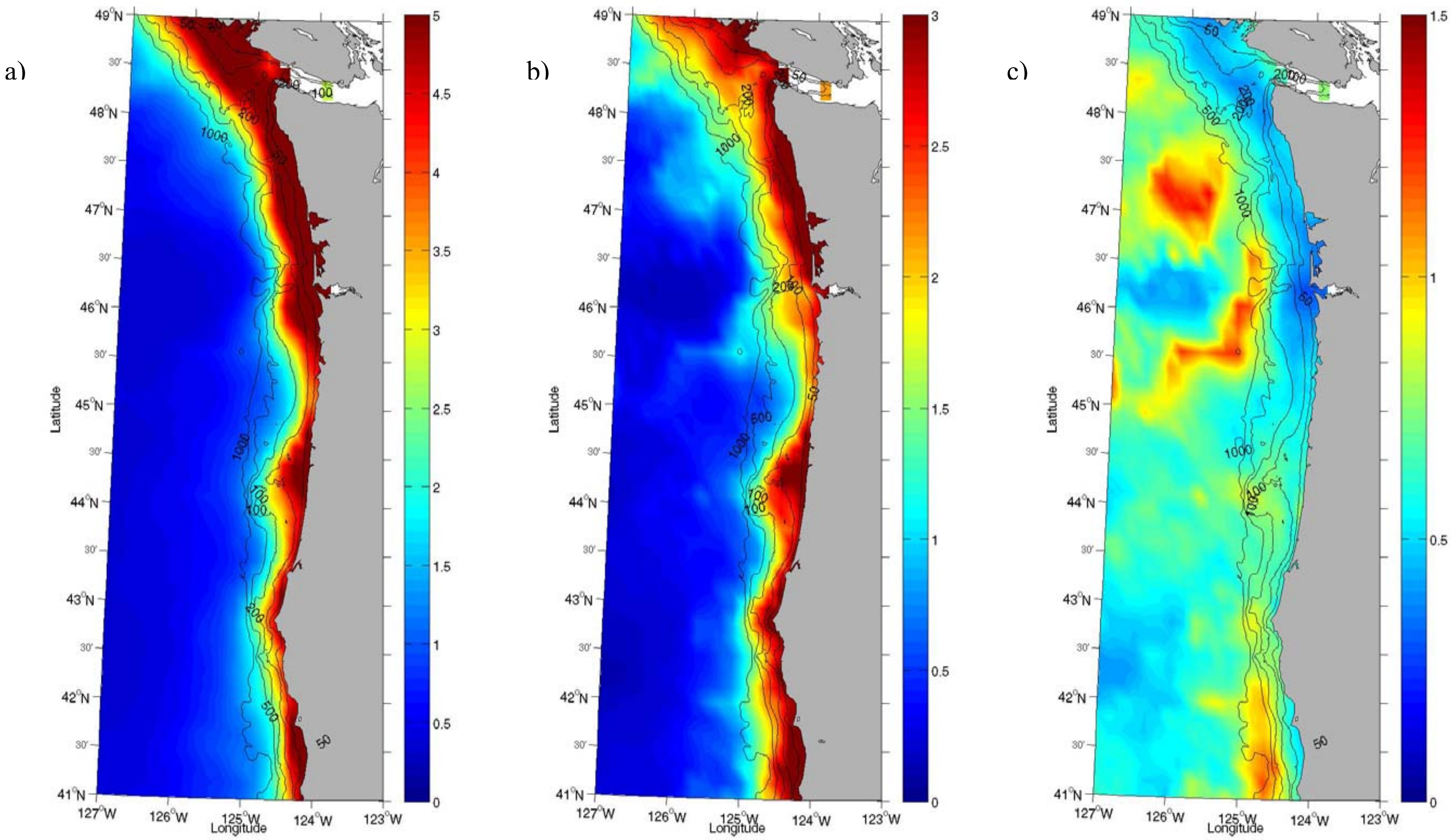


Figure 4-57 Cold regime summer climatological mean, standard deviation and coefficient of variation (respectively) for chlorophyll-a (from SeaWiFS) at the surface including the months from May-October.

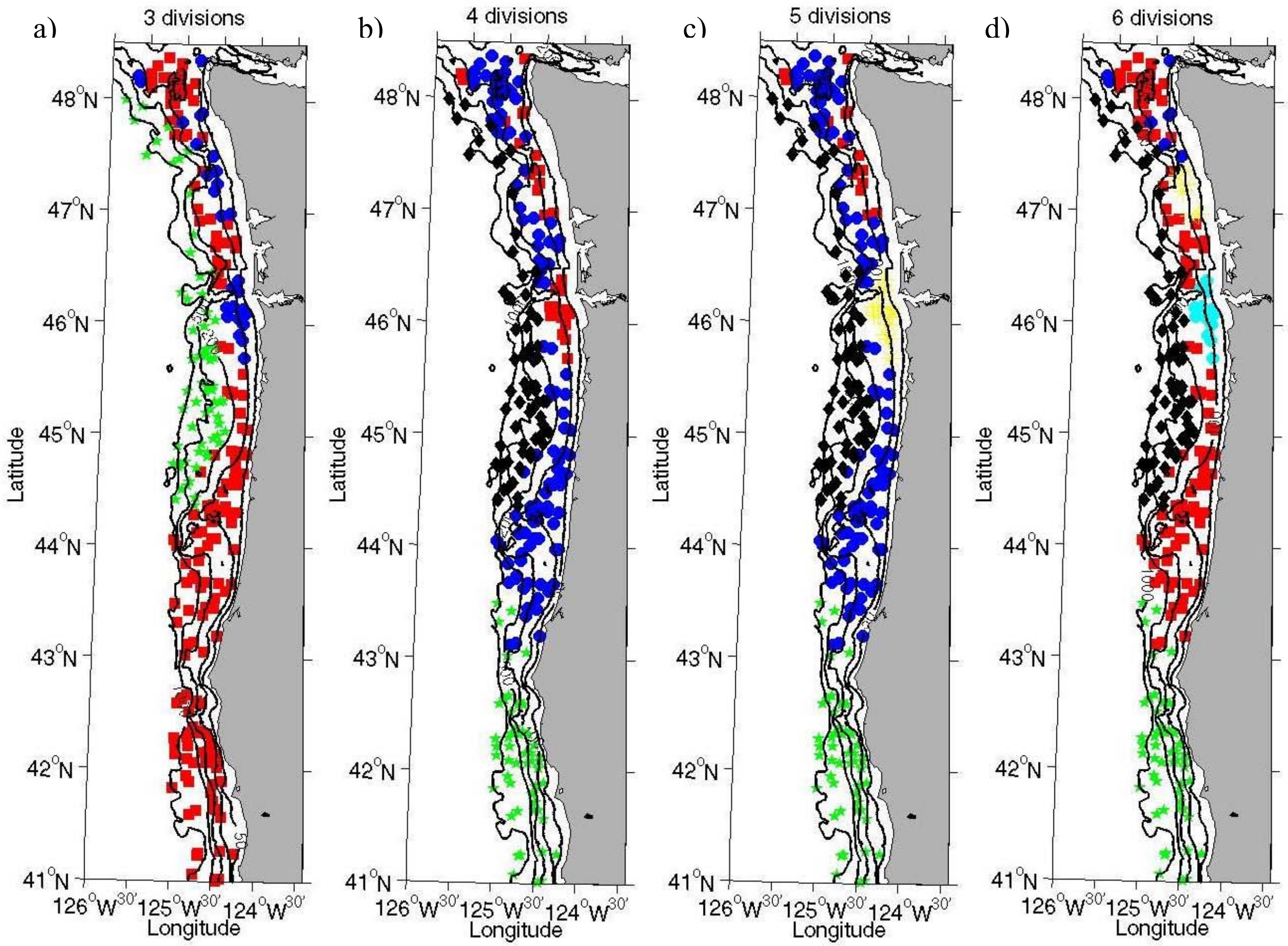


Figure 4-58 Clustering results of the oceanographic data in each of the trawls stations illustrating three, four, five and six group partitioning. These graphs represent the cold-regime summer ocean habitats for each partitioning. a) clustering was divided into three groups, b) clustering was divided into four groups, c) clustering was divided into five groups and d) clustering was divided into six groups.

Offshore Habitat
Upwelling Habitat
Highly Variable Upwelling Habitat
River Plume Habitat
Highly Variable Habitat

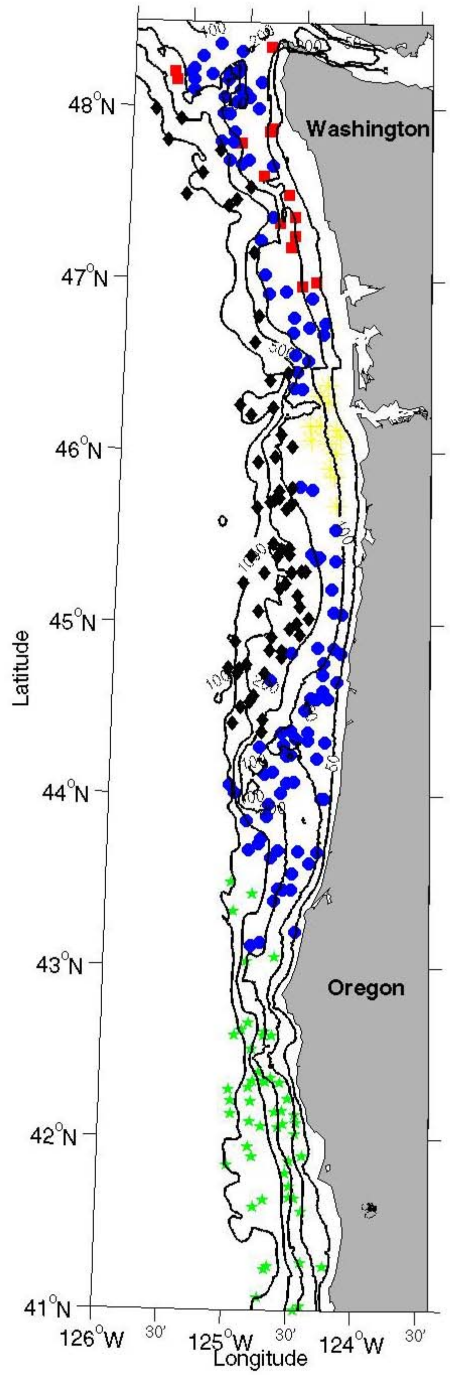


Figure 4-59 Clustering analysis results partitioning the environmental matrix into five cold-regime summer ocean habitats. Five cold-regime summer upwelling ocean habitats with different biological-physical characteristics were identified.

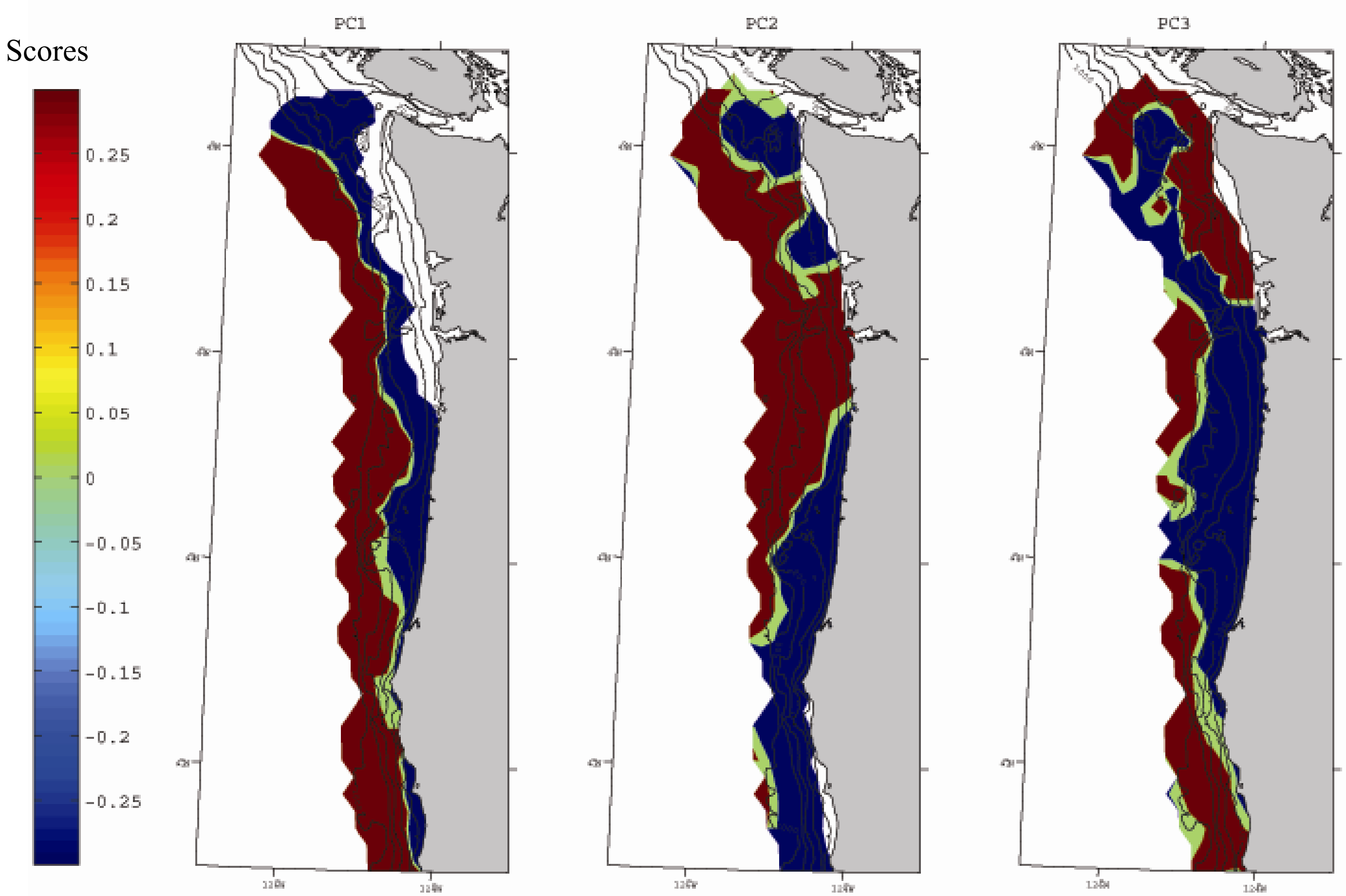


Figure 4-60 Results from principal components analysis. Graphs illustrate the scores of the first three principal components of the cold-regime summer climatologies of temperature, salinity and chlorophyll-a at three depths (0 and 50 m and near the bottom) describing ocean habitats in the water column. The first principal component (PC1) explained 28% of the variance. The second principal component (PC2) explained 23% of the variance and the third principal component (PC3) explained 13% of the variance.

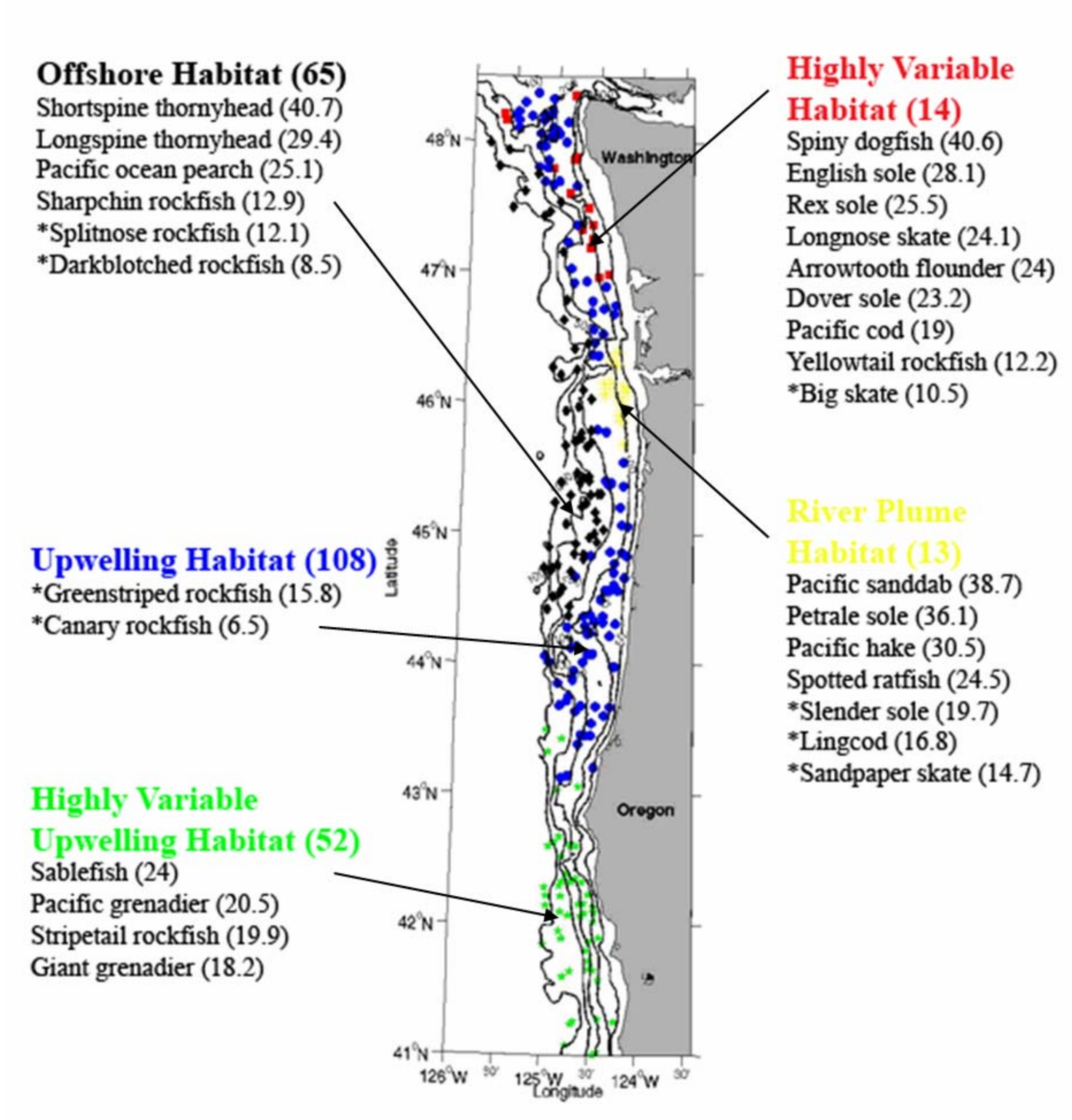


Figure 4-61 Cold-regime summer ocean habitats identified in the clustering analysis and their associated indicator species along with their indicator value. An asterisk next to a specie name indicates that the indicator value for that species was statistically non-significant according to the Monte-Carlo test.

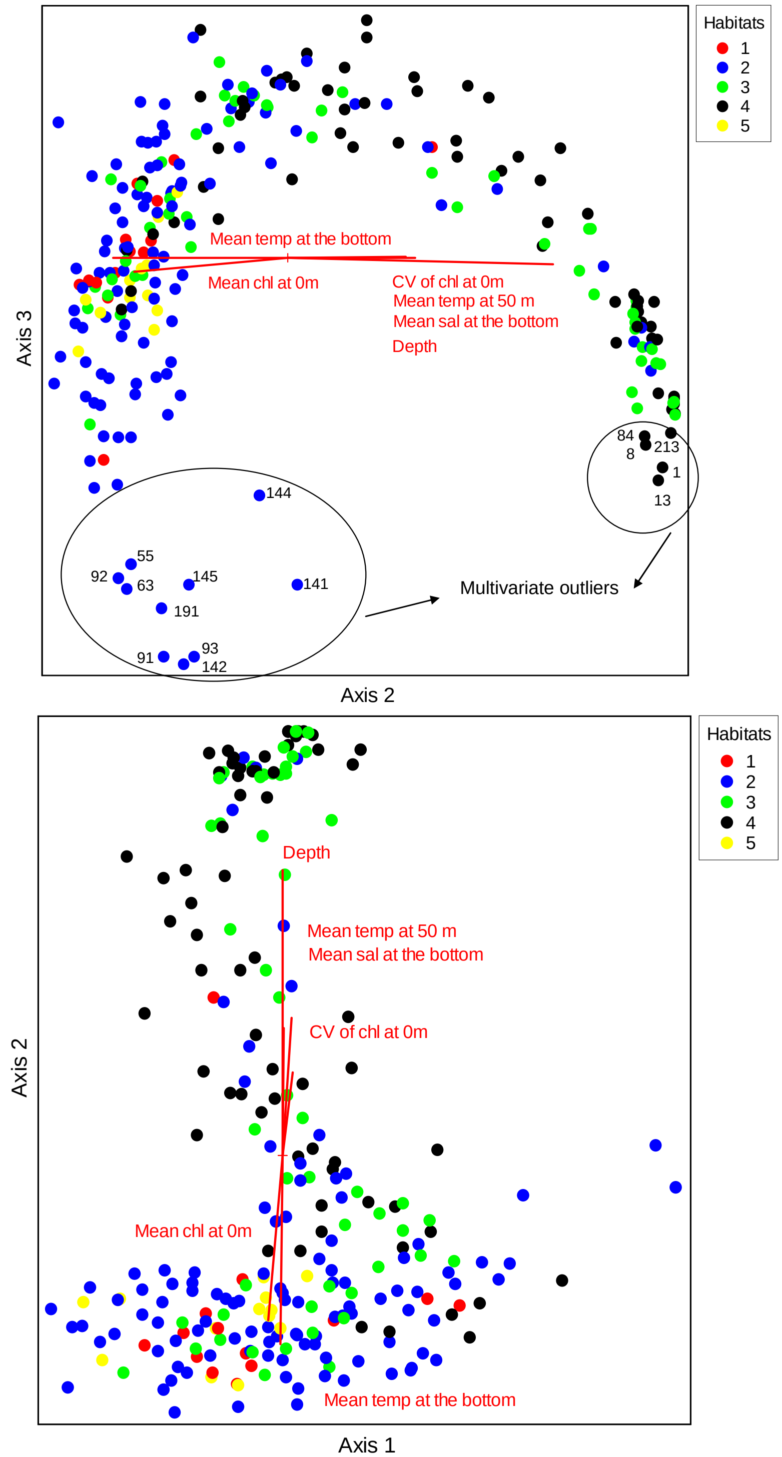


Figure 4-62 Biplots of a non-metric multidimensional scaling (NMDS) ordination (after 25° and 211° rotation respectively) from a three-dimensional solution for: (a) axis two versus three and (b) axis one versus two. The points represent sample units (trawl stations) in species space. Vectors for environmental variables with |r| >=0.2 in respect to both axes are shown.

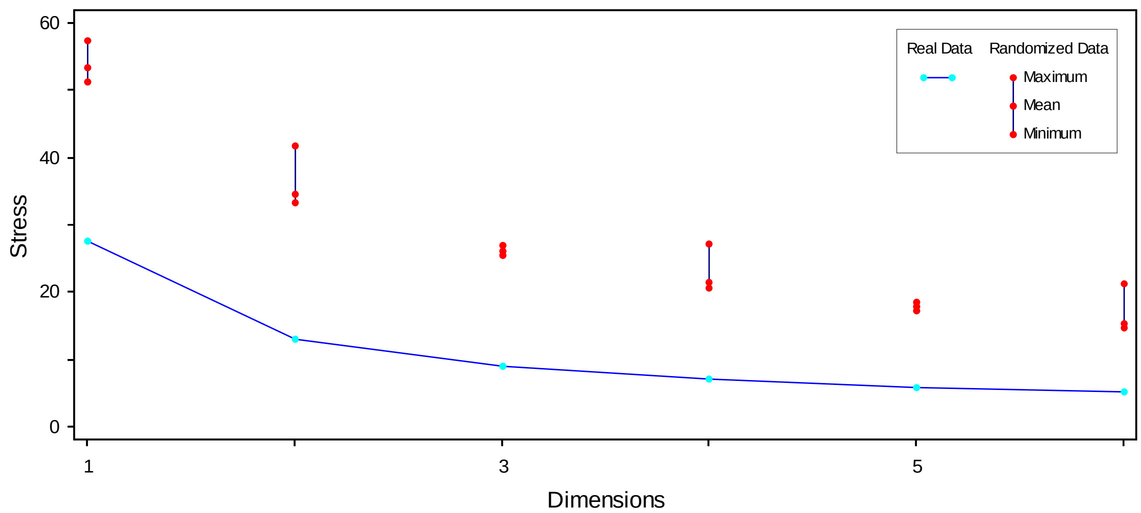


Figure 4-63 Scree plot versus dimensions from the initial unconstrained NMDS runs for real and randomized data. Blue dots are the minimum stress in the real data. Red stars are the mean, minimum and maximum stress in the randomized data.

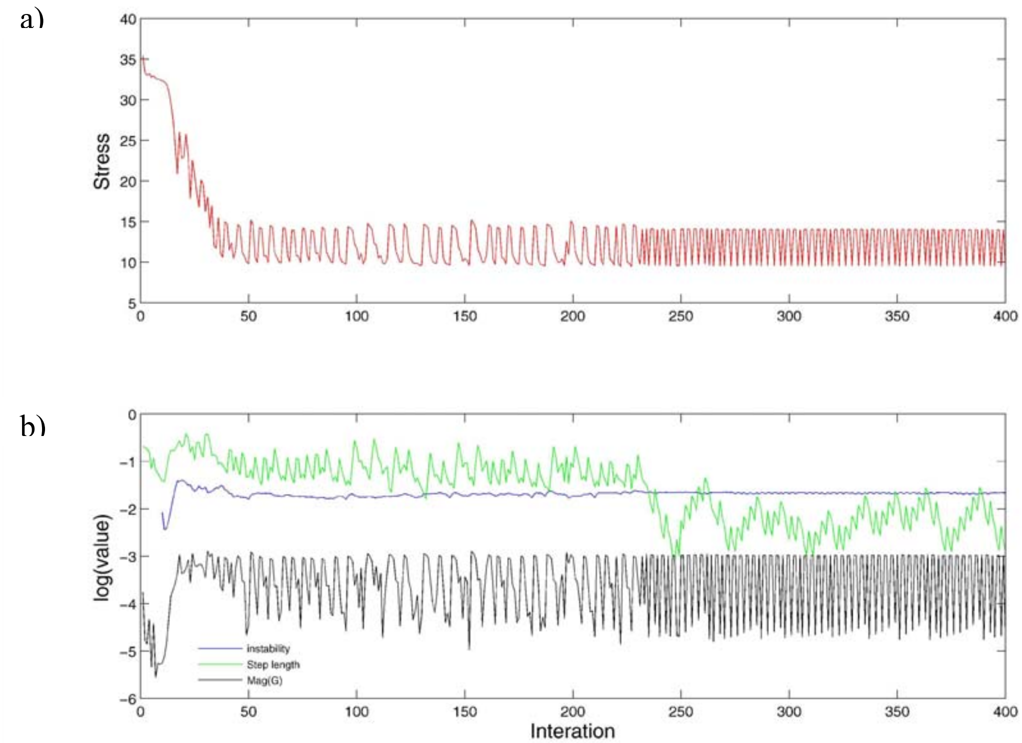


Figure 4-64 Stability of the final three-dimensional NMDS solution. The top graph is stress versus iteration. The bottom graph is instability, step length and magnitude of the gradient vector versus iteration.

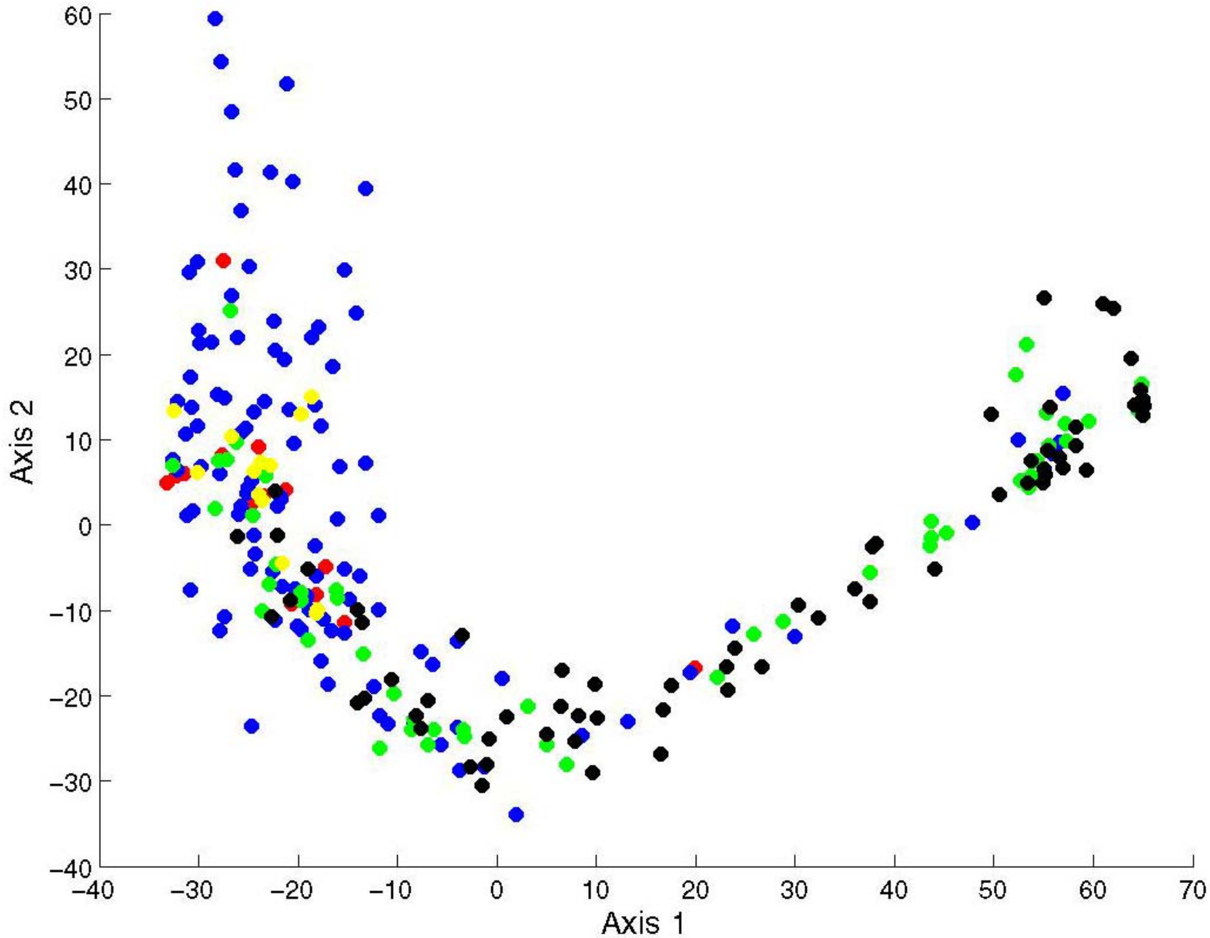


Figure 4-65 Results from the canonical analysis of principal coordinates, type I canonical discriminant analysis. Principal coordinate analysis (unconstrained ordination) on the fish data matrix. This is the first step of CAP. The color-coding from the ocean habitats identified by the clustering analysis has been overlaid for interpretation.

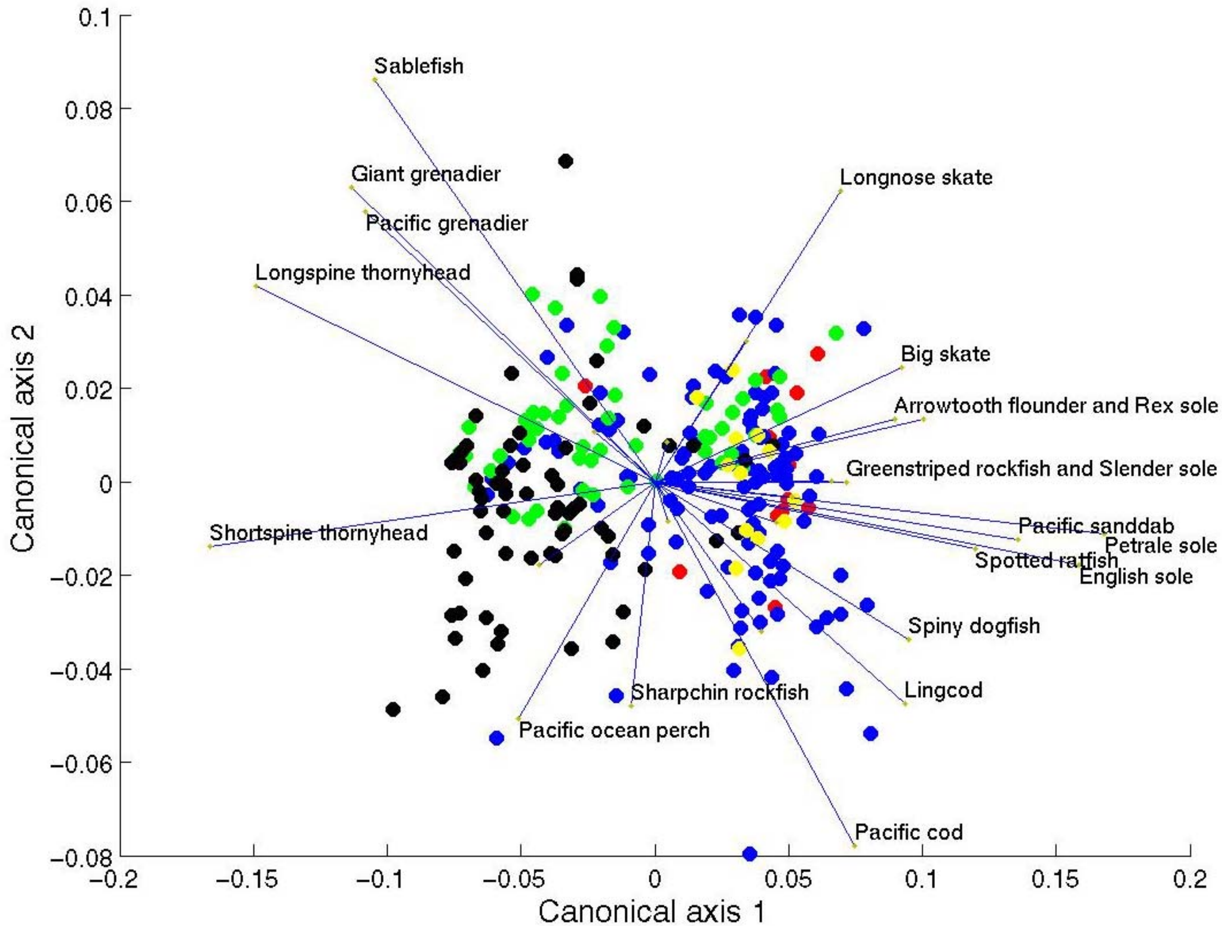


Figure 4-66 Results from the canonical analysis of principal coordinates, type I canonical discriminant analysis. Results from canonical discriminant analysis (constrained ordination). This is the second step of CAP. Plot of canonical axes of groundfish data from the 2004 bottom trawl survey off the Washington and Oregon coasts. The color-coding from the ocean habitats identified by the clustering analysis has been overlaid for interpretation. A biplot has been overlaid on top of the two canonical axes with the correlations of fish species with values of |r| >=0.2. For species correlation values refer to Table 4.9.

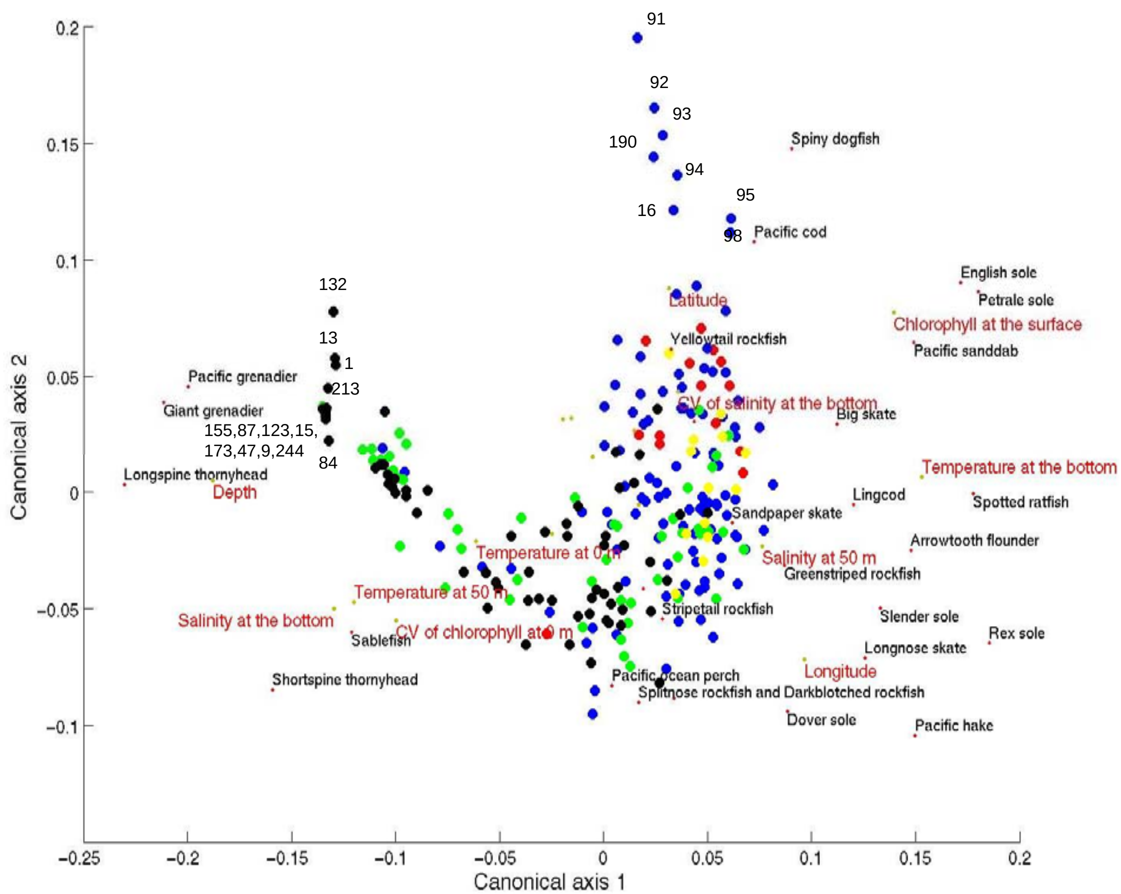


Figure 4-67 Results from canonical analysis of principal coordinates, type II canonical correlation analysis, examining the relationship between the 28 most abundant species and depth, longitude, latitude and oceanographic variables at different depths. The data graphed are the ordination canonical axes. The color-coding from the ocean habitats identified by the clustering analysis has been overlaid for interpretation. Species and environmental correlations with the canonical axes have also been overlaid with values of |r| >=0.2. Overlay of species correlations in black (refer to absolute correlation to table 4.10) and overlay of environmental correlation in red (refer to correlation values in Table 4.11).

Table 4-1 List of 28 groundfish species compositions making up 95% of the total biomass from trawl survey conducted in 2004. Species with an asterisk are not classified as groundfish species by the Pacific Coast Groundfish Fisheries Management Plan.

Species Common name	Biomass($kg\ km^{-2}$) Median	Range		Depth (m) Median	Range		Latitude(^oC) Median	Range		Biomass total($kg\ km^{-2}$)
*Sandpaper skate	127	2.07	2300	180	52	1114	45.6	41	48.4	23317.39
Stripetail rockfish	81	2.01	8874	191	103	273	42.8	41	47.5	27210.41
Darkblotched rockfish	100	2.4	11351	215	103	417	44.9	41	47.8	30875.18
*Slender sole	96	1.25	2139	154	52	621	45.4	41	48.4	33800.2
Pacific cod	321	46.8	5176	127	61	285	47.2	44.1	48.4	35806.77
Pacific ocean perch	68	1.07	23282	275	130	497	45.1	42.2	48.2	37120.9
Big skate	669	19.69	2899	97	52	237	44.7	41.3	48.4	45516.58
Greenstriped rockfish	106	1.1	5597	146	91	340	45.4	41	48.4	47347.16
Petrale sole	253	9.04	2618	118	52	401	45.7	41.3	48.4	49118.88
Spotted ratfish	201	15.29	7387	132	52	711	45.4	41	48.4	60219.64
Lingcod	286	2.37	6154	127	54	276	44.6	41	48.4	60819.53
*Giant grenadier	434	33.06	13032	871	537	1428	44.5	41.1	48	61778.7
Splitnose rockfish	278	0.97	16844	253	127	411	44.8	41	47.9	85091.51
Canary rockfish	197	3.9	70441	154	54	220	45.9	41.3	48.4	88319.93
Shortspine thornyhead	450	6.74	5794	444	96	1297	44.9	41	48.4	90379.7
Pacific grenadier	66	0.48	29230	851	537	1428	44.4	41.1	48	92433.29
Yellowtail rockfish	375	52.75	29408	150	67	181	47.7	43.1	48.2	92523.14
Sharpchin rockfish	84	3.87	54169	217	120	404	45.5	41	48.3	122655.12
Longspine thornyhead	1865	3	7676	702	371	1428	44.7	41.1	48.2	151654.77
Longnose skate	721	7.81	6726	155	52	1162	45.2	41	48.4	163903.33
English sole	792	2.57	9255	115	52	290	45.7	41.3	48.4	176036.92
Pacific sanddab	1032	7.02	21023	97	52	155	45.1	41.3	48.4	192869.37
Arrowtooth flounder	481	8.36	41191	149	52	560	45.4	41	48.4	213781.02
Rex sole	746	2.46	8860	153	52	695	45.2	41	48.4	237120.72
Sablefish	600	11.88	48022	252	52	1428	45	41	48.4	312429.82
Spiny dogfish	356	2.37	260206	146	52	417	46.7	41.3	48.4	448740.13
Pacific hake	1027	14.37	62486	157	52	1162	45.1	41	48.4	716255.3
Dover sole	1911	9.05	20172	172	52	1235	45	41	48.4	727164.72

Table 4-2 Results from the discriminant function analysis showing the average oceanographic conditions and groundfish biomass within each cold-regime summer ocean habitat.

	Offshore Habitat	Upwelling Habitat	Highly Variable Upwelling Habitat	River Plume Habitat	Highly Variable Habitat
Mean Temperature at 0m	14.34	12.66	11.46	13.74	12.83
Mean Temperature at 50 m	8.49	7.98	8.83	7.77	8.16
Mean Temp near the bottom	4.97	6.91	6.41	7.24	7.39
Mean Salinity at 0m	31.30	31.84	32.96	28.04	31.52
Mean Salinity at 50 m	32.66	33.13	33.54	33.39	33.02
Mean Salinity near bottom	34.17	33.92	34.09	33.87	33.52
Mean Chlorophyll-a at 0m	1.59	3.67	2.51	5.88	5.26
CV of Temperature at 0m	0.094	0.108	0.135	0.094	0.125
CV of Temperature at 50m	0.073	0.052	0.060	0.055	0.210
CV of Temperature near the bottom	0.097	0.044	0.056	0.069	0.158
CV of Salinity at 0 m	0.045	0.022	0.015	0.139	0.046
CV of Salinity at 50 m	0.005	0.007	0.007	0.009	0.019
CV of Salinity near the bottom	0.002	0.002	0.001	0.003	0.022
CV of Chlorophyll-a at 0 m	0.671	0.583	0.829	0.378	0.497
Depth	554	193	504	99	134
Number of samples (n)	65	108	52	13	14
Priors	0.26	0.43	0.21	0.05	0.06
Fish Biomass (kg km^{-2})	720,569.04	2,177,897.90	972,853.65	243,417.01	309,552.55

Table 4-3 Loadings (eigenvectors) for the first three principal components (PC) of the cold-regime summer climatologies of temperature, salinity and chlorophyll-a at three depths (0 and 50 m and near the bottom) describing cold-regime summer ocean habitats in the water column. Loading values >=0.3 are shown in bold to highlight the variables with the greatest contribution to each PC. The eigenvalues and the cumulative variance represented by the PC are also indicated.

Variables	PC1	PC2	PC3
Mean temperature at 0 m		**0.508**	
Mean temperature at 50 m	**0.353**		0.285
Mean temperature at the bottom	-0.359	-0.297	
Mean salinity at 0m	0.23	**-0.411**	0.22
Mean salinity at 50m		**-0.447**	
Mean salinity at the bottom	**0.435**	0.128	
Mean chlorophyll-a at 0 m	**-0.456**	-0.133	
CV of temperature at 0 m		-0.176	0.249
CV of temperature at 50 m		0.157	**0.53**
CV of temperature at the bottom	-0.11	0.204	**0.34**
CV of salinity at 0m	-0.167	**0.331**	
CV of salinity at 50m	-0.136		**0.397**
CV of salinity at the bottom	-0.266		**0.429**
CV of chlorophyll-a at 0 m	**0.385**	-0.185	0.209
Eigenvalue	1.98	1.79	1.34
Cummulative Variance (%)	28	51.1	64.1
Variance Fraction (%)	28	23.1	13

Table 4-4 Results from multi-response permutation procedure (MRPP). Average within-group distance, chance-corrected (A) and *p-value* on the rank transformed distance matrix. The number of sample units in each group is also given.

Groups	Average within-group distance	Sample units
Highly Variable Habitat	0.34	14
Upwelling Habitat	0.49	108
Highly and Variable Upwelling Habitat	0.54	53
Offshore Habitat	0.51	65
River Plume Habitat	0.26	13
A	0.167	
p-value	0.0001	

Table 4-5 Results from the indicator species analysis (ISA) from each of the cold-regime summer ocean habitats showing species indicator values and their associated group. An asterisk next to a specie name indicates that the indicator value for that species was statistically non-significant according to the Monte-Carlo test.

Species Common name	Indicator value	*p-value*	Habitat type
Spiny dogfish	40.6	0.001	High Variable Habitat
English sole	28.1	0.003	
Rex sole	25.5	0.017	
Longnose skate	24.1	0.036	
Arrowtooth flounder	24	0.048	
Dover sole	23.2	0.03	
Pacific Cod	19	0.02	
Yellowtale rockfish	12.2	0.04	
Big skate*	10.5	0.287	
Greenstriped rockfish*	15.8	0.171	Upwelling Habitat
Canary rockfish*	6.5	0.398	
Sablefish	24	0.049	High Variable Upwelling Habitat
Pacific grenadier	20.5	0.023	
Stripetail rockfish	19.9	0.006	
Giant grenadier	18.2	0.027	
Shortspine thornyhead	40.7	0.001	Offshore Habitat
Longspine thornyhead	29.4	0.002	
Pacific ocean perch	25.1	0.003	
Sharpchin rockfish	12.9	0.075	
Splitnose rockfish*	12.1	0.138	
Darkblotched rockfish*	8.5	0.646	
Pacific sanddab	38.7	0.001	River Plume Habitat
Petrale sole	36.1	0.001	
Pacific hake	30.5	0.001	
Spotted ratfish	24.5	0.029	
Slender sole*	19.7	0.216	
Lingcod*	16.8	0.139	
Sandpaper skate*	14.7	0.363	

Table 4-6 Stress in relation to dimensionality (from 6 dimension stepping down to 1) from the initial NMDS runs for real and randomized data.

	Stress in real data (40 runs)			Stress in randomized data (Monte Carlo test, 50 runs)			
Axes	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**	**Maximum**	***p-value***
1	27.728	49.755	57.627	51.254	53.459	57.503	0.0196
2	13.148	18.152	41.976	33.459	34.659	41.762	0.0196
3	9.06	13.738	33.375	25.649	26.297	26.948	0.0196
4	7.143	14.71	27.648	20.623	21.644	27.33	0.0196
5	5.965	9.528	24.024	17.279	17.858	18.545	0.0196
6	5.215	9.416	22.21	14.756	15.342	21.353	0.0196

Table 4-7 Pearson (2) and Kendall (tau) correlation of groundfish abundances with each of the ordination axes (after 25° and 211° rotation) for the 28 most abundant species from NMDS analysis. Only absolute correlation of |r|>=0.2 are highlighted bold.

Species Common name	1			2			3		
	r	r^2	tau	r	r^2	tau	r	r^2	tau
Sandpaper skate	**0.286**	0.082	0.262	**-0.3**	0.09	-0.091	**0.571**	0.326	0.453
Stripetail rockfish	**0.351**	0.123	0.302	-0.166	0.028	-0.098	**0.227**	0.052	0.193
Darkblotched rockfish	**0.315**	0.099	0.313	-0.173	0.03	-0.013	**0.527**	0.278	0.448
Slender rockfish	**0.351**	0.124	0.295	**-0.586**	0.343	-0.323	**0.529**	0.28	0.369
Pacific cod	0.077	0.006	0.053	**-0.375**	0.14	-0.349	-0.081	0.006	-0.057
Pacific ocean perch	**0.219**	0.048	0.177	-0.01	0	0.099	**0.403**	0.162	0.375
Big skate	-0.175	0.031	-0.15	**-0.423**	0.179	-0.393	**-0.227**	0.051	-0.197
Greenstriped rockfish	**0.544**	0.296	0.422	**-0.444**	0.197	-0.3	0.132	0.017	0.126
Petrale sole	-0.141	0.02	-0.108	**-0.744**	0.554	-0.59	**-0.277**	0.077	-0.217
Spotted ratfish	0.182	0.033	0.114	**-0.716**	0.512	-0.441	0.059	0.003	0.038
Lingcod	**0.462**	0.213	0.3	**-0.545**	0.297	-0.416	**-0.258**	0.067	-0.158
Giant grenadier	-0.025	0.001	0.006	**0.81**	0.656	0.535	**-0.348**	0.121	-0.341
Splitnose rockfish	**0.33**	0.109	0.337	-0.109	0.012	0.061	**0.523**	0.274	0.469
Canary rockfish	**0.349**	0.121	0.271	**-0.235**	0.055	-0.182	-0.006	0	0.008
Shortspine rockfish	0.027	0.001	0.036	**0.673**	0.452	0.513	**0.412**	0.17	0.312
Pacific grenadier	0.013	0	-0.003	**0.745**	0.555	0.561	**-0.346**	0.12	-0.321
Yellowtail rockfish	**0.315**	0.1	0.248	**-0.213**	0.045	-0.175	0.058	0.003	0.048
Sharpchin rockfish	**0.511**	0.261	0.403	-0.137	0.019	-0.034	0.189	0.036	0.194
Longspine thornyhead	-0.139	0.019	-0.107	**0.938**	0.88	0.64	-0.199	0.04	-0.189
Longnose skate	**0.344**	0.118	0.313	**-0.578**	0.334	-0.271	**0.505**	0.255	0.366
English sole	**-0.25**	0.063	-0.167	**-0.693**	0.481	-0.591	**-0.288**	0.083	-0.227
Pacific sanddab	**-0.476**	0.227	-0.374	**-0.543**	0.295	-0.509	**-0.421**	0.177	-0.363
Arrowtooth rockfish	**0.275**	0.076	0.293	**-0.651**	0.424	-0.304	**0.527**	0.278	0.382
Rex sole	0.011	0	0.043	**-0.727**	0.528	-0.335	**0.491**	0.241	0.308
Sablefish	0.087	0.007	0.163	**0.473**	0.223	0.417	**0.475**	0.226	0.302
Spiny dogfish	0.154	0.024	0.166	**-0.47**	0.221	-0.349	0.11	0.012	0.126
Pacific hake	-0.097	0.009	-0.04	**-0.546**	0.298	-0.32	**0.551**	0.304	0.326
Dover sole	0.107	0.011	0.205	**-0.328**	0.107	-0.098	**0.651**	0.424	0.416

Table 4-8 Pearson (2) and Kendall (tau) correlation of environmental variables with each of the ordination axes (after 25° and 211° rotation) from analysis. Only absolute correlation of |r|>=0.2 are highlighted bold.

Enviromental Variables	1			2			3		
	r	r^2	tau	r	r^2	tau	r	r^2	tau
Longitude	**-0.239**	0.057	-0.173	**-0.392**	0.154	-0.293	0.121	0.015	0.037
Latitude	-0.005	0	-0.019	**-0.203**	0.041	-0.14	-0.054	0.003	-0.009
Depth	0.01	0	0.133	**0.916**	0.839	0.663	-0.141	0.02	0.141
Mean temperature at 0 m	-0.01	0	-0.012	**0.317**	0.101	0.213	**0.207**	0.043	0.144
Mean temperature at 50 m	0.045	0.002	0.037	**0.611**	0.374	0.412	0.069	0.005	0.034
Mean temperature at the bottom	-0.079	0.006	-0.076	**-0.745**	0.555	-0.508	-0.01	0	-0.069
Mean salinity at 0 m	0.112	0.013	0.058	0.118	0.014	-0.009	-0.087	0.008	-0.119
Mean salinity at 50 m	-0.123	0.015	-0.06	**-0.346**	0.12	-0.284	-0.142	0.02	-0.104
Mean salinity at the bottom	0.162	0.026	0.097	**0.635**	0.404	0.534	0.025	0.001	0.066
Mean chlorophyll-a at 0 m	**-0.209**	0.044	-0.091	**-0.697**	0.485	-0.555	**-0.209**	0.044	-0.118
CV of temperature at 0 m	-0.058	0.003	-0.032	0.073	0.005	-0.001	-0.169	0.029	-0.144
CV of temperature at 50 m	0.03	0.001	0.021	0.069	0.005	0.209	0.019	0	0.012
CV of temperature at the bottom	0.018	0	0.017	0.006	0	-0.006	0.072	0.005	0.083
CV of salinity at 0 m	-0.029	0.001	-0.067	-0.071	0.005	0.012	0.083	0.007	0.082
CV of salinity at 50 m	0.033	0.001	0.011	-0.085	0.007	-0.095	-0.023	0.001	-0.041
CV of salinity at bottom	-0.084	0.007	-0.082	-0.19	0.036	-0.128	-0.014	0	-0.113
CV of chlorophyll-a at 0m	0.171	0.029	0.139	**0.493**	0.243	0.309	-0.06	0.004	-0.034

Table 4-9 Results from canonical analysis of principal coordinates, type I canonical discriminant analysis. Individual fish species showing absolute correlation of |r|>=0.2 are highlighted bold.

Fish Species	Correlation with axis 1	Correlation with axis 2
Sandpaper skate	0.0246	-0.0419
Stripetail rockfih	0.0225	0.0424
Darkblotched rockfish	-0.1133	0.0532
Slender sole	**0.3295**	0.0008
Pacific code	**0.3728**	**-0.3894**
Pacific ocean perch	**-0.2539**	**-0.253**
Big skate	**0.461**	0.1229
Greestriped rockfish	**0.3573**	-0.0006
Petrale sole	**0.8389**	-0.0562
Spotted ratfish	**0.5996**	-0.0717
Lingcod	**0.4668**	**-0.2368**
giant grenadier	**-0.5668**	**0.3151**
Splitnose rockfish	**-0.2158**	-0.0886
Canary rockfish	0.1981	-0.1597
Shortspine thornyheads	**-0.8307**	-0.0691
Pacific grenadier	**-0.5407**	**0.2898**
Yellowtail rockfih	**0.2272**	**-0.0439**
Sharpchin rockfish	-0.0446	**-0.2402**
Longspine thornyheads	**-0.7444**	**0.2091**
Longnose skate	**0.3473**	**0.3118**
English sole	**0.7932**	-0.0892
Pacific sanddab	**0.6777**	-0.0614
Arrowtooth flounder	**0.4485**	0.0675
Rex sole	**0.5014**	0.067
Sablefish	**-0.523**	**0.4301**
Spiny dogfish	**0.4745**	-0.1681
Pacific hake	**0.2569**	-0.0166
Dover sole	0.1701	0.1508

Table 4-10 Results of canonical analysis of principal coordinates, type II canonical correlation analysis. Species correlation with both canonical axes. Only absolute correlation of |r|>=0.2 are highlighted bold.

Species Common name	Correlation with axis 1	Correlation with axis 2
Sandpaper skate	**0.25**	-0.05
Stripetail rockfish	0.11	**-0.22**
Darkblotched rockfish	0.14	**-0.35**
Slender sole	**0.53**	**-0.20**
Pacific cod	**0.29**	**0.43**
Pacific ocean perch	0.02	**-0.33**
Big skate	**0.45**	0.12
Greenstriped rockfish	**0.35**	-0.13
Petrale sole	**0.72**	**0.34**
Spotted ratfish	**0.71**	0.00
Lingcod	**0.48**	-0.02
Giant grenadier	**-0.85**	0.16
Splitnose rockfish	0.07	**-0.36**
Canary rockfish	0.17	0.12
Shortspine thornyhead	**-0.64**	**-0.34**
Pacific grenadier	**-0.80**	0.18
Yellowtail rockfish	0.13	**0.25**
Sharpchin rockfish	0.08	-0.17
Longspine thornyhead	**-0.92**	0.01
Longnose skate	**0.50**	**-0.28**
English sole	**0.69**	**0.36**
Pacific sanddab	**0.60**	**0.26**
Arrowtooth flounder	**0.59**	-0.10
Rex sole	**0.74**	**-0.26**
Sablefish	**-0.48**	**-0.24**
Spiny dogfish	**0.36**	**0.59**
Pacific hake	**0.60**	**-0.42**
Dover sole	**0.35**	**-0.38**

Table 4-11 Results of canonical analysis of principal coordinates, type II canonical correlation analysis. Environmental correlations with both canonical axes. Only absolute correlation of |r|>=0.2 are highlighted bold.

Enviromental Variables	Correlation with axis 1	Correlation with axis 2
Longitude	**0.48**	**-0.36**
Latitude	0.16	**0.44**
Depth	**-0.94**	0.03
Mean temperature at 0 m	**-0.31**	-0.10
Mean temperature at 50 m	**-0.60**	**-0.24**
Mean temperature at the bottom	**0.76**	0.03
Mean salinity at 0 m	-0.12	-0.09
Mean salinity at 50 m	**0.38**	-0.12
Mean salinity at the bottom	**-0.65**	**-0.25**
Mean chlorophyll-a at 0 m	**0.70**	**0.39**
CV of temperature at 0 m	-0.08	0.16
CV of temperature at 50 m	-0.10	0.16
CV of temperature at the bottom	-0.03	0.08
CV of salinity at 0 m	0.08	-0.03
CV of salinity at 50 m	0.07	0.13
CV of salinity at the bottom	0.18	**0.22**
CV of chlorophyll-a at 0 m	**0.50**	**-0.28**

5 DISCUSSION

5.1 Assembly and Computation of Ocean Data Products

The first major achievement of this study was the assembling and merging of disperse and disparate oceanographic datasets for temperature, salinity, chlorophyll-a and current velocity from the 1930 to the year 2004 off the Washington and Oregon coasts. The combined raw datasets for each oceanographic variable are available for other scientists to use in their research needs. The raw datasets give more flexibility to the individual researchers, who may retrieve specific spatial and temporal time series from the original datasets.

The merging of the oceanographic datasets off the Washington and Oregon coasts has been the first step in a much bigger project to incorporate oceanographic information off the U.S. west coast into fisheries research and management. The assembled datasets have given a broad insight into what data are more abundant and, at the same time, what types of data are abundant and scarce throughout the study region. This has allowed the identification of several data needs and potential areas that need further monitoring and research in the future. Thus, several general remarks about the historical sampling effort off the Washington and Oregon coast can be made. In terms of CTD data, which has been historically the most abundant data type, the Washington and Oregon coasts were sampled evenly and broadly before 1976. After 1976, the sampling effort was concentrated off the Strait of Juan de Fuca and along specific sampling lines up and down the coast. It is fascinating to note that after 1997 most of the oceanographic studies have been concentrated off the Oregon coast, especially during the summer season. The collection of CTD casts off the Washington coast dropped considerably after 1977 and their collection is almost non-existent at the present time, with the exception of some CTD casts collected by the NWFSC Pacific hake cruises in the year 2001 and 2003. We anticipate that data from the recent NSF-funded River Influence on Shelf Ecosystems (RISE) and NOAA-funded EcoHAB projects will help better characterize the Washington shelf. Another interesting observation is that ADCP data, starting in 1991, is concentrated off the Oregon coast. Only the biennial (in the past triennial) NWFSC Pacific hake cruises (at least that we am aware of) collected ADCP data off the Washington coast. However, the most recent Pacific hake survey ADCP data (2001, 2003) were not processed in time for this study and therefore, this study did not assemble any ADCP data off the Washington coast. The data suggested a clear pattern; the numbers of oceanographic cruises and monitoring efforts off the Washington and Oregon coasts have decreased over the last several decades. In particular, the Washington coast showed a drastic reduction in oceanographic cruises. Lastly, between 1997 and 2004, the number of oceanographic cruises has increased off the Oregon coast due to the GLOBEC and COAST interdisciplinary programs.

In order to manage present fisheries resources, and to apply more of ecosystem-based management approach, it is critical to start planning and implementing regular and broad monitoring that will collect physical and biological parameters with sufficient intensity in time and space in the CCS. This is not a new recommendation. NOAA fisheries recognizes that there is a need to improve climate and ecosystem observations and develop new strategies to incorporate climate variability and ecosystem observations into fisheries stock assessments (PaCOOS Board of Governors, 2004). Along the west coast of the *U.S.*, there is a group of academic institutions, foundations and agencies that is starting the process of creating the Pacific Coast Ocean Observing System (PaCOOS), which is one of the west coast contributions to the national Integrated Ocean Observing System (IOOS). If integrated ocean observing systems are fully established, they will provide invaluable physical and biological information to support management of marine resources and the assessment of the effects of climate variability on the of the CCS (PaCOOS Board of Governors, 2004).

The second achievement of this study has been the computation and the plotting of climatological monthly means, standard deviations and coefficients of variation for each ocean variable at different depths. These ocean data products will also be available for other scientists and managers to use for their research and management needs. The gridded climatological data are available on a regular 0.32^{o} x 0.32 spatial grid at 0, 50, 100, 500, and 1000 m depth. This study also attempted to import all the climatologies into a GIS. Due to time constraints, only the climatologies derived from satellite sensors have been imported into a GIS. However, in the near future all the climatologies will be imported into a GIS. This will allow easy access and visualization of each climatology computed in this study.

The computation of the climatologies offers many advantages. First, they are already a final product, ready to be used and visualized. The second advantage is that monthly climatologies are very useful for descriptive and exploratory purposes, especially to describe long-term seasonal oceanographic processes and their variability in the study region. The monthly climatologies represent the average oceanographic conditions for each month at different depths off the Washington and Oregon coasts. Therefore, they give insight to the evolution of spatial oceanographic patterns that develop throughout the seasons at different depths. In addition, each climatological variable is characterized with two different statistical measures of variability of the physical and biological parameters: standard deviation and coefficient of variation. The climatological monthly standard deviation provided an index of absolute variability, and a coefficient of variation provided an index of variability relative to the mean. These two statistical measures have been very useful to identify areas that experience higher variability in the physical and biological forcing of the system over time. The climatological standard deviations have been very useful to highlight large, relative low-frequency variations associated with seasonal warming trends. In contrast, the CVs highlight the short-term variation like the ones associated with the upwelling intensity.

However, the reader should be cautioned at this point that the monthly climatologies are dominated by the seasonal cycle and that other sources of variability (sources that are not seasonal) have been lost in the climatologies. This is a disadvantage, since it is known that the oceanographic processes off the Washington and Oregon coasts are subject to wide sources of variability from tides, coastal-trapped waves, and mesoscale eddies, to the ENSO cycle and regime shifts. Therefore, all the intra-seasonal, inter-annual and inter-decadal variability in the oceanographic processes off the Washington and Oregon coasts have been smoothed out or de-emphasized in the monthly climatologies. Certainly, it is acknowledged that the above oceanographic processes have an impact on the biology of the system, which eventually reaches higher trophic levels like groundfish. However, it should be recognized that seasonal variability and within seasonal variability, spatial variability, could be one of the most relevant scales in groundfish ecology to determine their reproductive success since they have long life cycles. Spatial variability could also influence groundfish distributions since some areas could be more favorable for feeding and growing than others. Groundfish at early life stages depend on the water column processes for their reproduction and larval dispersal. Most groundfish species spawn during winter in deep waters and then their larvae float to the surface. Ocean currents (downwelling conditions) favor their retention near the coast, preventing them from moving to the deep open ocean where the larvae certainly would die of starvation. During summer, rich upwelled waters provide the food supplies to ensure that larvae can develop and settle on the seafloor. During their juvenile and adult stages, groundfish in part depend on water column processes to supply their food supplies, to secure their growth as well as to ensure their physiological needs.

The third advantage of computing monthly climatologies is that they are especially useful to supplement data coverage of the oceanographic fields that are characterized by limited data sources, irregular sampling in space and time, and scarce and irregular coverage or spatial resolution. The climatologies attempt to combine/blend data from many several years to fill data gaps and increase data coverage. Until regular physical and biological observations are made throughout the water column at the same time and place as the fish trawls, we must rely on the climatologies. However, the users should be cautioned that when data from many different sources and years are combined together on a monthly basis, the sampling frequency for every month over time and space is different for each climatology. Therefore, some caution should be taken when interpreting the climatologies for months and regions that have been computed with few data points. In addition, the number of observations also decreases with depth and therefore, at deeper depths the coverage is less. Thus, the climatologies at 500 and 1000 meter depths can be of limited use since their coverage is irregular and infrequent.

5.2 Exploratory Analysis: Are Groundfish Distributions and Abundances off the Washington and Oregon Coasts Associated with any Ocean Habitat or Specific Oceanographic Characteristics?

The exploratory analysis has given a strong insight into the associations between groundfish communities and ocean habitats and individual oceanographic variables during the summer upwelling season during cold regime years. First, five ocean habitats with distinct physical and biological characteristics were identified off the Washington and Oregon coast. The ocean habitats were primarily delineated by depth gradients in the physical and biological parameters of the water columns and by latitudinal gradients caused by variation in upwelling intensity and river water discharge. Second, some clear associations between groundfish distributions and abundances and specific ocean habitats and specific oceanographic variables were also identified.

This section will be structured as follows: first, a discussion on the use of cold-regime summer climatologies to identify ocean habitats and the ocean habitats themselves; second, a discussion on the fish community analyses by interpreting the results for each of the statistical analyses, emphasizing their similarities and differences; and finally, a conclusion highlighting the main findings of the exploratory analyses and limitations of the study.

5.2.1 *The Use of Cold-Regime Summer Climatological Means and Coefficients of Variation to Identify Ocean Habitats*

Cold-regime summer climatological means and coefficients of variation of temperature, salinity and chlorophyll-a concentrations proved to be good descriptors to identify ocean habitats off the Washington and Oregon coast in terms of their physical and biological properties. A simple cluster analysis of the trawl stations with their associated ocean characteristics at three different depths was able to classify the study region into five meaningful ocean habitats (Highly Variable Habitat, River Plume Habitat, Upwelling Habitat, Highly Variable Upwelling Habitat and Offshore Habitat). Each trawl station was grouped into habitats based on its long-term mean physical-biological characteristics and in terms of their natural variability. Each of the ocean habitats had its unique physical and biological characteristics, which described the entire water column.

The decision to divide the study region into five ocean habitats (instead of 3, 4 or 6 ocean habitats) in the clustering analysis was initially based on the evaluation of the monthly climatologies (which show the main oceanographic processes in the study region). The decision was further supported by the principal component analysis. The principal component analysis broke down the physical and biological variations in the study region primarily into three principal components that explained most of the variation (64.1%). The principal components are perpendicular to each other and therefore each of them explain different biological and physical characteristics of the study region. By combining the information that came explicitly in each of the principal components, it turned out that their combined interpretation also described five distinct ocean regions within the study region. The first principal component (PC1) explained depth variations in temperature and salinity at the bottom of the seafloor, and cross-shore variations in chlorophyll-a concentrations between the inshore and offshore stations. Comparatively, the ocean habitats classified by the clustering analysis, in the general terms, also divided the study region into shallow inshore stations (River Plume Habitat, Upwelling Habitat and Highly Variable Habitat from Figure 4.59 could be considered shallow stations) and deep offshore stations (Offshore Habitat and Highly Variable Upwelling Habitat in Figure 4.59 could be considered deep stations).

The second principal component (PC2) differentiated the region influenced by the Columbia River plume and the offshore stations, which are characterized by low salinities and warm surface waters, from the colder more saline coastal stations, which are influenced by the upwelling phenomenon. PC2 explained most of the variation on the surface waters (0 to 50 meters). Comparing the variation explained by PC2 to the ocean habitats classified by the clustering analysis, I realized that the River Plume Habitat was not identified as an individual ocean habitat by the PCA. Notice how the second principal components of the PCA grouped together the river plume habitat characteristics (low mean salinities, high mean temperatures and high coefficient of variation for salinities at the surface) and the offshore habitat characteristics (low mean salinities and high temperatures at the surface), implying that the River Plume Habitat and the Offshore Habitat have similar physical-biological characteristics. However, I decided these two habitats were indeed different, as I will discuss a little bit later. Moreover, both PC2 and the clustering analysis were able to differentiate Upwelling Habitats versus offshore habitats.

The third principal component (PC3) was characterized by differentiating variable habitats from non-variable habitats. PC3 captured three variable regions: 1) the region located in near-shore waters off the Washington coast and off the Strait of Juan de Fuca (the clustering analysis also identified this region as a unique habitat); 2) the upwelling region off Cape Blanco (it was also identified by the clustering analysis); 3) the offshore region located off the central Oregon coast (this region was not identified by the clustering analysis). This region was identified by PC3 as a variable region because of the large coefficient of variation for temperature at 50 m. However, the CTD values in this region might not be 100% reliable, since most of the CTD casts in this region were done before 1976 with low-resolution CTDS. Therefore, this region was not recognized as an ocean habitat by itself.

To conclude, the clustering analysis identified five distinct ocean habitats in terms of the physical and biological characteristics of the study region. The Principal Component Analysis supported this classification with the exception of the River Plume Habitat, which was not identified as a separate habitat. However, the River Plume Habitat was classified as an individual habitat for two interrelated reasons. First, the PCA and the clustering analyses classified the region influenced by the Columbia River plume differently. The PCA ordinated the river plume region together with the offshore stations and the clustering analysis, when it was divided into four groupings instead of five (Figures 4.58b), classified the river plume region together with the highly variable near-shore region off the Washington coast. Therefore, since each of the analyses classified the region influenced by the Columbia River discharge differently, this region was classified as a habitat by itself. This decision was further supported by the results from the discriminant function analysis (Table 4.2), which showed that the means and CVs of each ocean variable at different depths are different among the High Variable Habitats (Offshore Habitat and the River Plume Habitat). The River Plume Habitat has fresher and warmer surface waters than the Highly Variable Habitat. It also shows less variability throughout the water columns than the Highly Variable Habitat, especially at 50 m and at the surface. In addition, the Offshore Habitat had warmer and saltier surface waters than the River Plume Habitat and it also showed less variability through the water column than the River Plume Habitat. Finally, the River Plume Habitat was the most productive in terms of chlorophyll-a concentrations of all the habitats. The above descriptions emphasize how each habitat is unique based on their physical and biological properties.

The following section attempts to evaluate the validity of the identified ocean habitats by discussing their individual characteristics. The discussion on the monthly climatologies in section 5.1 also applies to the cold-regime summer climatologies used for the identification of ocean habitats. In this case, the cold-regime summer climatologies are dominated by one season (from May to September), which covers the entire upwelling season, and are dominated by the cold-regime years. Once more, the intra-seasonal, inter-annual and inter-decadal variabilities have been lost in the climatologies. However, although these climatologies represent only the ocean processes during upwelling conditions, the importance of seasonal processes for groundfish species, and especially the importance of the summer upwelling season, should not be overlooked. The summer upwelling season is characterized by high biological production, especially in the cold-regime years where the productivity in the California Current System is higher than average. It is well documented that major upwelling regions such as our study region support a major portion of the word's fisheries (Pauly *et al.*, 1995).

Finally, the reader should also be cautioned that the identification of ocean habitats was limited to the ocean variables available for this study. For example, notice that the analyses only included chlorophyll-a concentration at the surface. Subsurface chlorophyll-a concentrations obtained from fluorometers and discrete Niskin bottle samples did not adequately cover the study area and was therefore removed from the analysis. The same situation occurred with surface and subsurface current velocities, so they too were removed from the analysis. This introduces one main drawback of the classification of the ocean habitats. The identification of ocean habitats relies on the assumption that the oceanographic variables incorporated into the analyses are the most significant and realistic variables to recreate the ocean processes in the study area. It is argued that this attempt was successful in classifying summer ocean habitats characteristic of cold-regime years in terms of the physical and biological properties of the system and produced meaningful ocean habitats. In the future, when new data become available, such as subsurface chlorophyll-a, water velocity, oxygen and nutrient distributions, among others, these ocean parameters could be a valuable addition into the identification of ocean habitats. In addition, this classification was limited to the summer upwelling season during cold-regime years. It would be interesting to identify the typical ocean habitats during a warm-regime period and then evaluate their similarities and differences in their physical and biological properties, as well as to identify winter ocean habitats during both the warm and cold regime ocean periods. We think that seasonal variability and regime variability are relevant scales in the groundfish ecology, since groundfish have a very long life span, they are high in the trophic levels, and some of the species show migration patterns throughout the season.

5.2.2 *Community Analysis; Are There any Associations between Groundfish Species and Ocean Habitats or any of the Individual Oceanographic Variables?*

The purpose of this exploratory analysis was to investigate if there was any association between ocean habitats and fish distributions and abundances, and, if so, to identify what species or groups of species (assemblages) were associated with those habitats. We also looked at the association between groundfish distributions and abundances and individual oceanographic variables.

Given that different statistical methods were used to explore groundfish distributions in association with five oceanic habitats and their oceanographic characteristics, it was very useful to compare the results of the different methods. Consistency in the results from the different methods would enhance the credibility of associations between specific species or assemblages of species and ocean habitats and oceanographic variables, while major inconsistencies would suggest further research is needed. We started by discussing each of the analyses individually and then attempted to interpret them in combination.

The identification of ocean habitats in the clustering analysis allowed the creation of groups (the ocean habitats) and therefore this gave us the chance to evaluate species differences among habitats. First, the MRPP analysis suggested that the species composition differ among the five ocean habitats. Second, the ISA indicated that all the ocean habitats identified in the clustering analysis except the Upwelling Habitat had statistically significant species indicators. Thus, both analyses suggested an association between groundfish species and ocean habitats. However, since only three species showed indicator values around 40% or higher (table 4.7) and the majority of the species showed statistically significant indicator values of around 20 to 40%. It is concluded that although species might be indicators of one particular habitat, they may also utilize other habitats too. This finding agrees with the seasonal variability hypothesis (Gaston and Blackburn, 2000), which states that marine species at high latitudes are subject to broader environmental conditions due to the seasonal variability, and therefore marine species develop greater tolerances to cope with a wider range of variability. This makes species at higher latitudes able to inhabit a wider range of environmental conditions than those living at lower latitudes.

In addition, the ISA illustrated that the smaller habitats (the River Plume Habitat and the High Variable Habitat) had the largest number of species indicators. This might be because both habitats are very productive due to upwelling and the discharge of nutrients from land. Furthermore, both habitats are shallow and therefore it was expected to find a higher number of species in the shallower habitats compared with the deeper habitats. Finally, it is also worth mentioning that there were no statistically significant species indicators in the Upwelling Habitat. Although greenstriped rockfish and canary rockfish came out as indicator species, they were not deemed statistically significant. This could be the result of a combination of the following factors: species are less abundant, species fidelity to the habitat is lower (lower occurrences of the species within the same habitat) and the number of stations is relatively large within the habitat. In the case of canary rockfish, this species is overfished. Therefore, its abundance was expected to be low and occur in a smaller number of trawls. In addition, the Upwelling Habitat was also the largest, composed of 103 trawl stations. Therefore, this habitat was expected to be more heterogeneous in species composition, making it more difficult for one particular species to arise from the analysis. Overall, ISA proved to be a very easy and simple technique to describe the value of different species of groundfish in each of the ocean habitats.

The following section focuses on the interpretation of the results from the NMDS (unconstrained analysis) and CAP (constrained analysis) statistical methods. Since both analyses were conducted on the basis of the same distance measure and the same normalization of the fish data matrix prior to the analyses, their results can be compared to get a better insight of the associations between groundfish species and ocean habitats and individual oceanographic variables. However, it should be emphasized that each analysis has a specific goal and purpose, and follows different criteria. Therefore, it is expected that they will demonstrate different things but overall they will describe important aspects of the fish community in relation to the ocean habitats and the oceanographic variables. Their joint information is expected to yield a better understanding of the multivariate dataset.

Beginning with the results from the NMDS analysis and keeping in mind that this analysis' purpose is to illustrate the broad patterns of groundfish communities across the entire multivariate data cloud without reference to the environment, the analysis primarily suggested that groundfish species are mainly organized along a bathymetric gradient. To a lesser extent, the results also suggested that groundfish communities are also influenced by chlorophyll-a concentration, temperature and salinity at the surface, suggesting that variation in upwelling intensity and productivity along the coast is also an important factor influencing groundfish communities.

Axis 2 in the NMDS ordination plot is the axis that explained most of the variation in groundfish species (77%) by primarily differentiating the trawl stations from the shallower productive habitats to the deeper less productive habitats (Figure 4.62) and suggesting that groundfish species are mainly organized along a bathymetry gradient. Since, temperature and salinity at the bottom of the seafloor were the environmental variables that most strongly correlated with axis 2, together with depth, the NMDS primarily suggested that depth gradients in the physical properties of the water column are the main factors explaining fish distribution and abundances in the study area. In contrast, axis 3 in the NMDS ordination plot, which explained 14% of the variation, uncovered an additional pattern among the shallower stations. In this case, chlorophyll-a concentration, and to a smaller extent, surface temperature and salinity, correlated with ordination axis 3, suggesting that coastal productivity and upwelling intensity along the coast varies, making some areas more productive that others. A study by Tolimieri and Levin (2006) investigating assemblage structure of groundfish on the U.S continental slope in relation to environmental variables (longitude, latitude, depth, bottom temperature and inter-annual variation), also showed that groundfish assemblage structure was strongly correlated with depth and latitude. They also suggested that latitudinal changes affecting fish assemblages are probably caused by variations in temperature and upwelling intensity along the coast.

In order to better interpret the results of the NMDS plots, next axis 2 and 3 were interpreted and this translated in investigating the banana shape of the ordination plot (Figure 4.62a). The stations located on the extremes of both sides of the banana are composed of trawl stations, whose groundfish abundances are higher than average for a given species or group of species (multivariate outliers) (Figure 4.62a). Remember the fish matrix is made up of the 28 most abundant species, which compose 95% of the biomass in the study region and also that the species matrix was normalized with a logarithm transformation to account for the skewness nature of ecological data. The point here is that we did not want to standardize the fish data matrix by columns or rows to bring down the high abundance values, because we give importance to the biomass values at each trawl station. We also wanted to investigate the abundances (not only distributions) of groundfish species in relation to ocean habitats and the environmental variables. Specifically, we also wanted (if possible) to identify highly productive regions in terms of chlorophyll-a concentration and to investigate the effect of such regions on fish abundances and distributions. Therefore, we looked at the species composition at the stations located at the far end of the banana (Figure 4.62a, see the side that correlates negatively with both axes) to identify their locations in the study region and their species composition. Stations 141, 144 and 55 had high abundances of lingcod. Station 142 had high abundances of petrale sole. Station145 had high abundances of greenstriped rockfish. Interestingly, all these station are located over the Heceta Bank region. Station 91, 92 and 93, located off the Strait of Juan de Fuca, had high abundances of spiny dogfish and station 191 had high abundances of Petrale sole.

Since we thought these results were interesting, we did a closer investigation of all the trawl stations that showed high association with high chlorophyll-a concentrations at the surface (these are the stations that ordinated in the negative side of axis 2 and 1) and we found an unexpected pattern. The stations that showed high association with high chlorophyll-a concentrations are located in three discontinuous regions (with some exceptions) along the coasts of Washington and Oregon (Figure 5.1). The first region was located over Heceta Bank. The second region was located off the Strait of Juan de

Fuca over the Juan de Fuca canyon. These two regions are represented mostly by all the blue stations in this side of the ordination (negative side of axis 2 and 1). The last region is the River Plume Habitat, which is represented by the yellow stations. This suggests that these three regions are associated with high chlorophyll-a concentrations (implying that they are very productive region) and associated with the following species of groundfish (Pacific sanddab, English sole, petrale sole, and lingcod).

The Heceta Bank region has already been identified as a very productive area and a hotspot (Reese and Brodeur, in press; Pearcy *et al.,* 1989). The River Plume Habitat was also characterized as the most productive habitat in this study, since it showed the highest surface chlorophyll-a concentrations among all the habitats. Finally, the region off the Strait of Juan de Fuca also has been identified as a highly productive area as well as highly productive foraging grounds for birds, fish and whales and an important commercially fishing ground (Healy *et al.,* 1990). Interestingly, over the Juan de Fuca Canyon, during the summer months a large anti-clockwise (cyclonic) eddy develops over the Juan de Fuca Canyon at the mouth of the strait. The eddy is responsible for upwelling of deep nutrient rich water into the surface (Freeland and Denman, 1982).

Finally, the multivariate fish data cloud of points in the NMDS ordination plot (Figure 4.62b) reproduced a similar data cloud as in Figure 3.62a but emphasizing along axis 1 the cross-shore gradient in chlorophyll-a concentration in the study region. As before, axis 2 illustrated how groundfish distributions varied according to depth gradients. However, in this case, the environmental variables, longitude (implying depth since the coastline is almost a straight line) and chlorophyll-a at the surface correlated with axis 1. Therefore, axis 1 primarily emphasized how chlorophyll-a concentration decreases, as it gets further offshore. The stations that were located within 0 to 100 m depth were generally negatively correlated with axis 1 and the shallowest species as expected had the strongest negative correlations with this axis. Then, the stations within 200 to 500 m depth were positively correlated with axis 1 and as expected, the middle depth species had the strongest correlation with this side of the axis. Overall, this ordination plot suggested that groundfish distributions varied according to depth gradients but with a major shift in groundfish structure at around 500 m depth. Below the 500 metes, groundfish species are associated with depth and chlorophyll-a concentration and show more heterogeneous species compositions and above 500 meters, groundfish species are mainly associated with depth and show more uniform compositions. Tolimieri and Levin (2006) also found out that an abrupt change in groundfish assemblage structure at approximately 500-600 m along the west coast of the U.S.

The NMDS analysis proved to be a powerful tool to examine the main patterns of groundfish off the Washington and Oregon coasts for the spring-summer 2004. Overall, the multivariate cloud in the NMDS analysis primarily illustrated that fish distributions vary with depth and secondarily with chlorophyll-a concentration. The NMDS ordination differentiated among shallow and deep groundfish species with an abrupt change in species structure at approximately 500 m and among high chlorophyll-a regions with their specific community of species from the less productive regions. In addition, the overlay of the ocean habitats on the NMDS ordination plots also suggested that there is some overlap among the ocean habitats. The Offshore Habitat and the Highly Upwelling Habitat overlapped suggesting they share similar species composition. This disagrees to some extent with the ISA, which suggested different indicator species for each of these habitats. The shallower habitats also shown some overlap but the River Plume Habitat and the Highly Upwelling Habitat tended to group closer together, suggesting that their community structure is similar within those habitats. This was also suggested by the ISA.

The following section provides the interpretations of the CAP, which is the unconstrained method of ordination. First, the results from the CDA are discussed, and second, the results from the CCorA. Beginning with the results from the CDA analysis and keeping in mind that the analysis' purpose was to test if there was any significant difference in fish assemblages among the five ocean habitats, the analysis showed straightforward insights about the association of groundfish distributions and abundances with the five ocean habitats. The plot of the first two canonical axes show how distinct the shallow habitats (the River Plume Habitat, the Highly Variable Habitat and the Upwelling Habitat) are from the deep habitats (Offshore Habitat and the Highly Variable Upwelling Habitat) in terms of species compositions (Figure 4.66), indicating that depth is the main factor explaining the differences in species composition between shallow and deep habitats. There was very little overlap of species between the shallower and deeper habitats with most of the species either having high correlation with the shallower habitats or high correlation with the deep habitats. This showed a clear break between the species with ecological adaptations to shallow habitats and those adapted to deeper habitats. However, six species did not correlate either with the shallow or deep habitats (most of these species did not correlate either with depth in the NMDS analysis). Sandpaper skate and Dover sole showed no correlation because they occupy the entire depth range (50-1200 meters). In the case of canary rockfish, darkblotched rockfish and striptail rockfish, since they were among the species with the least biomass in the trawl survey, their low biomass may have made it difficult for them to show a pattern. Darkblotched rockfish and canary rockfish have been listed as overfished, so their biomasses were expected to be small. Finally, although sharpchin rockfish did not show any correlation with depth, they showed a small correlation with the Offshore Habitat, suggesting that a latitude effect could be having an effect on its distributions.

While there was a clear distinction between shallow and deep groundfish species, the three shallow habitats (the Upwelling Habitat, the Highly Variable Habitat and the River Plume Habitat) showed substantial overlap in species composition. This was unexpected since the three habitats have different physical and biological characteristics and in addition, the species indicator analysis showed how some species had high indicator values at least for the River Plume Habitat and the highly variable habitat. Finally, the deeper habitats, the Offshore Habitat and the highly variable Upwelling Habitat, showed up as having different species composition. Although the canonical square correlation showed that the differences between both habitats are weak. Sablefish, giant grenadier and pacific grenadier groundfish species showed association with the highly variable Upwelling Habitat. This agreed with the results from the indicator species analysis. Only Pacific Ocean perch in the CDA showed a weak association with the Offshore Habitat. Pacific Ocean perch also was an indicator species of the Offshore Habitat. Interestingly, neither of the thornyheads showed correlation with the Offshore Habitats (their correlations were very small). This could be due to the fact that their distributions and abundances overlap both habitats practically.

Overall, the CDA analysis, which looked at the community structure of groundfish species and their association with the five ocean habitats, suggested a weak relationship between groundfish species and individual ocean habitats. The CDA primarily showed that groundfish species compositions differ between the shallow and deep habitats. It also showed very clearly that there are more groundfish species associated with the shallower habitats, suggesting that the overall abundance and diversity of groundfish species is higher in the shallower habitats. However, the CDA showed a high overlap in species composition among the shallower habitats, not showing a clear difference in species compositions among the River Plume Habitat, the Highly Variable Habitat and the Upwelling Habitat. These results do not agree with the indicator species analysis, which identified indicator species analysis for each of the ocean habitats. Nevertheless, the deep habitats did not show much overlap with species composition, with the exception of the thornyheads. These results agree fairly well with the species indicator analysis. Overall, the results of the analysis suggest that it is very hard to determine assemblages of species off the Washington and Oregon coast using the five ocean habitats, implying that we cannot use the boundaries of these ocean habitats as the main framework to define fish assemblages. Either the ocean boundaries have been inaccurately defined or the physical and biological properties defining these ocean boundaries are not strong enough to stop fish from crossing these boundaries. Maybe, the study region is too small to perceive associations between groundfish distributions and ocean habitats, and therefore, the interpretation of these ocean habitats as biogeographical boundaries is not possible. At this point, it is worth mentioning that the association between biogeographical boundaries associated with major oceanographic processes and fish species distribution has been explored at other sites of the world. For example, MacPherson (2003) explored marine species distributions (pelagic and benthic fish and invertebrates) in the Atlantic Ocean in relationship to depth, longitude, latitude and major biogeographic boundaries. He found the main pattern in benthic species tended to be associated with major geographical provinces, associated with major oceanographic processes. Benthic fish patterns were mainly influenced by the upwelling region in the Eastern Atlantic and boundaries of currents (the Labrador and Falkland currents), and river plume boundaries (Amazon River plume). These findings would suggest that the reason why the analysis could not capture clear associations between ocean habitats and fish distributions might be because the spatial scale of our study area is too small. The study area only covers the waters off Washington and Oregon States, when groundfish species distributions examine in this study are found from the Bering Sea to Baja California. Thus, there is the possibility that the groundfish species examined here might have evolved to adapt to the wide ranges of oceanographic variability found in the study area. However, even though groundfish might be adapted to wide ranges of environmental variability, still they may prefer some regions over others, and this is what eventually we are trying to pursue, what are the main factors creating preferable habitats or essential fish habitats? Oceanographic processes can only be one part of the equation. As stated before, there are many indications in the analyses suggesting that there are other factors in addition to oceanographic variables determining groundfish distributions and abundances. Many studies have shown how seafloor habitat characteristics are some of the most important factors known to explain groundfish abundances and distributions (Hixon *et al.,* 1991; Stein *et al.,* 1992; Yoklavich *et al.,* 2000). Therefore, future studies should be directed to use the combined information (seafloor habitat characteristics and water column habitat characteristics) to improve the knowledge of groundfish ecology, their habitats, their function in the ecosystem and their responses to climate variability.

Since, the CDA suggested a weak relationship between groundfish species and individual ocean habitats, we though it will be critical to investigate the variation in groundfish species distributions and abundances in relation to individual environmental variables (instead of looking it from a habitat perspective) with the CCorA. The results from the CCorA analysis showed strong association between groundfish structure (distributions and abundances) and environmental variables. Specifically, depth, bottom salinity and temperature, and chlorophyll-a at the surface were the main environmental variables explaining fish variations. The overlaying of the color-coded ocean habitats over the ordination plot of the CCorA further supported the fact that fish distributions and abundances are mainly organized along a bathymetry gradient. These results agree very well with the NMDS analysis, the CDA and ISA. All the species, except one, correlated either negatively or positively with canonical axis 1, separating very clearly shallow species versus deep species. The exception was sharpchin rockfish which did not correlate either with axis 1 or 2. The reason only one species did not correlate with depth, compared with the other analysis where there are five or six species which did not correlate with depth, is due to the nature of the CCorA. This is a constrained method with the goal to optimize and strengthen the fish community structure relationship with the environment.

Moreover, the second canonical axes in the CCorA analysis also depicted a second pattern in groundfish community structure. Latitude, temperature, salinity and chlorophyll-a at the surface loaded with canonical axes 2. This suggests that differences in upwelling intensity along the coast, as well as, fresh water river discharge from land are also producing some of the variation in fish distributions and abundances. This was also suggested by the NMDS analysis, supporting those latitudinal changes in upwelling intensity and freshwater river discharge might be also influencing shallow species community structure.

Looking at the overlay of the ocean habitat on the CCorA ordination plot (Figure 4.67), in this case, observing the spread of the trawl stations along canonical axes 2, it is worth noting that the CCorA grouped some stations according to the ocean habitat colors along axes 2. The Highly Variable Habitat trawl stations (red) seem to cluster together on the positive side of axis 2. These stations seem to be correlated with high latitudes, high coefficient of variation for salinity at the bottom and high chlorophyll-a concentrations at the surface. Pacific dogfish, Pacific cod and English sole seemed to be found predominantly in these stations, which primarily showed associations with the Highly Variable Habitat. Petrale sole and Pacific sanddab also appeared to prefer the northerly highly productive stations, too but they showed weaker correlations with axis 2 indicating that they occupy a little bit more southerly stations than spiny dogfish, Pacific cod and English sole. The species indicator analysis partially supported these results. Spiny dogfish, Pacific cod and English sole came out as indicator species for the highly variable habitats, agreeing with this analysis, and Pacific sanddab and petrale sole came out as an indicator species of the River Plume Habitats. The overlap of species in the habitats suggests that it is hard to draw boundaries between the habitats. Moreover, trawl stations from the River Plume Habitat and the Upwelling Habitat seemed to be scattered all over along canonical axis 2, indicating that there is a huge overlap in species composition among these two ocean habitats. The NMDS also showed the overlap of species among the shallow habitats. However, NMDS analysis results are similar to the canonical correlation analysis in that petrale sole, Pacific sanddab, English sole and bigskate are associated with the Highly Variable Habitat and the River Plume Habitat.

Further extreme stations (91, 92, 93, 94, 190, 16, 95, 98) were investigated, which correlated positively with canonical axes 2, found in the canonical correlation analysis ordination plot to see if they corresponded to be the same extreme stations found in the NMDS analysis. The only common stations were 91 and 93. All the extreme stations in the CCorA ordination plot were located off Strait of Juan de Fuca over the Juan de Fuca Canyon. Stations number 91, 92, 93, 190 and 16 were clustered together at about 48.3^{o} N and 125.3^{o} W and were characterized by having high biomass of Spiny dogfish. Station 94, 95 and 98 were clustered together a little bit shallower around 48.2 N and 123.0 W and were characterized by having high biomasses of canary rockfish, English sole, and Pacific sanddab. As mentioned before, this productive region has been identified as important foraging grounds for birds, fish and whales, as well as commercially fishing grounds (Healy *et al.,* 1990). The NMDS analysis also identified this area together with the Heceta bank region as a highly productive area with trawl stations showing high abundances for specific species. When we are trying to understand this level of detail, what areas are more productive and therefore sustain more groundfish and why, the knowledge of bottom habitat type among many other factors becomes essential.
Finally, the CCorA suggested that the group of groundfish species (Pacific grenadier, giant grenadier, longspine thornyhead, sablefish, shortspine thornyhead) are associated mainly with depth and salinity at the bottom. Pacific grenadier, giant grenadine and

longspine thornyhead showed the strongest correlation with depth. This was expected since they are found at the deepest stations in the study region. The trawl stations that were most highly correlated with the canonical axis 1 were the deepest stations of the trawl survey. These stations (132, 13, 1, 213, 155, 84, 155, 87, 123, 15, 173, 47, 9, 244) showed higher than average biomasses of longspine thornyheads and Pacific grenadine. We think that the high abundances found on these stations are creating the circular shape of the ordination plot. Moreover, sablefish and shortspine thornyhead also correlated with depth but less strongly. This is because they occupy slightly shallower depths. They showed an association with high bottom salinities, warm temperatures at 50 m and high coefficient of variation for chlorophyll-a concentrations at the surface. These characteristics describe the Offshore Habitat and the highly variable Upwelling Habitat. This is why there is a high overlap of stations between the offshore and highly variable Upwelling Habitat. The deep stations in the NMDS analysis showed the same groundfish community structure in association with the same environmental variables. The same deep stations clustered at the end of the NMDS ordination, creating the banana shape characteristic of the ordination. Even the NMDS analysis and the CCorA showed that deep species utilize both the Offshore Habitat and the highly variable Upwelling Habitat. The EIS and the CDA showed that Pacific grenadine, Giant grenadine and sablefish might have a stronger association with the highly variable Upwelling Habitat. Since the deep species seem to show a very strong correlation with depth, it is worth noting that there are many other variables such us oxygen, density, and light which vary also with depth making them potential factors underlying fish distributions.

5.2.3 *Final Remarks: What are these Different Analyses Telling Us?*

First, it should be emphasized that the nature of this analysis was exploratory and, therefore, the results presented here intended to give a broad outline of community structure of groundfish species and their relationship with ocean habitats and oceanographic variables. There were two main approaches to investigate groundfish communities in relation to the oceanographic processes occurring off the Washington and Oregon coast. The first approach investigated groundfish associations with ocean habitats. The second approach investigated groundfish associations with individual oceanographic variables. Therefore, conclusions were made from each of the approaches separately.

The ocean habitat approach suggested a weak association between individual species and individual ocean habitats. There was a high degree of consistency among the different analyses associating shallower species with the shallowest habitats (the Highly Variable, River Plume and Upwelling habitats), and associating the deeper species with the deeper habitats (the Offshore and the Highly Variable Upwelling habitats). The analyses consistently identified the following deep species (Pacific grenadier, giant grenadier, longspine thornyhead, shortspine thornyhead and sablefish) as the deep assemblage occupying the deepest habitats (the Offshore Habitat and the highly variable Upwelling Habitat). However, the analyses also showed some indications that sablefish, Pacific grenadine and giant grenadine had a preference for the Highly Variable Upwelling Habitat over the Offshore Habitat. Among the shallower species, the analysis consistently showed shallow species have a high degree of overlap among the shallower ocean habitats (the Highly Variable Habitat, the River Plume Habitat and the Highly Variable Upwelling). However, the River Plume Habitat and the Highly Variable Habitat showed less amount of overlap than the Upwelling Habitat. The ISA, NMDS analysis and CCorA consistently agree that some groundfish species (spiny dogfish, English sole, petrale sole, Pacific sanddab) had a preference for the River Plume Habitat and the Highly Variable Habitat, suggesting that both habitats have similar species compositions.

So, why is there so much overlap among the shallow species when the ocean habitats show distinct physical and biological characteristics? It may be possible that the ocean habitats have not been defined accurately due to the scarcity of data to properly defined ocean habitats. Alternatively, the physical and biological properties of the ocean habitat boundaries may not be strong enough to prevent fish from crossing these boundaries, indicating that groundfish species are adapted to a wide range of environmental factors.

In contrast, the individual oceanographic variables approach revealed a different picture. There was a high consistency among the NMDS analysis and the CCorA, suggesting a strong association between groundfish communities and environmental variables. Specifically, depth, bottom temperature and salinity, and chlorophyll-a at the surface were the main environmental variables explaining variations in fish distributions and abundances. These associations were expected, as we concluded before. There was a clear distinction between groundfish species inhabiting shallow habitats and groundfish species inhabiting deep habitats. The NMDS analysis and the CCorA also showed consistent results suggesting that latitudinal variations in upwelling intensity, river discharge and productivity along the coast are also important factors influencing shallow species distributions and abundances. However, these variations in upwelling intensity and chlorophyll-a concentrations along the coast did not occur progressively along the coast (they occurred at specific places). The analyses illustrated that there were discontinuous regions along the coast that showed high chlorophyll-a concentrations, and at the same time, high association with high abundances of specific groundfish species. The first region was located over the Heceta Bank. The second region was located off the Strait of Juan de Fuca over the Juan de Fuca canyon. The third region was the region influenced by the Columbia River plume. All these regions have already been reported as important foraging grounds for birds and whales, as well as important commercial fishing grounds (Healy *et al.,* 1990; Reese and Brodeur, in press). This suggests that chlorophyll-a concentration is an important factor in determining fish distributions and abundances at the regional scale and therefore, we think it should be taken into consideration in the process of identifying Essential Fish Habitats.

Finally, there were several species of groundfish (sharpchin rockfish, stripetail rockfish, darkblotched rockfish, canary rockfish, yellowtail rockfish, splitnose rockfish, sandpaper rockfish and Dover sole), which showed a consistent lack of association or only a very weak association with any of the ocean habitats or environmental variables. Several reasons could contribute to this apparent lack of association. First, their distributions occupy most of the study region. For example, sandpaper skate and Dover sole had wide distributions. Second, their abundances were small on average, scattered over the study region and had large abundances in only a few places. This may be the case with striptail, canary rockfish, yellowtail rockfish and darckblotched rockfish, which have been enlisted as overfished. Third, bottom habitat type could be the determining factor influencing their distributions. It is widely known that groundfish abundances and distributions show clear associations with specific seafloor habitat characteristics (Hixon *et al.,* 1991; Stein *et al.,* 1992; Yoklavich *et al.,* 2000). Fourth, it is known very little about trophic interactions in groundfish species. This could be also an important factor establishing assemblages of groundfish. Fifth, the lack of association could be due to the fact that significant smoothing was applied to the cold-regime summer climatologies. Hence, the spatial heterogeneity in the study region has been lost by averaging a large number of observations. Finally, the combination of fish data over several months (from May to October) may also have been a factor. Species may migrate between the seasons or months and therefore this may have obscured the results.

5.3 Future Work

Throughout the thesis, several future research directions and suggestions to proceed in this relatively new field, fisheries oceanography, been recommended. They come down to the following several points. First, it is important we continue with the integration of oceanographic information off the west coast of the U.S. by integrating the oceanographic information existing off the California coast with the oceanographic information off the Washington and Oregon coasts. This would benefit fisheries studies since groundfish populations have wide distributional ranges (from the Bering sea to Baja California). Second, there is a clear need for regular and broad monitoring programs to collect ocean data with sufficient intensity in time and space so it can be used in regional fisheries studies. It is critical that NOAA Fisheries collect ocean data, including CTD casts, shipboard ADCP observations and chlorophyll-a samples, at each of the locations of the trawl surveys. Until regular physical and biological observations are made at the same time and place as the fish trawls, we must rely on the climatologies as proxies to characterize oceanographic processes. Fortunately, this is one of the goals driving the development of the Pacific Coast Ocean Observing System (PaCOOS), which is one of the west coast contributions to the national Integrated Ocean Observing System (IOOS).

Third, the potential use of the ocean information collected and the ocean products computed in this study in the process of identifying groundfish essential fish habitats should be investigated. This will be briefly discussed in the management chapter (Chapter 6). The point here is that now we have accessible fisheries independent data, benthic habitat information (seafloor lithology) and ocean habitat information for the Washington and Oregon coasts. Therefore, future studies should be directed to use the combined information to improve the knowledge on groundfish ecology, their habitats, their function in the ecosystem and their responses to climate variability. We propose as a first step to bring the benthic habitat information off the Washington and Oregon coasts such as the surficial geological habitat map developed by Oregon State University Active Tectonics and Seafloor Mapping Lab and regrid it to 0.3^{o} longitude and latitude in order to match the ocean habitat information developed in this study. The second step would be to explore the utility of the combined benthic and ocean habitat information and if significant, the combined information should be analyzed conjointly to improve our understanding of what factors determine groundfish distribution and abundances and to identify their essential fish habitats.

Finally, we encourage the development of interdisplinary studies between fisheries and oceanography. This study started by developing some preliminary ocean data products (climatological monthly means, standard deviation and coefficients of variation for temperature, salinity, chlorophyll-a and current velocity at several depths) relevant to fisheries studies. However, there are other potential ocean products that could potentially benefit fisheries studies such us the computations of mixed-layer depth, and thermocline, halocline and pycnocline depth and strength. In addition, as new data become available, such us subsurface chlorophyll-a, water velocity, dissolved oxygen and nutrient distributions, among others, its addition into the main oceanographic data set will enhance more interdisciplinary studies.

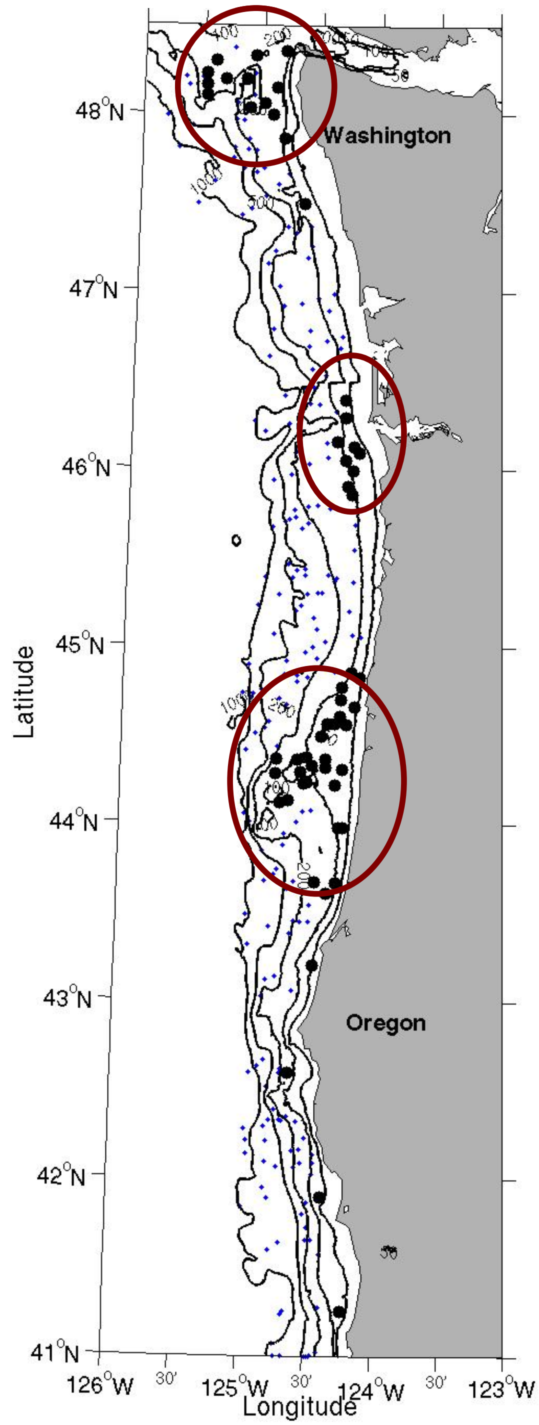


Figure 5-1 Trawl stations within the study region from 2004 groundfish survey in blue circles. Trawl stations in black circles delineate three regions where trawl stations have been found to have high associations with high chlorophyll-a-concentrations and high biomass of specific species of groundfish. The three regions are from top to bottom: the Juan de Fuca Canyon, the Columbia River Plume and Heceta Bank.

6 IMPLICATIONS TO FISHERIES SCIENCE AND MANGAGEMENT

The oceanographic datasets assembled in this study, as well as the ocean data products computed have direct implications for the current demands of groundfish fisheries research. The long-term goal is to use information on ocean habitats to inform ecosystem-based management of groundfish in the Pacific Northwest. The following section will present some of the most relevant applications and their use in supporting ecosystem-based fisheries management.

In more general terms, the oceanographic datasets assembled in this study as well as the ocean data products computed are a small but critical component to support the implementation of ecosystem-based fisheries management for groundfish. One of the many recommendations from NOAA's National Marine Fisheries Service, Ecosystem Principle Advisory Panel urged the development of a Fisheries Ecosystem Plan (Ecosystem Principles Advisory Panel, 1999). This includes the identification and bounding of ecosystems that occur within fisheries Council authorities. The advisory panel emphasized the need to describe the hydrography, bathymetry, productivity and trophic structure of the ecosystem, as well as how climate and ocean processes affect the biological and chemical cycles of the ecosystem and how food web structure and dynamics are affected. Thus, this study starts a long-term strategy to integrate oceanographic information off the entire west coast of the U.S. to support science for ecosystem-based management of groundfish by assembling physical and biological datasets from the 1930s to 2004 and computing ocean climatologies off the Washington and Oregon coast.

The next section introduces four direct uses of the oceanographic datasets assembled and the ocean data products produced in this study, which should receive the most attention in the short term. However, the list of applications could be expanded much more. First, the ocean climatologies have the potential to be used as part of the process to identify groundfish Essential Fish Habitat (EFH). The need for biological and physical oceanographic data was acknowledged recently by a Comprehensive Risk Assessment, which was generated in the process of creating "the Pacific Coast Groundfish EFH Draft Environmental Impact Statement (EIS)" by the National Marine Fisheries Service and the Pacific Fishery Management Council (NMFS, 2005). The comprehensive risk assessment was created to develop a scientific tool for the identification of EFH. The EFH tool is composed among other things of an EFH Model. The EFH Model uses two main sources of information. First, it utilizes information on habitat uses of fish species at each life stage, and second, it uses three habitat characteristics that are benthic habitat, latitude and depth. Benthic habitats refer to the seafloor lithology, the different bottom-types and physiographic features associated with groundfish. The effort and time put towards the creation of the comprehensive risk assessment and with it the EFH Model are remarkably important, since it triggered a major effort to compile disperse datasets and, most important, it has elucidated major gaps in data and knowledge along the progress (NMFS, 2005). However, it is still astonishing that only seafloor lithology, latitude and depth were the only habitat characteristic available on a coast-wide scale to be used in the EFH Model. Nevertheless, the comprehensive risk assessment had recognized that their model was missing crucial information on oceanographic processes, such as dynamic current structures, water temperatures and climate, which characterize the water column and certainly influence groundfish populations. They were also aware of the technical difficulty of identifying ocean habitats, which are less exact than mapping the seafloor, since the ocean is a dynamic system with many spatial and temporal scales. Thus, the monthly climatologies produced in this study, which reflect the average physical and biological oceanographic processes occurring off the Washington and Oregon coast, are a good place to start characterizing the oceanographic processes. In the future, they could have the potential to strengthen the model, if added, by producing more reliable and realistic results. Finally, we would like to continue emphasizing the importance of oceanographic processes as a key component to identify EFH. The proper identification of EFH eventually will lead to the conservation and enhancement of EFH as well as to the minimization of effects of fishing on them as is mandated in the Magnuson-Stevens Fishery Conservation and Management Act. The protection and conservation of EFH for groundfish is essential for the recovery and sustainability of groundfish stocks of the Northeast Pacific.

Second, the monthly climatologies have the potential to be used to examine climate variability and its effects on marine fish populations. Climatologies offer the long-term average of the oceanographic condition off the Washington and Oregon coasts. Thus, changes noted within the climatological records can be used to examine climate variability and research the effects of climate change. This can be done by computing yearly anomalies to examine year-to-year variability. Anomalies are deviation from the mean, which are created by subtracting climatological values from the observed data. In addition, the monthly climatologies could be also used to compute monthly anomalies. This would allow the examination of seasonal variability. Thus, monthly climatologies would allow studies to focus on the effects of year-to-year variability and/or the effects of seasonal variability on marine fish populations.

There are numerous studies showing correlations between climate and ocean processes and ecosystem components ranging from plankton to top predators like fish (Mantua *et al.,* 1997; Peterson and Keister, 2002a; Peterson *et al.,* 2002b). However, although it is well recognized that climate and ocean processes can affect marine fish distributions, abundance, growth and survival, the details of the causal mechanisms are still poorly understood. Potentially, the use of the climatologies in climate studies could be applied to both demersal fish and pelagic fish species. For example, this study has developed an exploratory analysis in which the climatologies have been used to define ocean habitats in an attempt to investigate associations between groundfish distributions (which are mostly demersal in nature) and summer ocean habitats during cold-regime years. This analysis could be expanded to examine the association between groundfish communities and winter ocean habitats during cold-regime years, as well as to examine groundfish communities with ocean habitats during the warm-regime periods. These would allow the comparing of how groundfish communities differ between warm-regime periods and cold-regime periods. We might expect some species with wide tolerance for environmental changes to be able to withstand regime variability; in contrast, other species might not be able to sustain regime variability as well. We think it will be very useful for fisheries management to know what species are more vulnerable to climate variations, including the ENSO and decadal regime variations, in order to manage this species differently from the ones that show more adaptations to environmental changes. Overall, by understanding the complex relationships between climate and groundfish distributions, abundance, growth, and survival, researchers and managers can better anticipate the effects of climate on the ecosystem and the effects of the ecosystem on fisheries and eventually support ecosystem-based management initiatives.

In addition, pelagic fish species such us sardines and anchovies could also greatly benefit from the assembling of the oceanographic datasets and the computations of these climatologies. This is because pelagic species tend to have relatively short-lived life cycles, compared with groundfish species and consequently environmental driven variability can have a major impact on their life cycle, for example in their annual reproductive success. Finally, the oceanographic data sets and ocean climatologies could also assist fisheries scientist in developing stock assessment models which include environmental information to set the context for projections of population status. For example, Schirripa and Colbert (2006) have recently shown how several physical oceanographic variables (Ekman transport and sea level) can have significant effects on sablefish recruitment, leading to efficient predictions before the regular assessments surveys results are made available.

The third application consists of incorporating the oceanographic datasets and the ocean data products produced in this study into numerical ocean prediction models and ecosystem models. Climatologies are required to run these sophisticated models. They can be used for model initialization model boundary conditions and for model verification. The climatologies act as a baseline and this is essential for future work on climate change effects in relation to marine ecosystems.

The development of ecosystem models is a relatively new emerging field and the number of ecosystem models keeps increasing every year around the world (Christensen and Pauly, 1993) (see http://www.ecopath.org). An ecosystem model attempts to provide information on trophic linkages and reproduces how the removal of one species from the system can have effects on other species. Ecosystem models can also be run under different climate scenarios ranging from ENSO to decadal regime shifts to scenarios of climate change from the Intergovernmental Panel on Climate Change. These models require long-term historical physical and biological data to provide the scales of the temporal and spatial variability in the targeted system. The oceanographic datasets assembled in this study could potentially be used to assist fisheries ecosystem models.

How can the results of ecosystem modeling be translated into management decisions? To date, some scientists claim ecosystem models are not useful yet as a management tool to guide management decisions, due to the need to prove themselves by being able to reconstruct the past or by making future realistic predictions (Trites *et al.,* 1999). Instead, they have been shown to be a good scientific tool for identifying gaps in data needs and general understanding. They are also helpful to guide the choice of research needs (Walters *et al.,* 1997) and, more importantly, they bring people with different backgrounds together to share knowledge about ecosystems (Trites *et al.,* 1999). The reality is that ecosystem models do not yet have real predictive skills, as seen, for example, in modern meteorological forecasts, and it will probably be a while before they will (Olson *et al.,* 2005). Nevertheless, Pauly and Christensen (2002) claim that ecosystem models like Ecopath and Ecosym, although they are not predictive, can be used to identify key elements of management strategies that potentially would enable fisheries to be sustained by sustaining and conserving the ecosystem in which they are embedded. However, there are still some drawbacks. There are usually very complicated analyses behind these models and in order to make progress in ecosystem-based fisheries management, scientist still need to consider more fully how to validate and convey these complicated models to managers in ways that can guide management decisions and inform fishers (Trites *et al.*, 1999). Nonetheless, there is a huge push/will to improve ecosystem models. This is driven by the recognition that the advancement of our understanding of ecosystems through better simulation and predictive models will improve significantly resource management. Lastly, it should be noted that there are groups of government, academic and private institutions working actively to start a cooperative effort to move forward work on assessing and predicting climate impacts on marine ecosystems in the California Current System (e.g., PaCOOS, 2004).

Finally, the last application and probably the one with more direct use for fisheries managers, consists in the incorporation of all the ocean climatologies into a GIS, using the ESRI ArcGIS version 8.3. In the near future, all the monthly climatologies of temperature, salinity, chlorophyll-a and current velocity at different depths will be organized in a GIS tool. This study already started the integration of the ocean climatologies by importing the climatological means for sea surface temperature and chlorophyll-a derived from satellite sensors. However, due to time constraints this was not completed.

After the ocean climatologies are imported, the GIS will ensure compatibility regarding projection and distance units among all the ocean layers, as well as facilitating the combination of the data via layering (Figure 6.1). We expect that the GIS tool will make the integration of the benthic habitat and ocean habitat information more efficient, as well as promoting the integration of other data sets in the future such as dissolved oxygen concentration in the water column. Eventually, this tool will become accessible to all type of users: scientists, fisheries managers, policy makers and the interested public. In addition, metadata will be created in order to document the parameters defining each of the ocean data layers. The collection of metadata is an important component of an organized database. Metadata will enhance the value of the data and will reduce any information loss during data exchange.

The incorporation of layers of oceanographic information into a GIS is part of joint effort to collect data relevant to the West Coast groundfish habitats, fisheries and ecosystems. This joint effort involves researches from academia (Oregon State University), federal agencies (NOAA Fisheries) and state agencies. The overall project goal is to create a comprehensive and easily accessible, multilayer GIS database with data relevant to groundfish habitats, fisheries and ecosystems where fisheries managers, marine researches and members of the public such as fishers and educators can have access. For example, recently, a map of the surficial geologic habitat was developed along the continental margin of Oregon to assist in the management of groundfish (Romsos, 2004). In addition, GIS techniques are being used to classify seafloor habitats using remotely sensed geophysical data to improve groundfish habitat-based assessment techniques (Nasby, 2000; Whitmire, 2003).

Eventually, this GIS database will be a basis to address management and conservation questions by providing easy visualization of the spatial relationships among all the data layers of information. In addition, this project also addresses the direct need and importance of providing better tools for fisheries managers to facilitate a more thorough understanding of marine habitats, fisheries and ecosystems, and to support their decision process. A public web site is collaboratively being developed by the NOAA Fisheries Northwest Fisheries Science Center, Oregon State University Active Tectonics and Seafloor Mapping Lab, Pacific States Marine Fisheries Commission and Alsea Geospatial Inc., which will provide ready access to marine spatial data and spatial representations. The ocean data products developed in this study could potentially be added to this website to continue the integration of marine spatial data as well as other popular websites such us the Oregon Coastal Atlas (www.coastalatlas.net), the goal of which is to provide data and decision-making tools in support of Oregon coastal zone management (Haddad *et al.,* 2005).

Finally, it should be emphasized that one of the great advantages of an integrated GIS database for the west coast is that it will facilitate more interdisciplinary studies, which in the past were constrained by limited data availability and accessibility. For example, a GIS could be used to support decision making for marine reserves by providing the main framework to compile, query, and visualize all the spatial datasets crucial for siting marine reserves and their effects on other marine resources (e.g., Wright and Scholz, 2002). Different intuitive visualization and querying mechanisms could be developed with the GIS database to investigate possible siting of locations and their effects on other marine resources. For example, if the goal was the creation of a network of marine reserves representing different marine habitats, the climatological means computed in this study could facilitate the identification of different marine habitats based on their oceanographic characteristics.

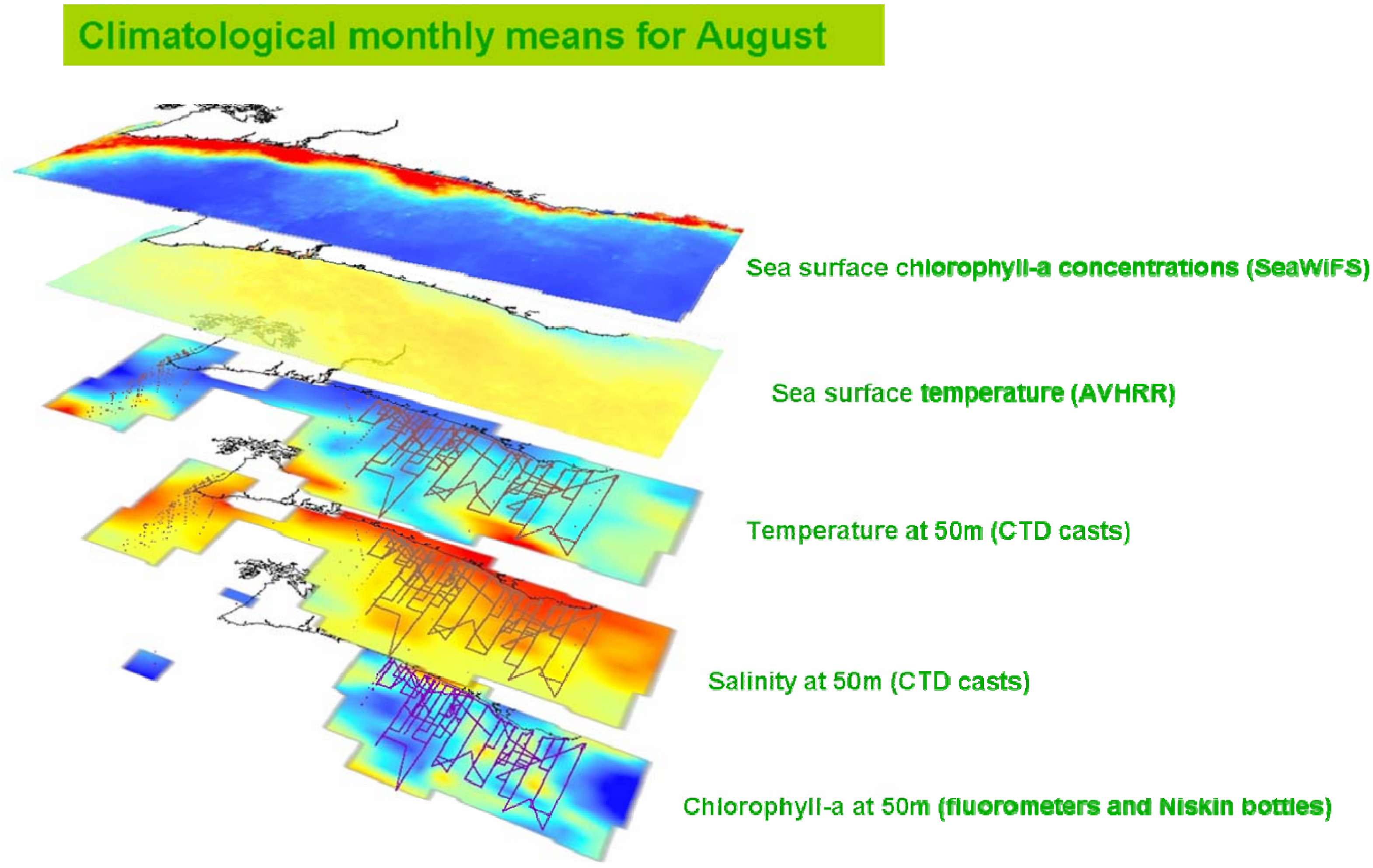


Figure 6-1 **Overlays of climatological monthly means of sea surface temperature, surface chlorophyll-a concentrations, temperature at 50 meters, salinity at 50 m and chlorophyll-a at 50 m for August plotted with ESRI ArcGIS 8.3 software.**

7 CONCLUSION

This study started a long-term strategy to incorporate oceanographic information off the west coast of the U.S. into fisheries science and management, beginning with the incorporation of oceanographic information from the Washington and Oregon coasts. The first major achievement in this study was the assembling and merging of disperse oceanographic datasets for temperature, salinity, chlorophyll-a and current velocity from the 1930's to the year 2004. The data were derived from a variety of sources, including remotely sensed data from satellite sensors and land-based coastal radars, and in situ measurements from conductivity-temperature-depth instruments, shipboard Acoustic Doppler Current Profilers, fluorometers and Niskin bottle samples. The second achievement of this study was the computation and the plotting of climatological monthly means, standard deviations and coefficients of variation for each ocean variables (temperature, salinity, chlorophyll-a and current velocity) at different depths. The gridded monthly climatologies are available on a regular 0.32^o x 0.32^o (longitude ~25.3km and latitude ~35.5km)spatial grid at 0, 50, 10, 500, 1000 m and 10 m above the seafloor. Only the climatologies derived from the satellite data (sea-surface temperature and chlorophyll-a) were exported into a GIS due to time constraints. However, in the near future the rest of the climatologies will be imported into a GIS. This will allow easy access and visualization of the climatologies. Finally, an exploratory analysis was conducted with the intention of giving an example of how the data and the ocean products collected in this study can be of use to improve the science and management of groundfish. Specifically, an exploratory analysis was developed to investigate if there are any ocean habitats associated with groundfish distribution and abundances.

The assembling and merging of the datasets shed light on what types of data are more abundant and, at the same time, what types of data are more scarce within the study region. We were astonished to see how oceanographic research cruises have decreased over time (especially off Washington coast), or perhaps the data are not being submitted to the national archives, and how sampling efforts over time have been reduced to the spring-summer months and to a few cross-margin sampling lines. However, there has been an increase in the number of oceanographic cruises off the Oregon coast between 1997 and 2004 due to the GLOBEC and COAST programs, and renewed efforts off the Washington coast are taking place through the ECOHAB and RISE programs. We expect to see an increase in ocean monitoring and sampling in the future, if an ocean observing system is established off the west coast of the U.S. The ocean data product (the monthly climatologies) proved to be a useful tool to describe the long-term seasonal evolution of the oceanographic processes and the variability throughout the water column in our study region. We expect that their improved spatial resolution (0.32^{o} x 0.32^{o}, longitude ~25.3km and latitude ~35.5km) (compared with the existing 1^{o}x1^{o} grids, longitude 79.32 and 11.12 km in the LEVITUS climatologies) will create an opportunity to improve fisheries research at the regional scales.

The exploratory analysis gave insights into the associations between groundfish communities and ocean habitats and individual oceanographic variables during summer upwelling conditions during cold-regime years off the Washington and Oregon coasts. Five ocean habitats (Highly Variable Habitat, River Plume Habitat, Upwelling Habitat, Highly Variable Upwelling Habitat, Offshore Habitat) were identified based on their physical and biological characteristics throughout the water column, which characterize cold-regime summer upwelling conditions in the study region. The ocean habitats were primarily delineated by depth gradients in the physical and biological parameters of the water columns and by latitudinal gradients caused by variation in upwelling intensity and river water discharge.

When the association between groundfish species and the ocean habitats was investigated, the exploratory analyses suggested that the species composition differs among the five ocean habitats. However, the associations were weak due to the high degree of overlap of the ocean habitats in terms of species composition. Nevertheless, there was a high degree of consistency among the different analyses associating shallower species (less than 500 meters) with the shallowest habitats (the Highly Variable, River Plume and Upwelling habitats) and associating the deeper species with the deeper habitats (the Offshore and the Highly Variable Upwelling habitats), suggesting that groundfish species are adapted and utilize a wide range of ocean habitats. The analyses also showed that there are more groundfish species associated with the shallower habitats suggesting that the overall abundance and diversity of groundfish is higher in the shallower habitats. In contrast, when the association between groundfish species and individual oceanographic variables were investigated, there was a strong association between groundfish communities and environmental variables within the study region. The most consistent environmental parameters explaining the main patterns in groundfish distributions were primarily depth, surface chlorophyll-a, and salinity and temperature at the bottom of the seafloor indicating that groundfish distributions are mainly organized along depth gradients. However, there were also indications suggesting that latitudinal variations in upwelling intensity, river discharge and productivity along the coast also are important factors influencing shallow species distributions and abundances.

The oceanographic datasets assembled in this study, as well as the ocean data products computed (monthly climatologies), have direct implications for the current demands of groundfish fisheries research, which eventually will lead to inform ecosystem-based management of groundfish in the Pacific Northwest. The outputs of this study could potentially be used as part of the process to identify groundfish Essential Fish Habitats. The climatologies also have the potential to be used to examine climate variability and its effect on groundfish populations. Finally, we recommend that the climatologies computed in this study be incorporated into the West Coast GIS effort to assemble relevant data for the West Coast groundfish habitats, fisheries and ecosystems.

We are starting to grasp how oceanographic information can improve groundfish fisheries research and management and understand how oceanographic information can fit in ecosystem-based fisheries management. We encourage the development of more interdisplinary studies between fisheries and oceanography. This study started by developing some preliminary ocean data product (monthly climatologies of temperature, salinity, current velocity and chlorophyll-a) relevant to fisheries studies. However, there are other potential ocean products that could potentially benefit fisheries studies such us the computations of mixed-layer depth, and thermocline, halocline and pycnocline depth and strength. We also emphasize the importance of continuing the integration of oceanographic information off the west coast of the U.S. by integrating the oceanographic information existing off the California coast with the oceanographic information off the Washington and Oregon coasts, as well as the collection of concurrent ocean data at each of the locations of the trawl surveys.

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9 APPENDIX 1 – SOURCES OF DATA

Table 9 - 1 Remotely sensed data sources.

DATA SOURCES	INSTRUMENTS	VARIABLES	SOURCES	RECEIVED	TEMPORAL COVERAGE	SPATIAL RESOLUTION
Remotely-Sensed Data	SeaWiFS	Chlorophyll-a	Courtesy of Dr. Andrew Thomas, University of Maine	Monthly means for the Northeast Pacific	Sept. 1997 to August 2003	~4km
	AVHRR	Temperature	Courtesy of Roberto Venegas, OSU	8 days composites	Sept. 1997 to august 2003	~1km
	High frequency coastal radars	Surface current velocity	Courtesy of Mike Korso, OSU	Monthly composites	April 2002 to March 2003	~2km

Table 9 - 2 In situ data sources.

DATA SOURCES	INSTRUMENTS	VARIABLES	SOURCE	RECEIVED	TEMPORAL COVERAGE	SPATIAL RESOLUTION
In Situ Data	Conductivity-Temperature-Depth (CTD)	Temperature And Salinity	National Oceanographic Data Center (NODC)	CTD casts	From 1934 to 2000	-Not gridded -Random sampling
			Northeast Pacific GLOBEC Program	CTD casts	From1997-2004	-Not gridded -CTD transects off OR
			COAST Program	CTD casts	Summer 2001, Wnter 2003	-Not gridded -CTD transects off OR
			Hake trawl	CTD casts	Summer 2003	-not gridded – CTD transects off WH and OR
			Newport Hydrographic Line Data (Courtesy Bill Peterson,OSU)	CTD casts	year 2004	-not gridded – CTD transects along the Newport line

Table 9 – 2 Continued in situ data sources.

DATA SOURCES	INSTRUMENTS	VARIABLES	SOURCE	RECEIVED	TEMPORAL COVERAGE	SPATIAL RESOLUTION
In Situ Data	Conductivity-Temperature-Depth (CTD)	Chlorophyll-a	NODC	Niskin Bottle Samples	From 1958 to 1993	-Not gridded – CTD transects of OR
			GLOBEC Program	Niskin Bottle Samples and Fluorometers	From1997-2004	-Not gridded – CTD transects off OR
			COAST Program	Niskin Bottle Samples and Fluorometers	Summer 2001 Winter 2003	-not gridded - CTD transects off WH and OR
	Advanced Doppler Current Profiler (ADCP)	Current velocity	Joint Archive for shipboard ADCP database	ADCP Transect Cruises	From 1991 to 2002	-not gridded - ADCP transects
			GLOBEC	ADCP Transect Cruises	From1997 to 2004	-Not gridded -ADCP transects off OR
			COAST	ADCP Transect Cruises	Summer 2001, Winter 2003	-not gridded – ADCP trasects off OR

10 APPENDIX 2 – ADDITIONAL CLIMATOLOGICAL MEANS

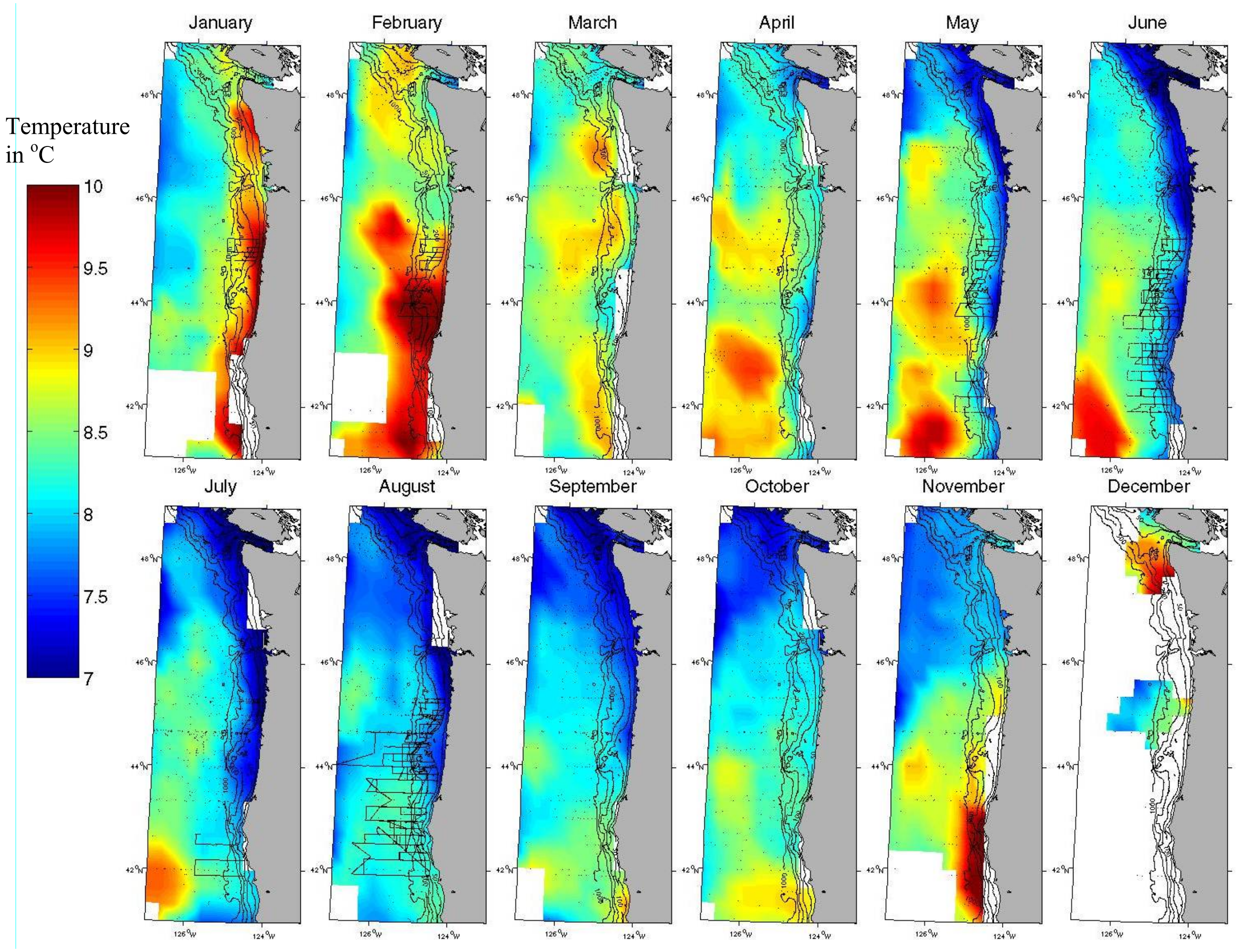

Figure 10-1 Climatological monthly means for temperature at 100 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

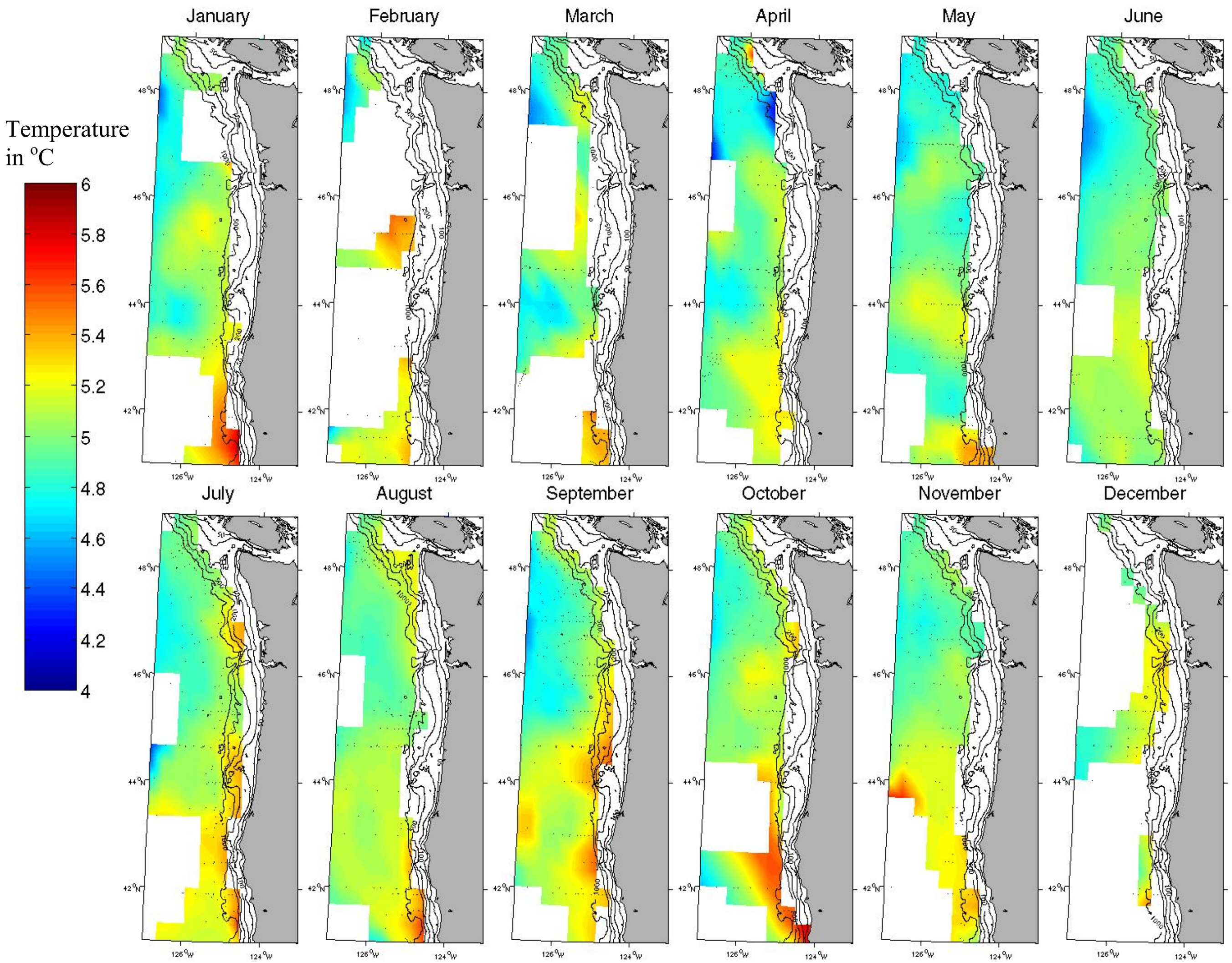

Figure 10-2 Climatological monthly means for temperature at 500 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

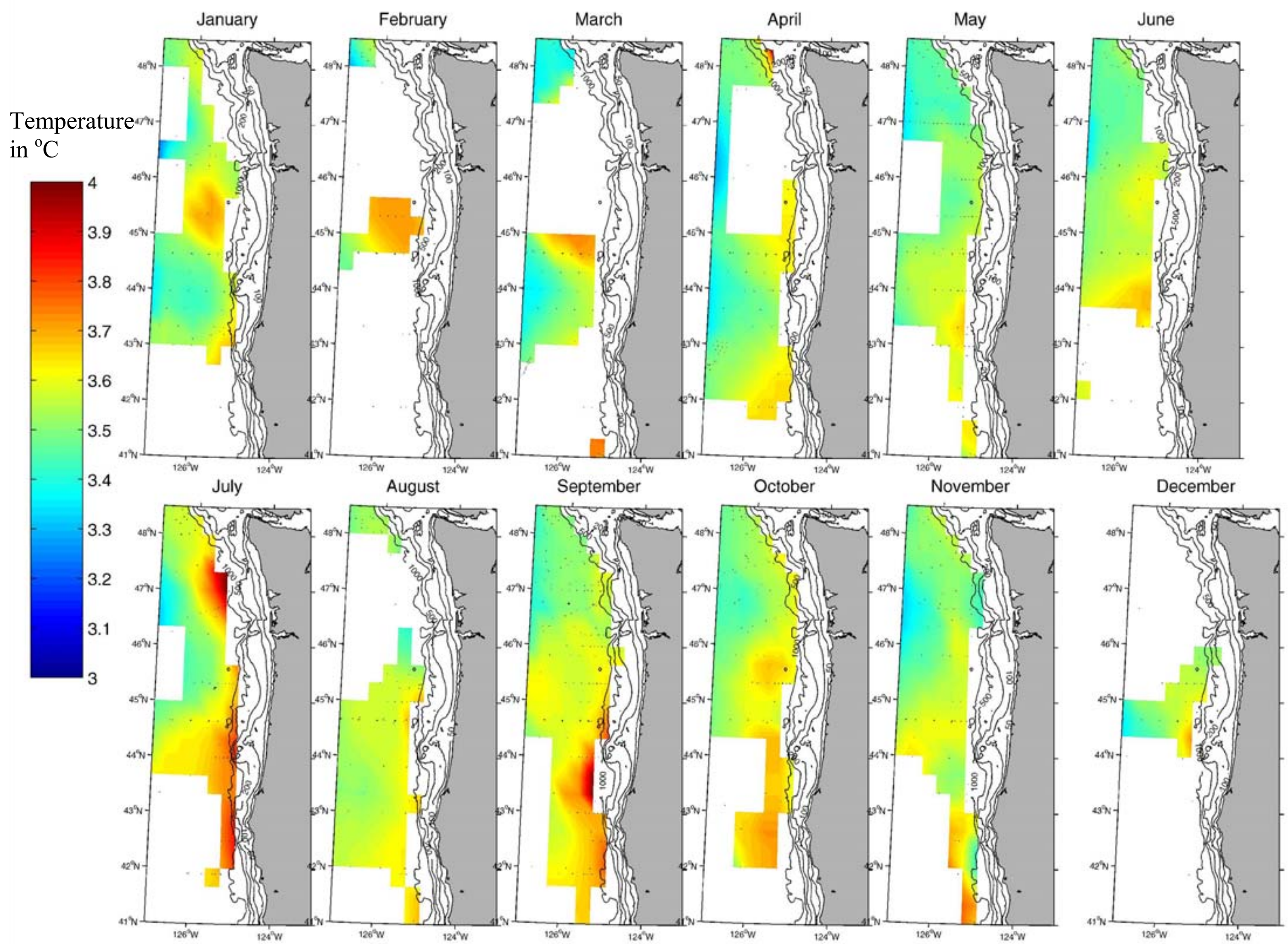

Figure 10-3 Climatological monthly means for temperature at 1000 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

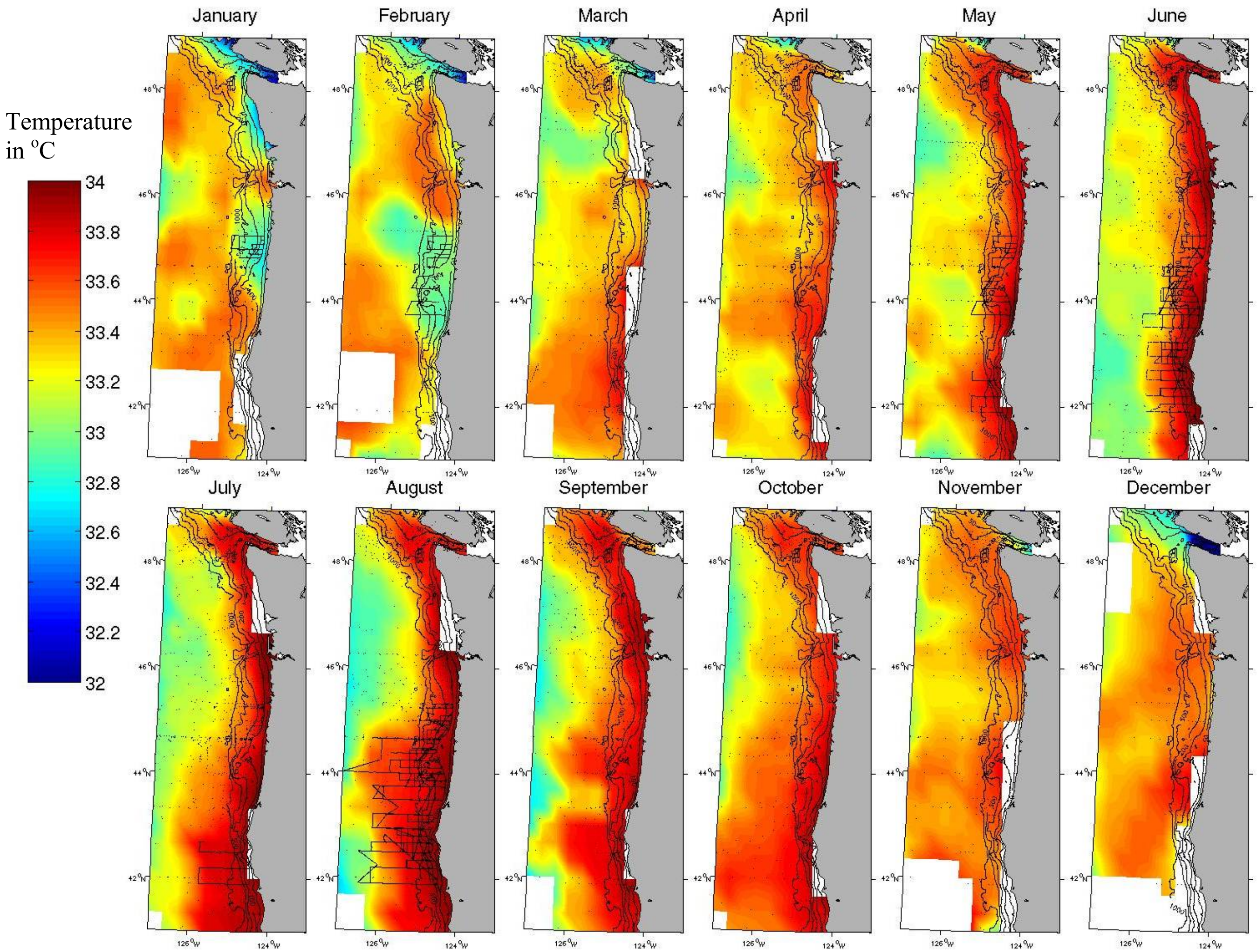

Figure 10-4 Climatological monthly means for salinity at 100 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

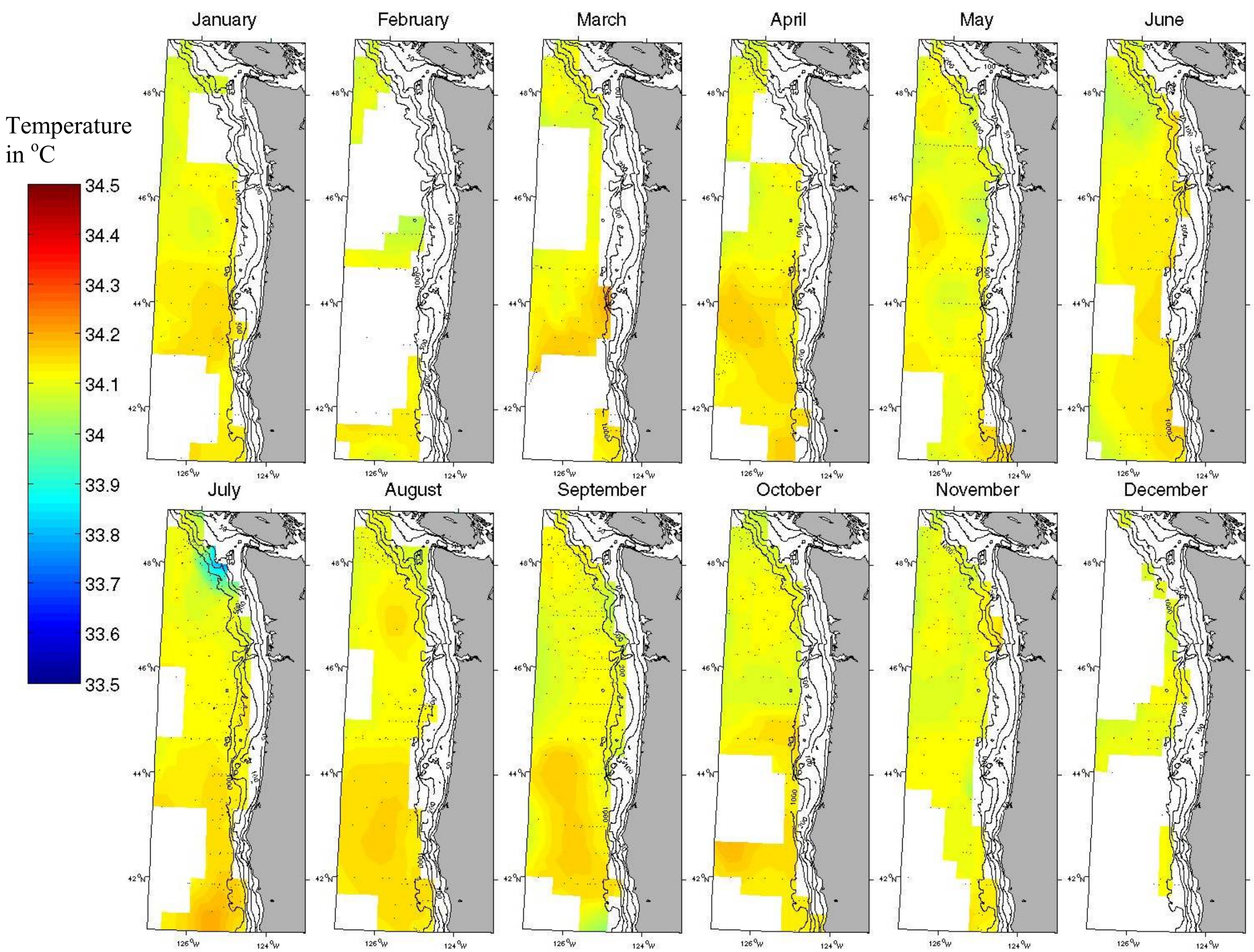

Figure 10-5 Climatological monthly means for salinity at 500 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

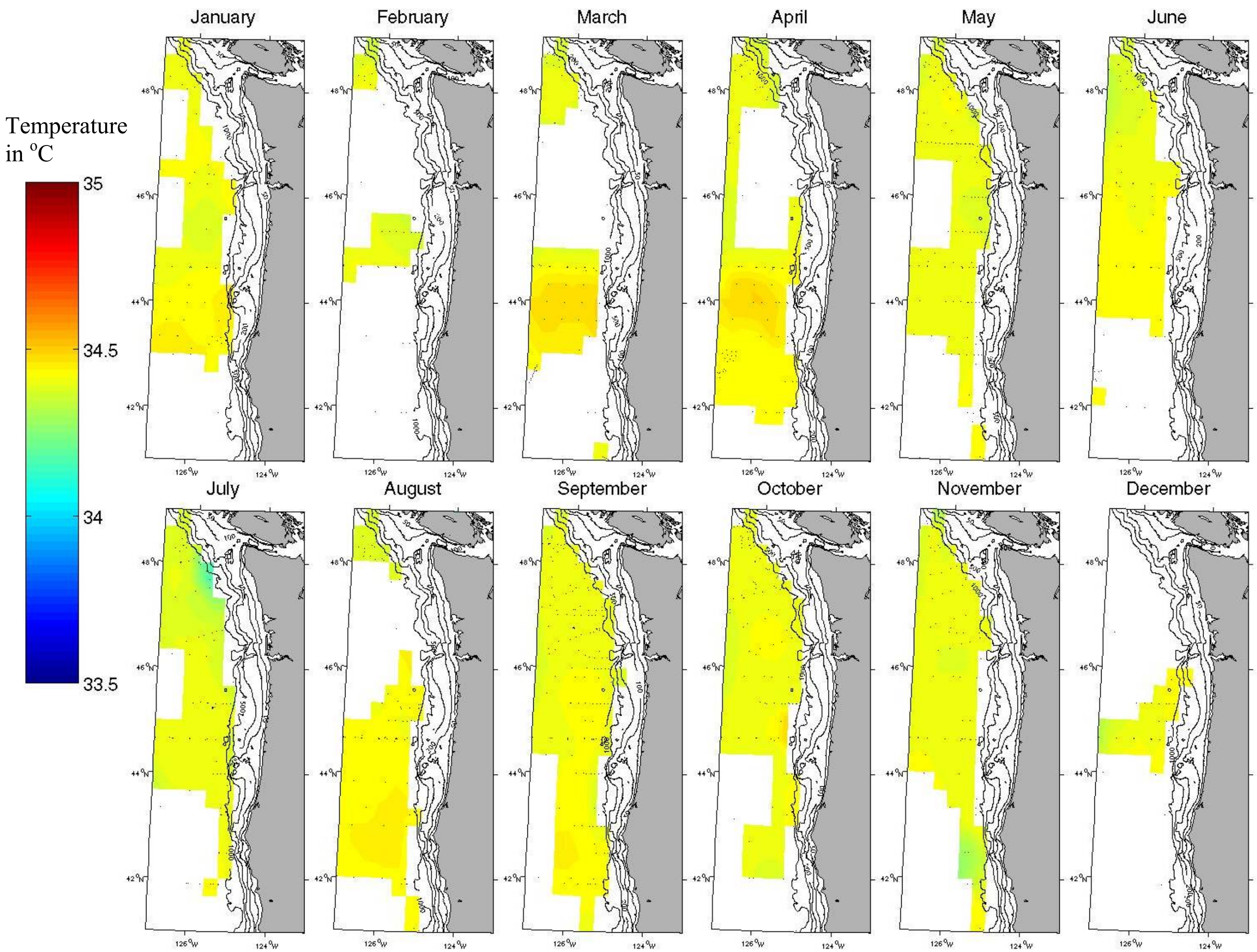

Figure 10-6 Climatological monthly means for salinity at 1000 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

11 APPENDIX 3 – ADDITIONAL CLIMATOLOGICAL STANDARD DEVIATIONS

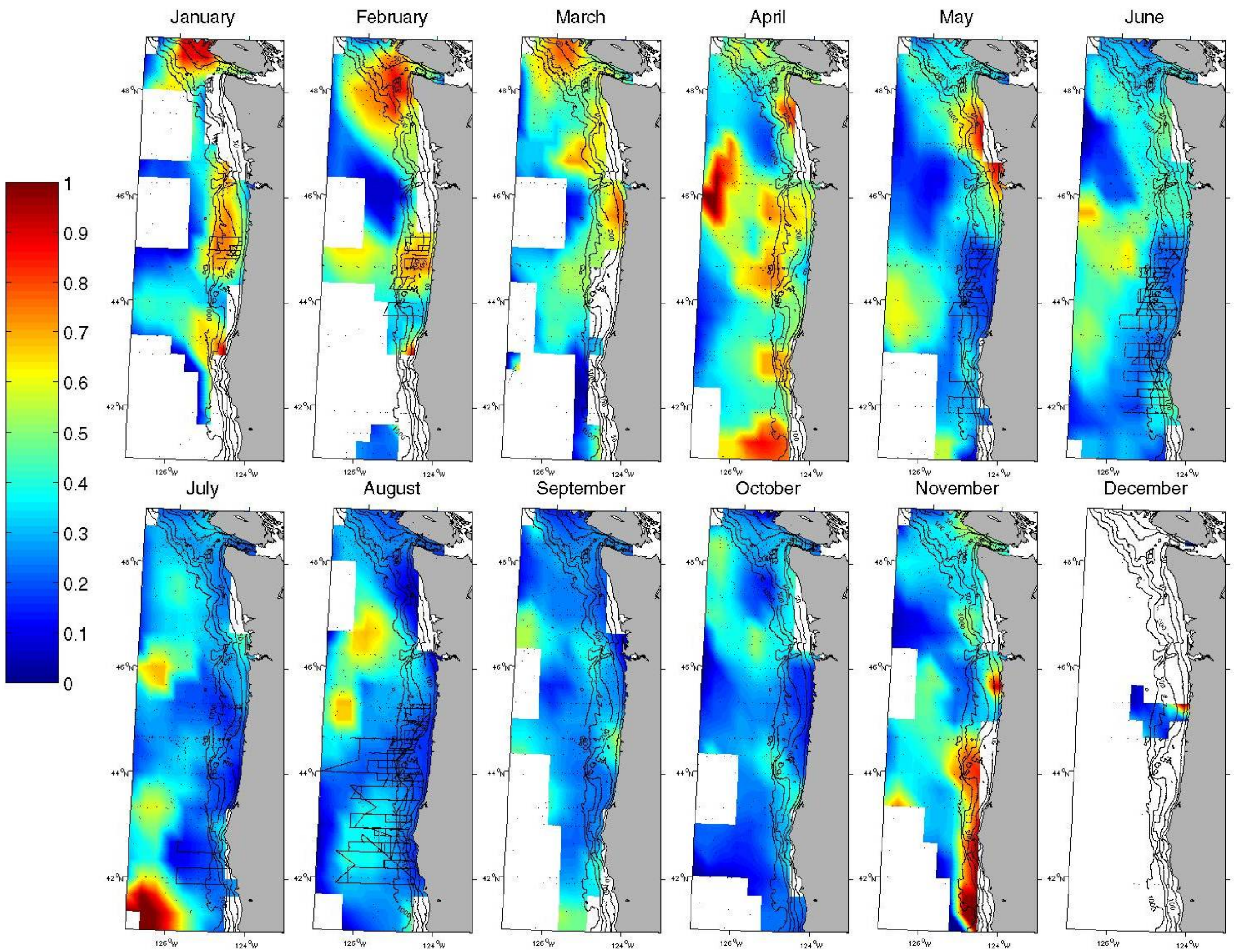

Figure 11-1 Climatological monthly standard deviations for temperature at 100 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

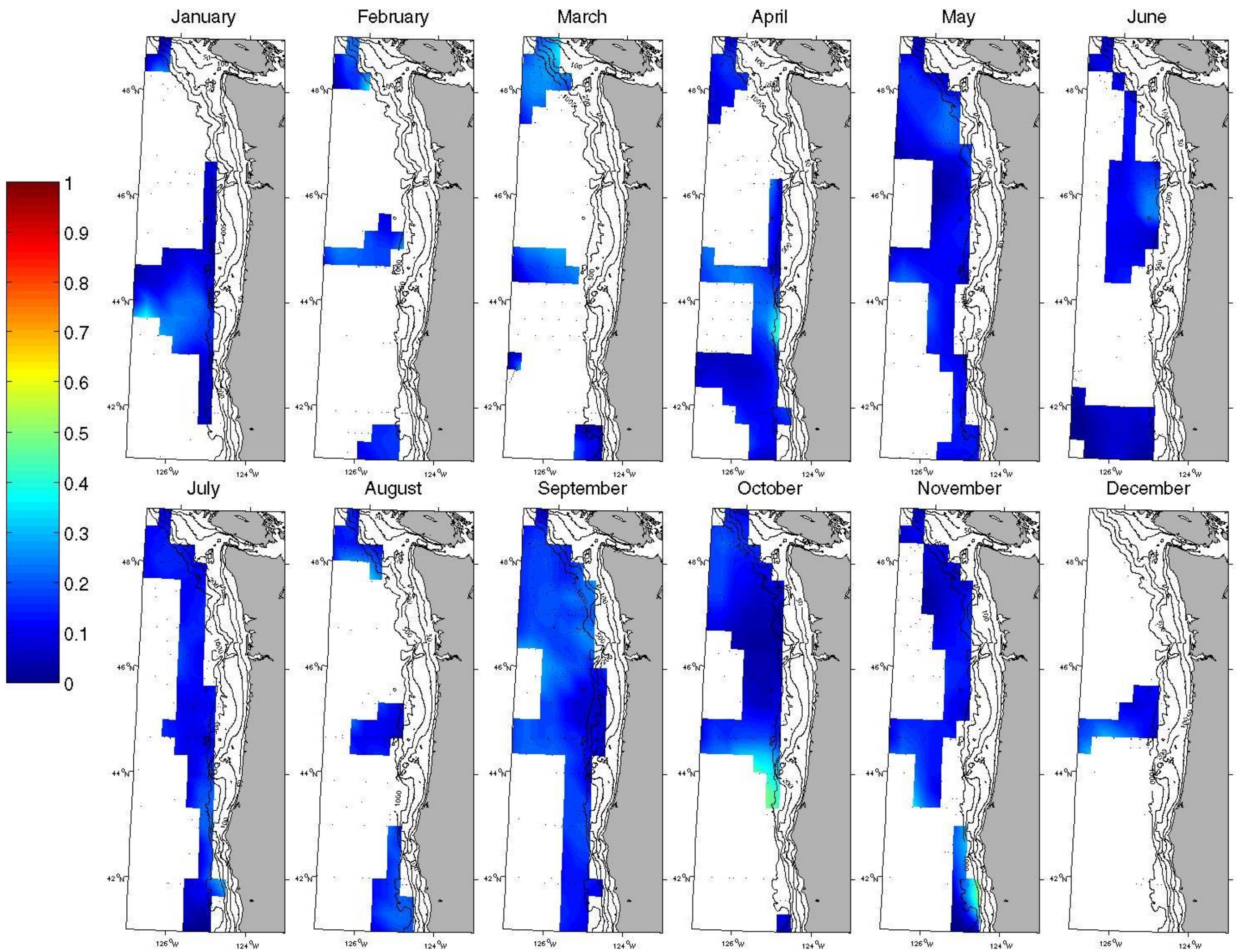

Figure 11-2 Climatological monthly standard deviations for temperature at 500 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

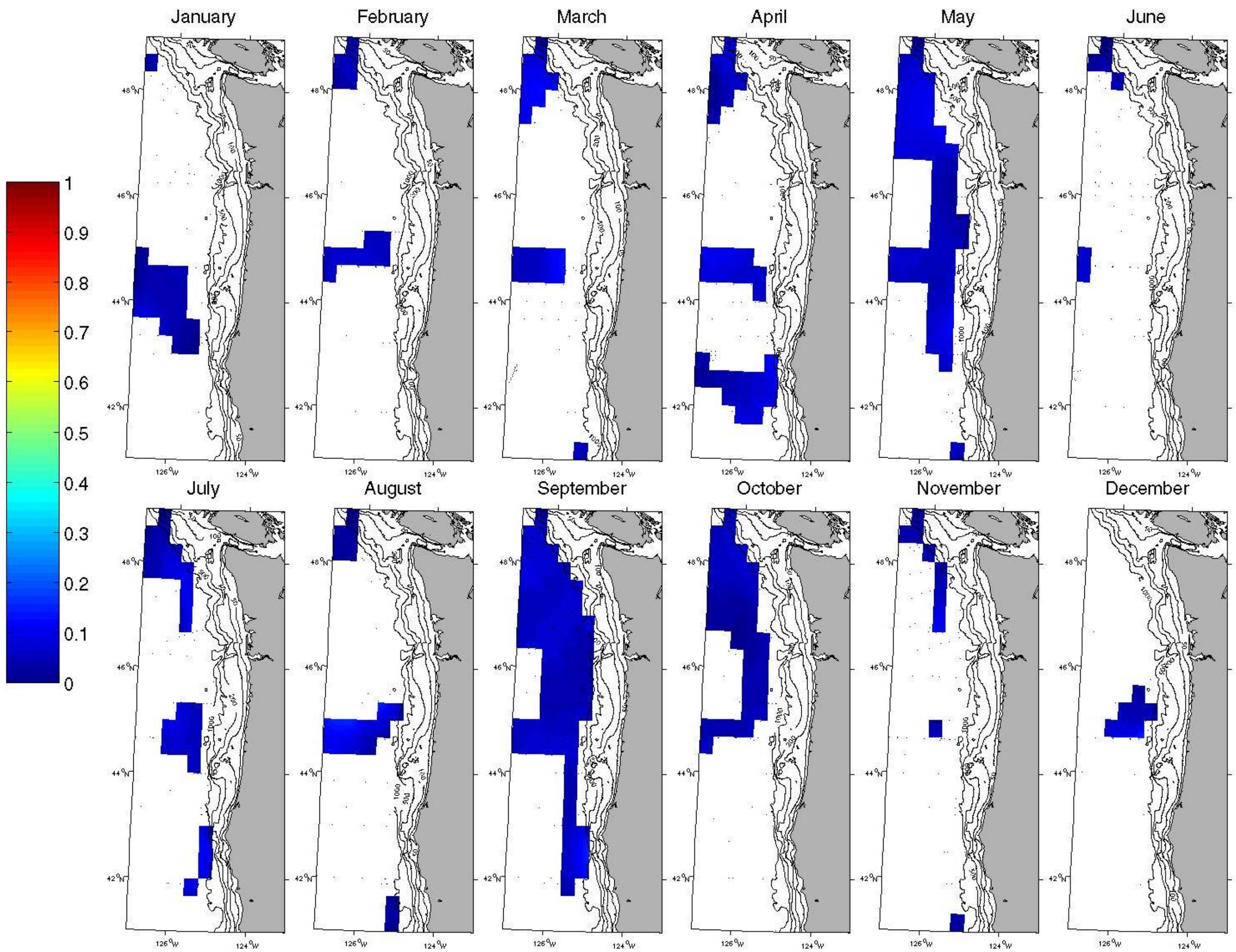

Figure 11-3 Climatological monthly standard deviations for temperature at 1000 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

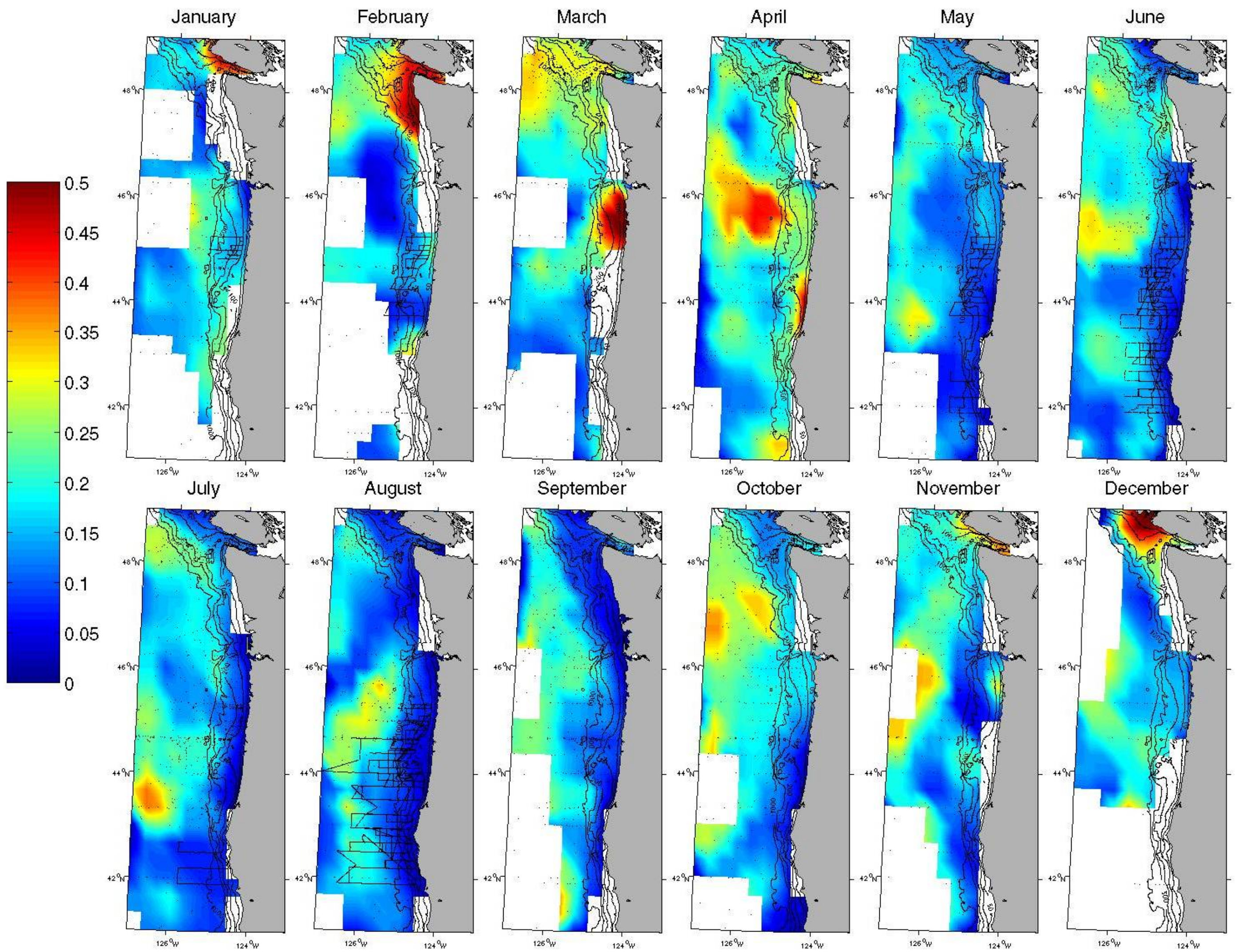

Figure 11-4 Climatological monthly standard deviations for salinity at 100 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

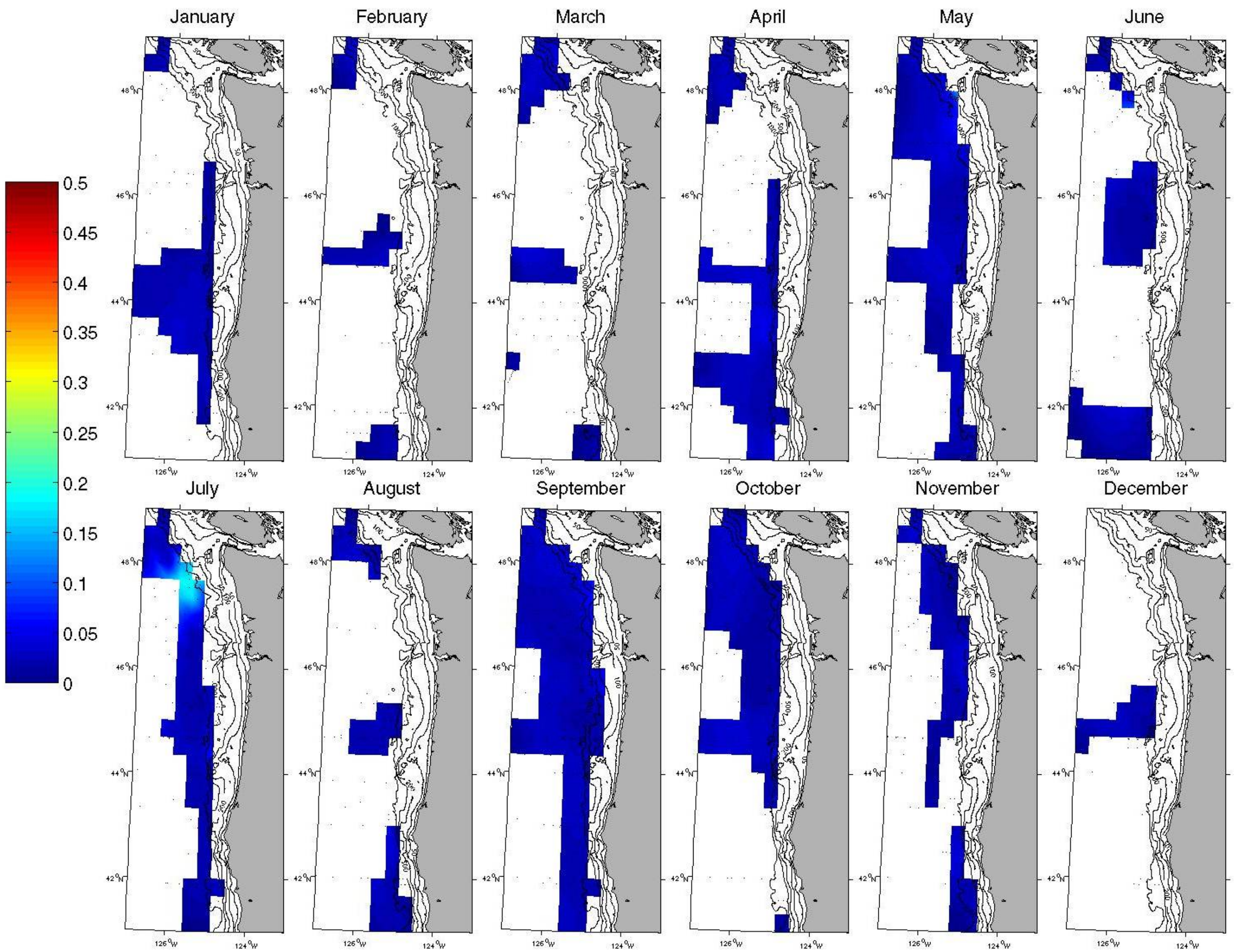

Figure 11-5 Climatological monthly standard deviations for salinity at 500 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

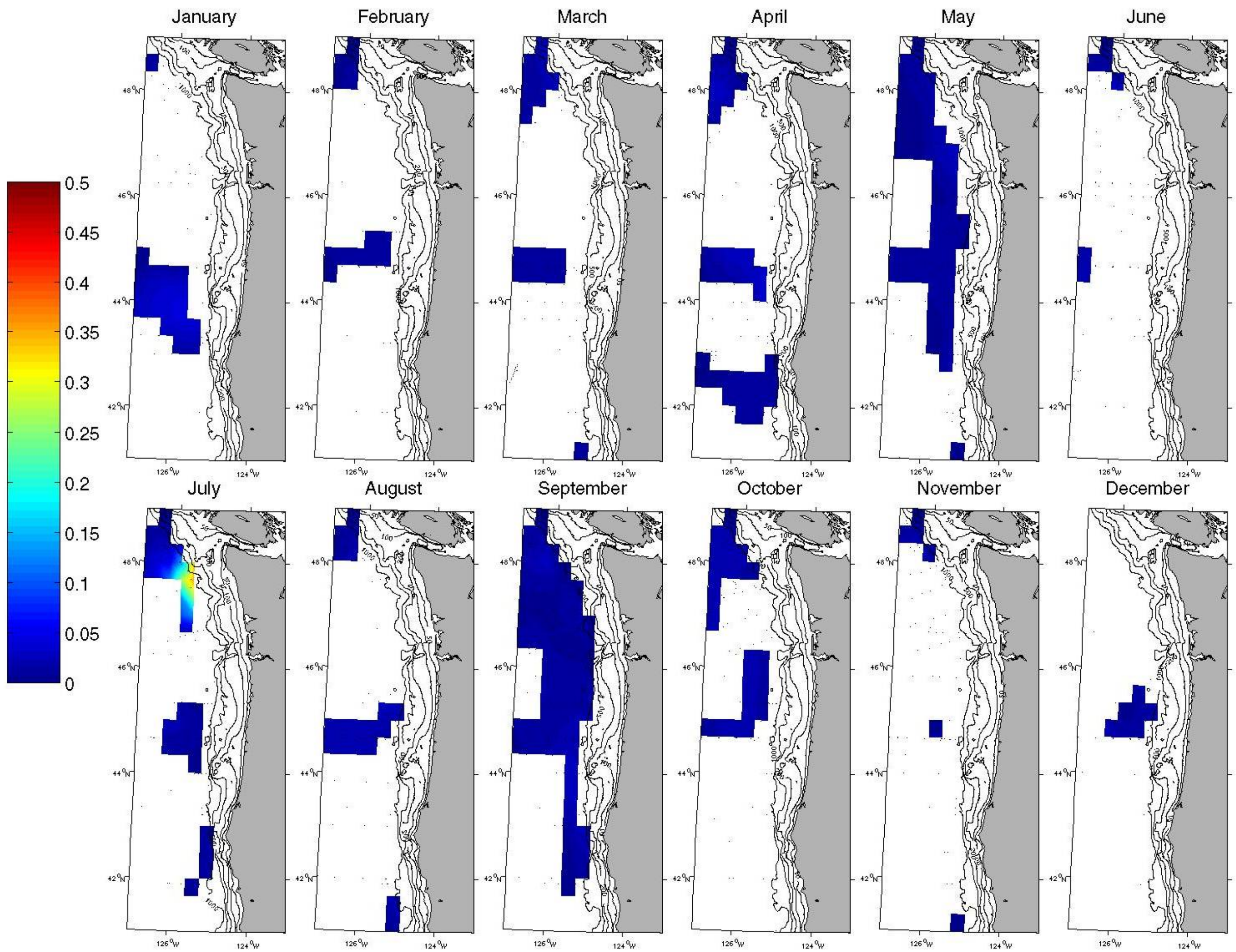

Figure 11-6 Climatological monthly standard deviations for salinity at 1000 m depths off the Washington and Oregon coasts from CTD cast observations (1930-2004).

12 APPENDIX 4 – CLIMATOLOGICAL COEFFICIENTS OF VARIATION

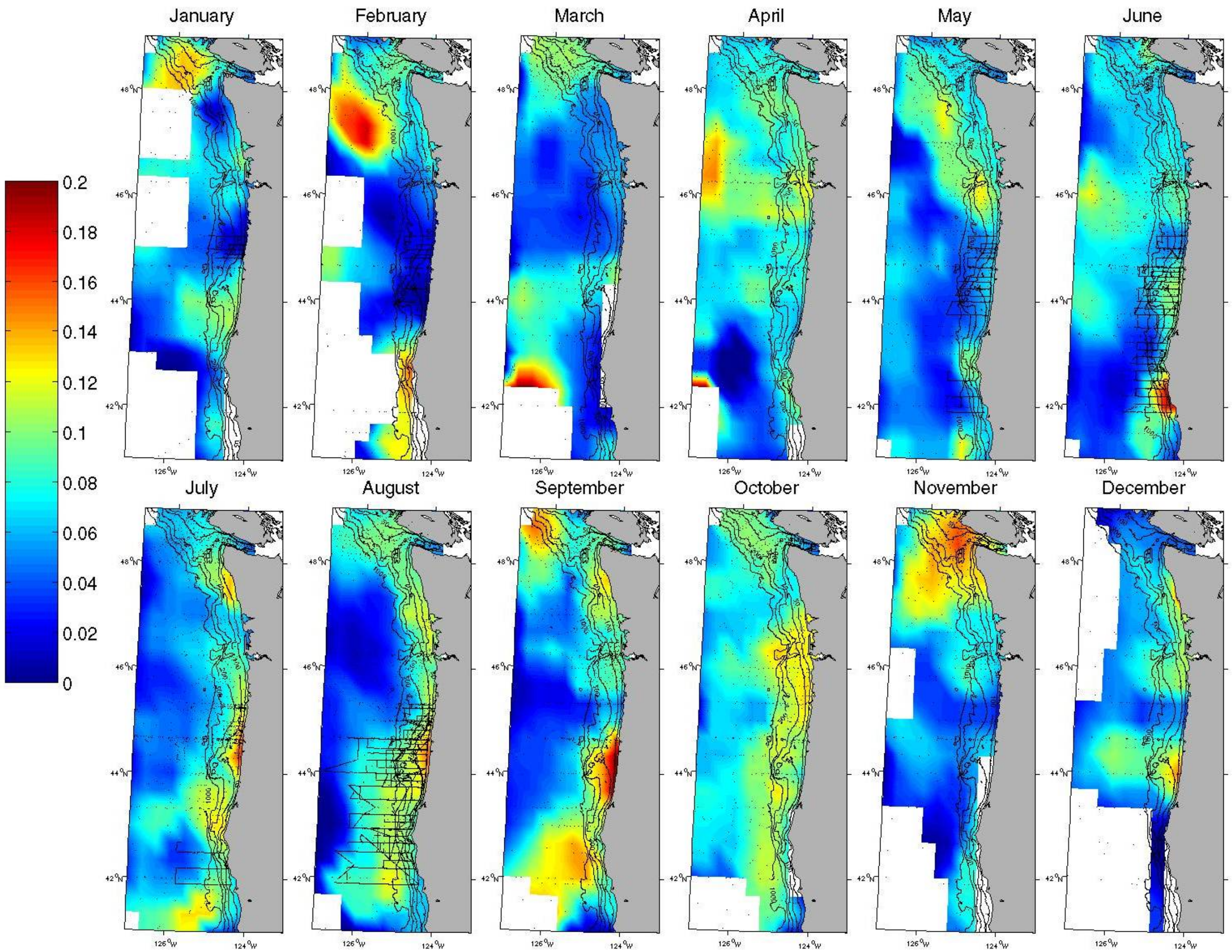

Figure 12-1 Climatological monthly coefficient of variations for temperature at the surface off the Washington and Oregon coasts from CTD cast observations (1930-2004).

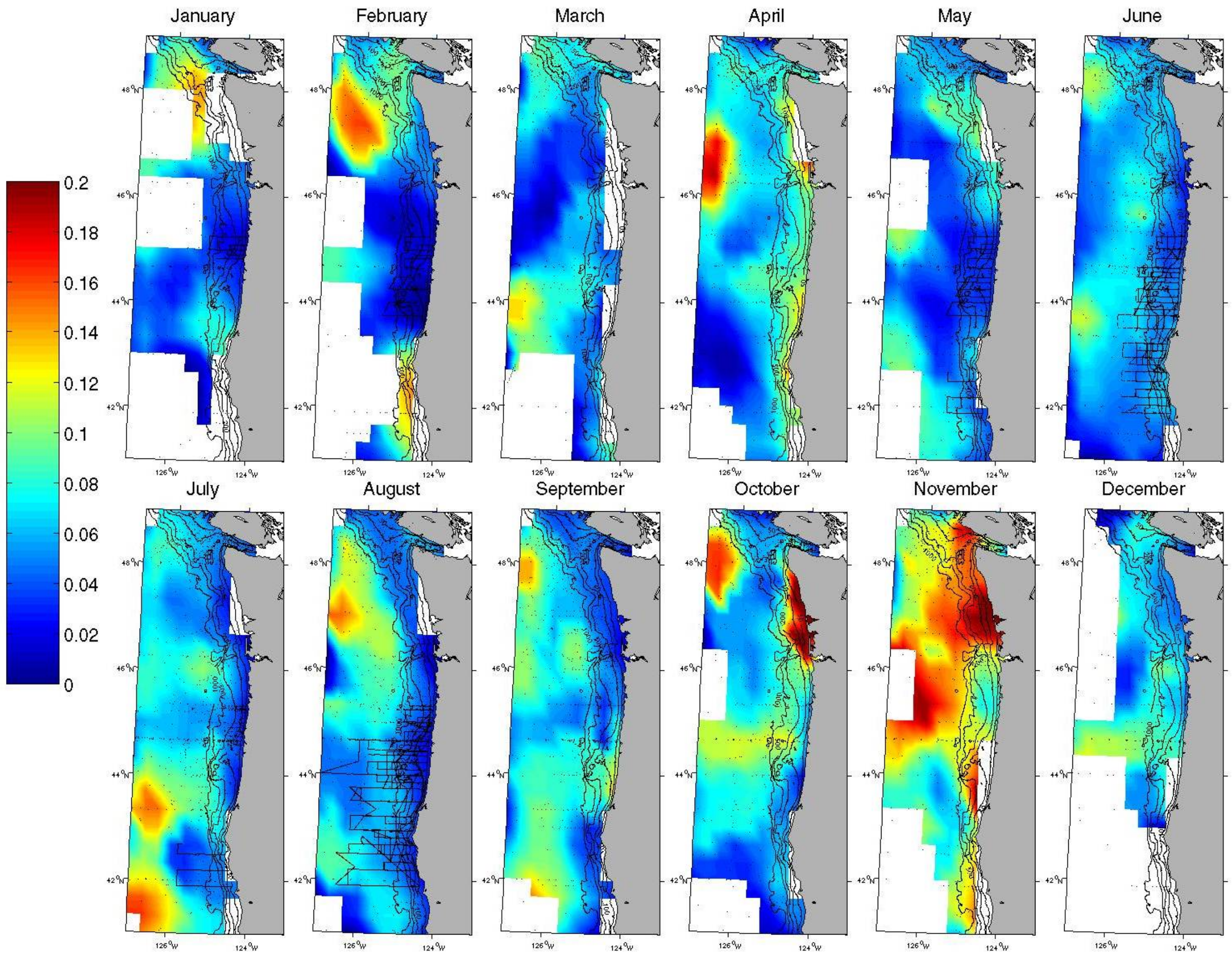

Figure 12-2 Climatological monthly coefficient of variations for temperature at 50 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

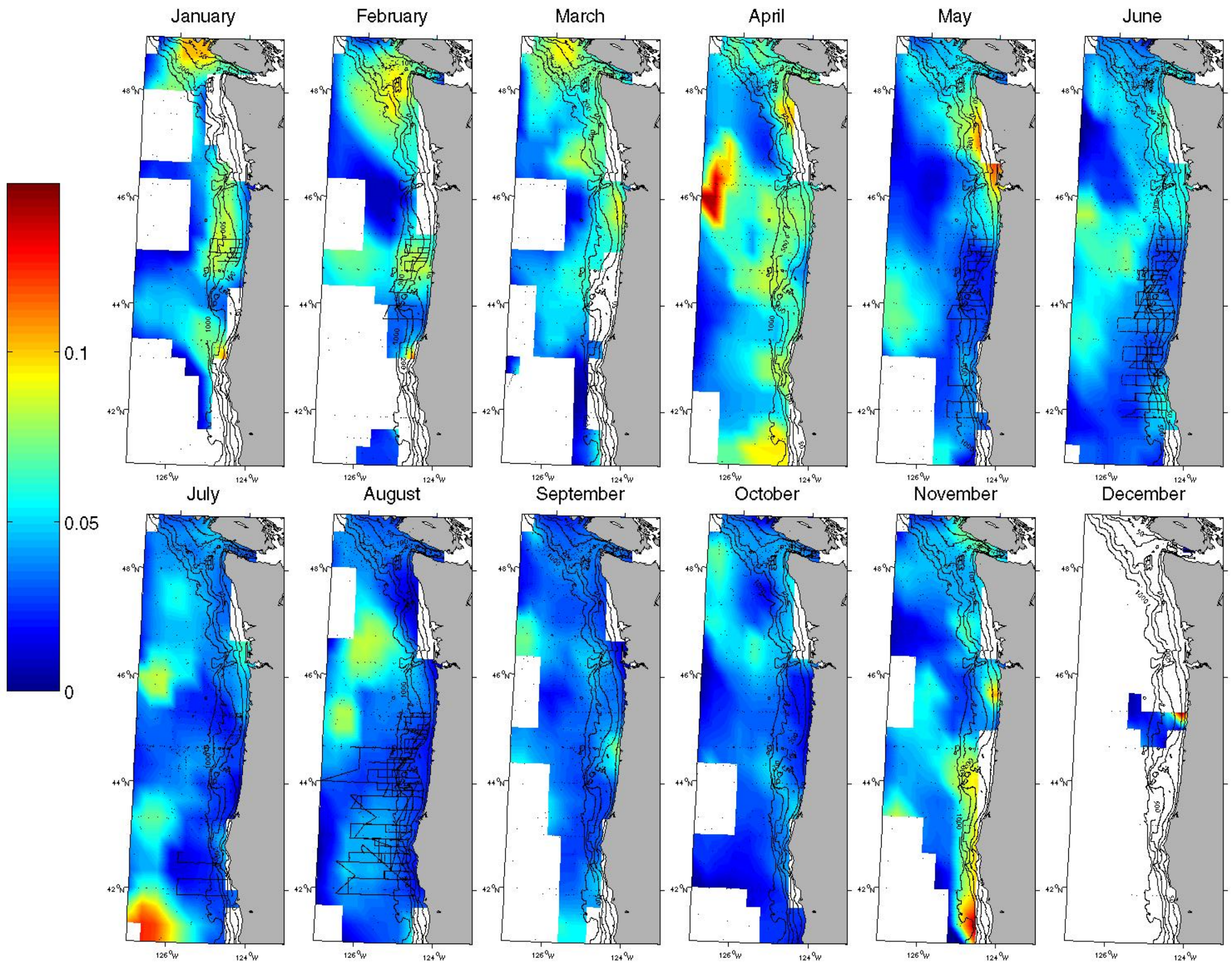

Figure 12-3 Climatological monthly coefficient of variations for temperature at 100 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

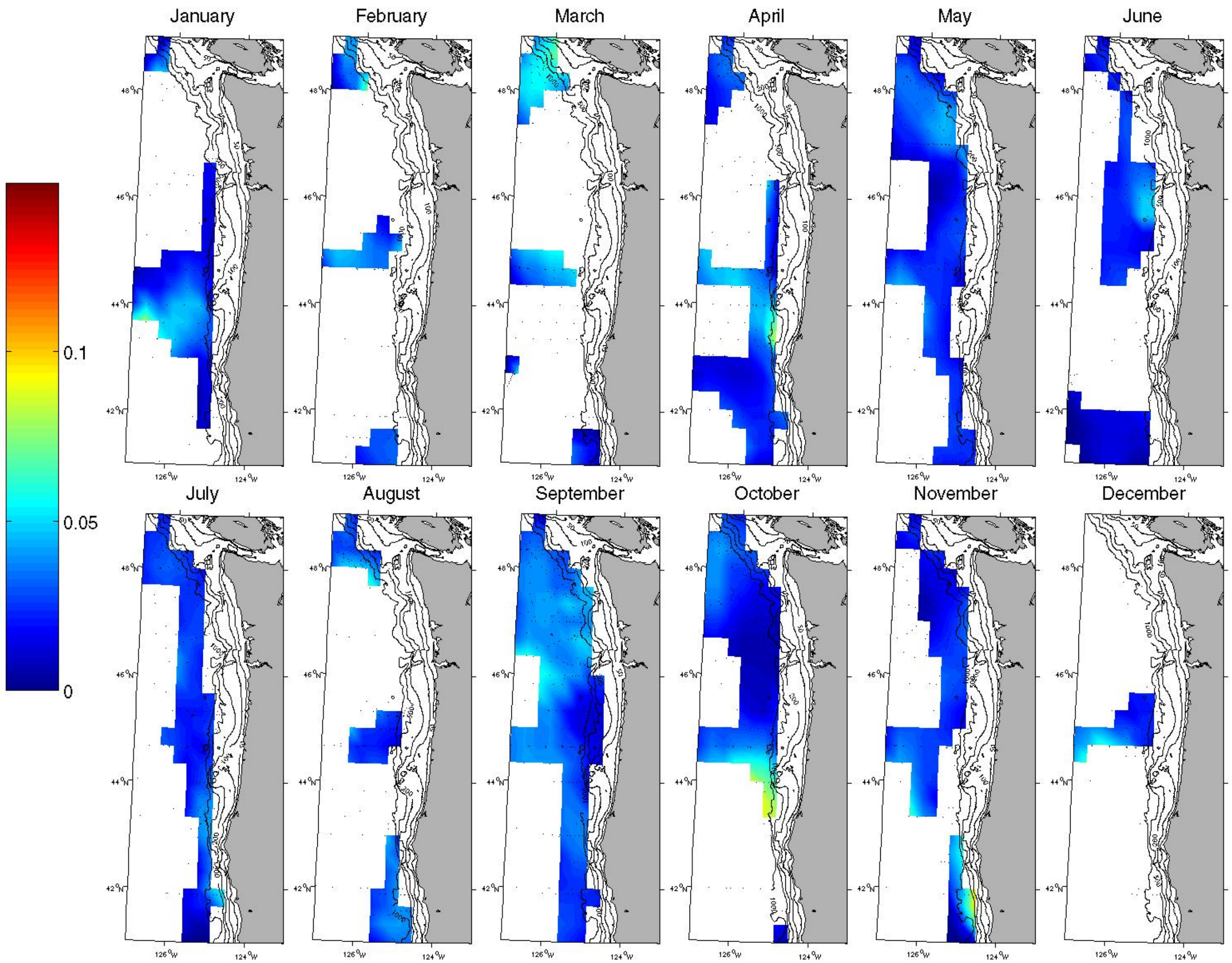

Figure 12-4 Climatological monthly coefficient of variations for temperature at 500 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

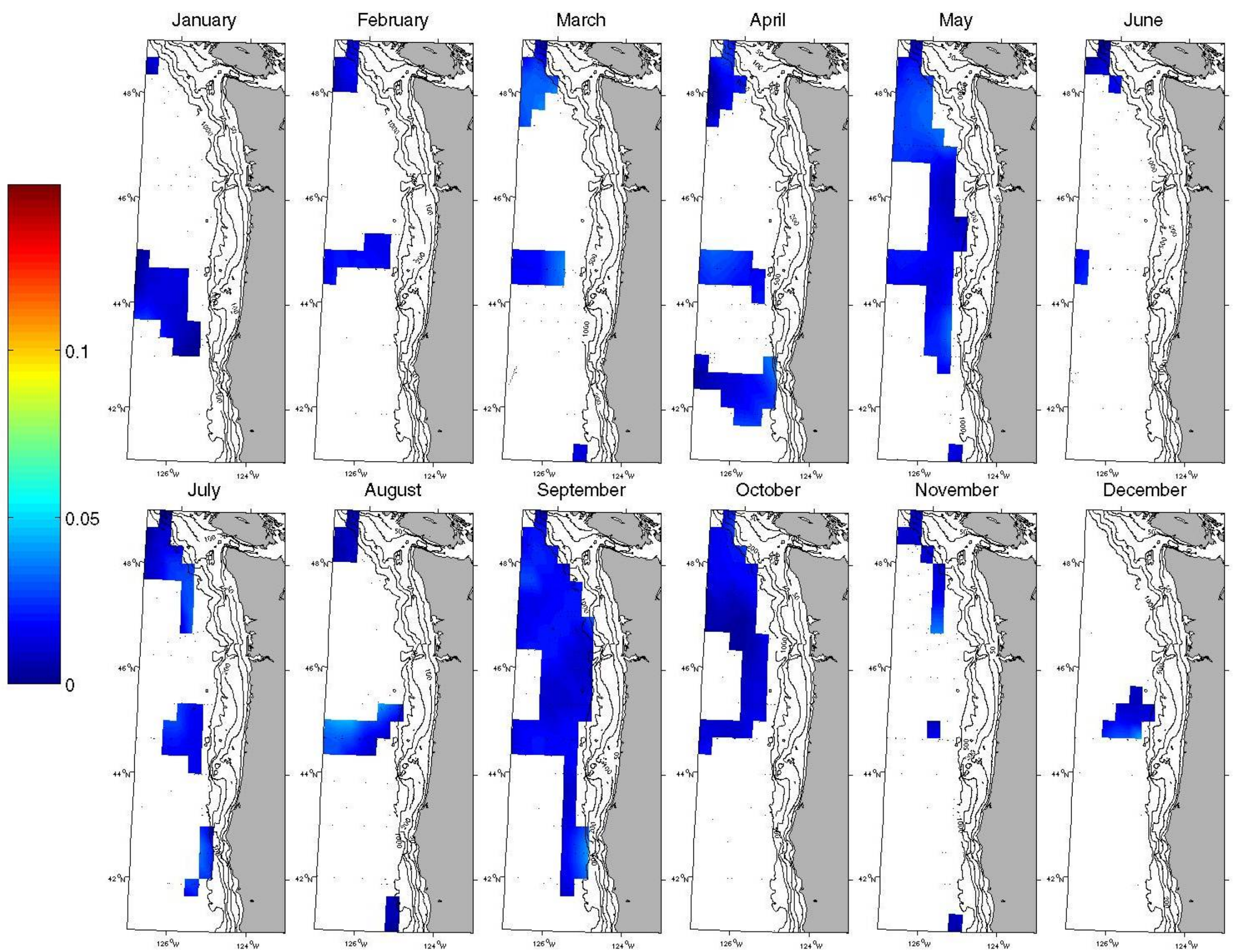

Figure 12-5 Climatological monthly coefficient of variations for temperature at 1000 m depth off the Washington and Oregon coasts from CTD cast observations (1930-2004).

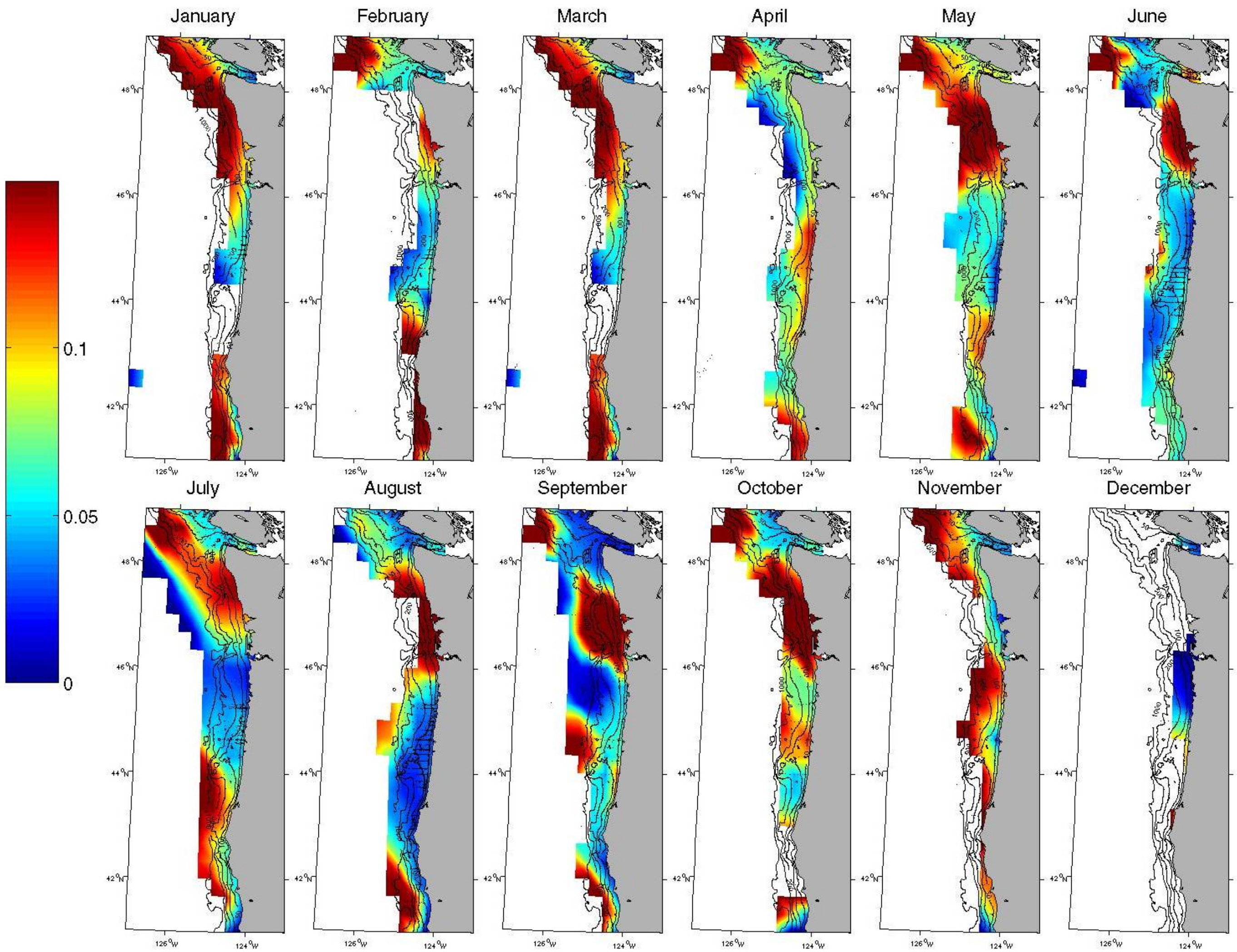

Figure 12-6 Climatological monthly coefficient of variations for temperature at the bottom of the seafloor off the Washington and Oregon coasts from CTD cast observations (1930-2004).

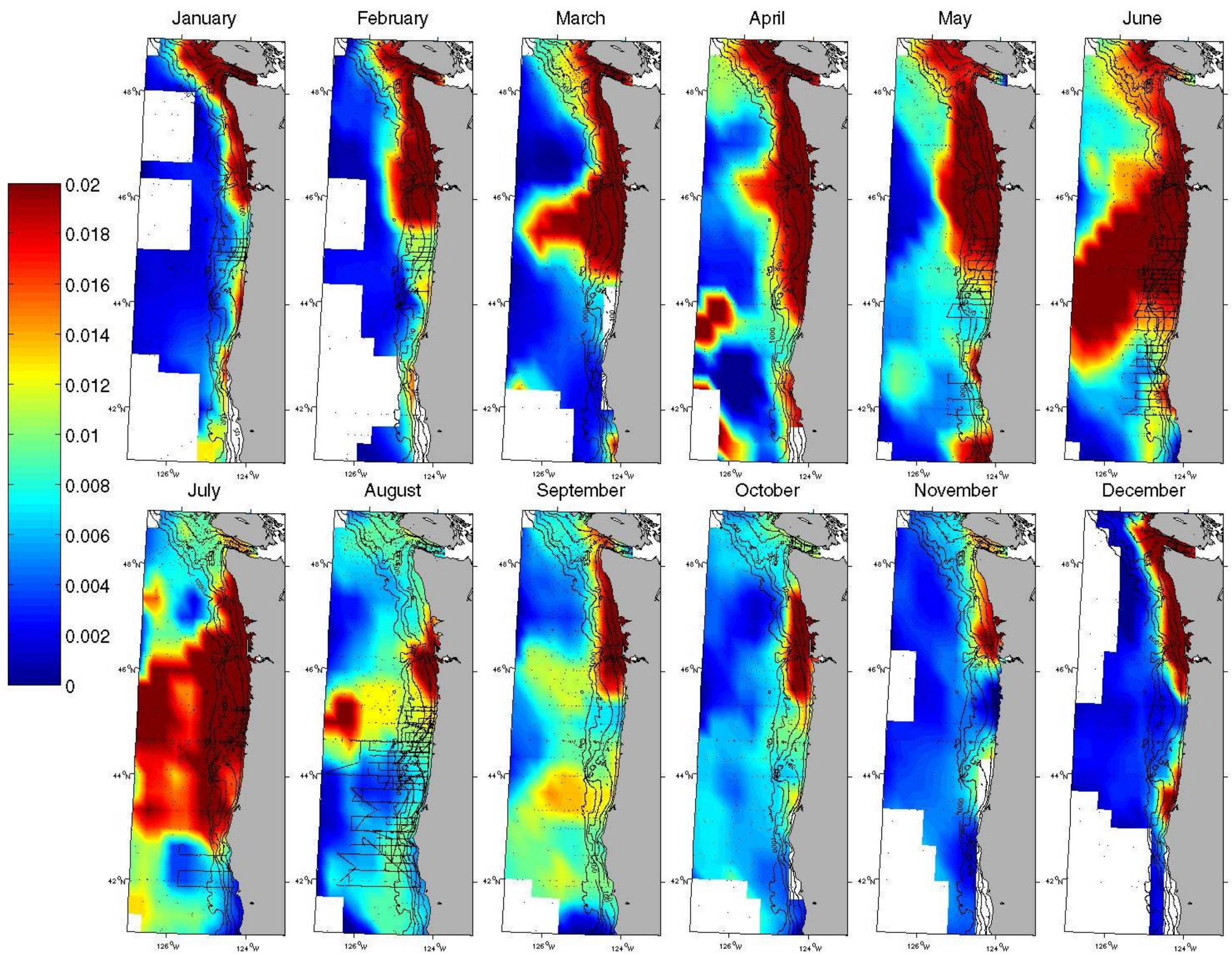

Figure 12-7 Climatological monthly coefficient of variations for salinity at the surface off the Washington and Oregon coasts from CTD cast observations (1930-2004).

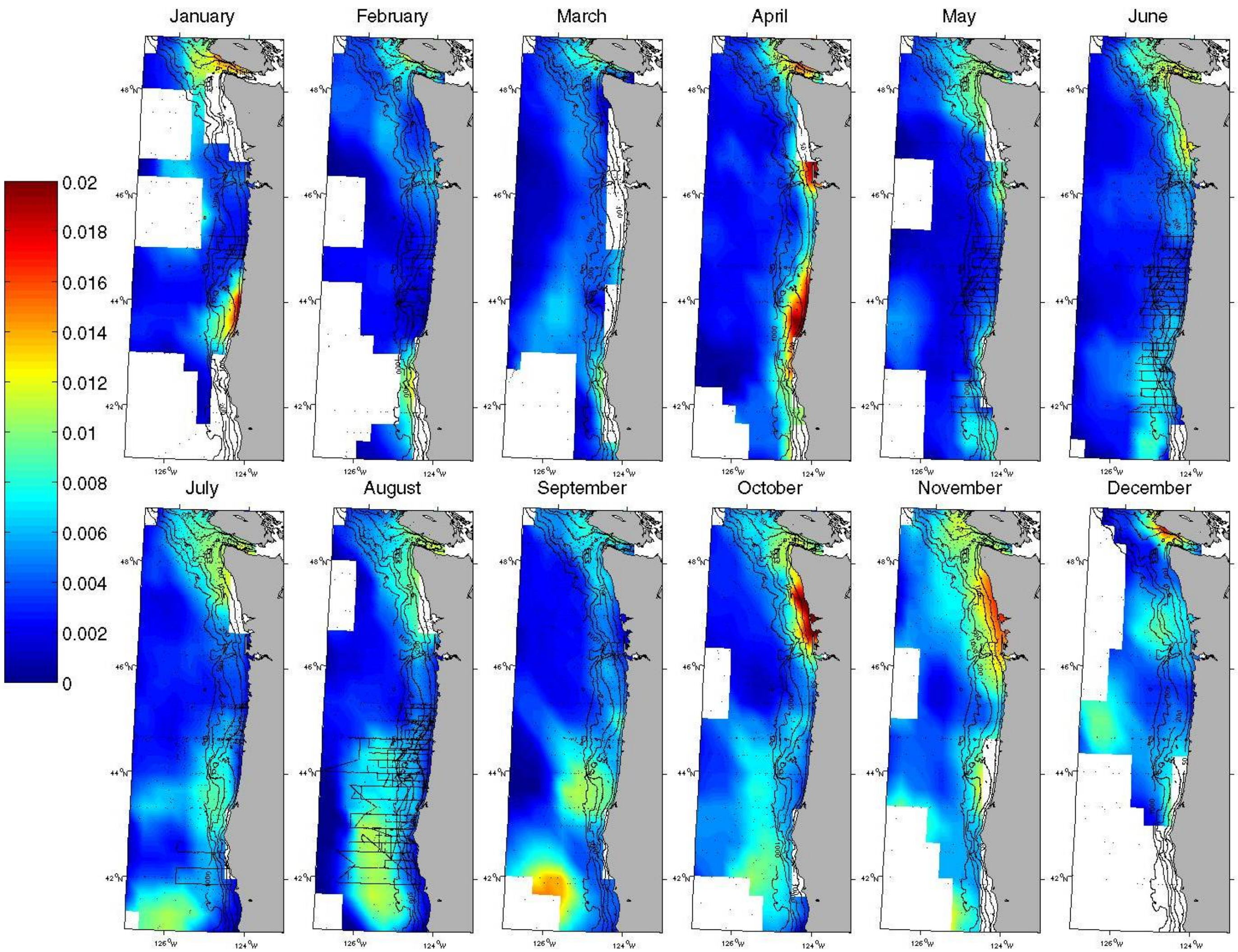

Figure 12-8 Climatological monthly coefficient of variations for salinity at 50m off the Washington and Oregon coasts from CTD cast observations (1930-2004).

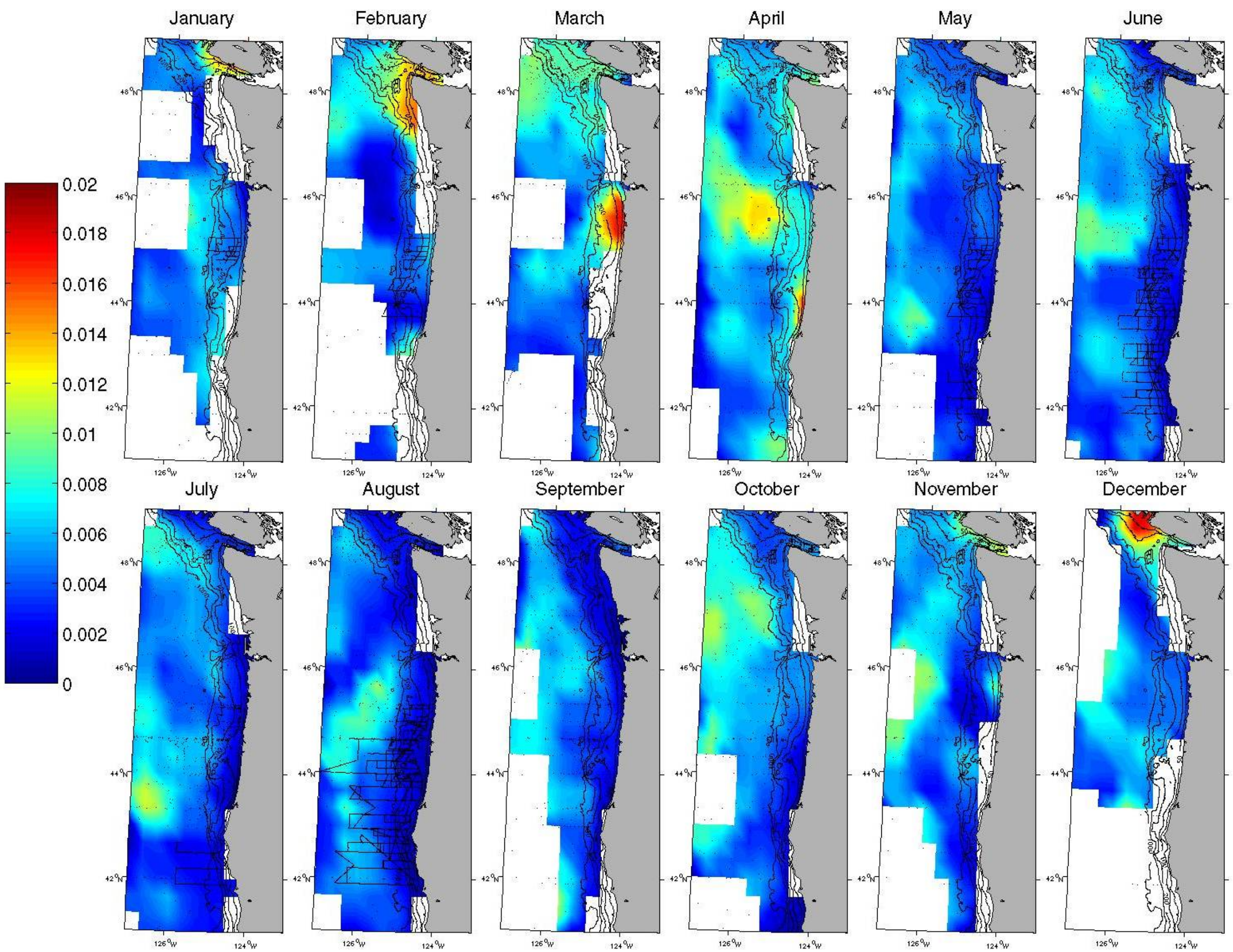

Figure 12-9 Climatological monthly coefficient of variations for salinity at 100m off the Washington and Oregon coasts from CTD cast observations (1930-2004).

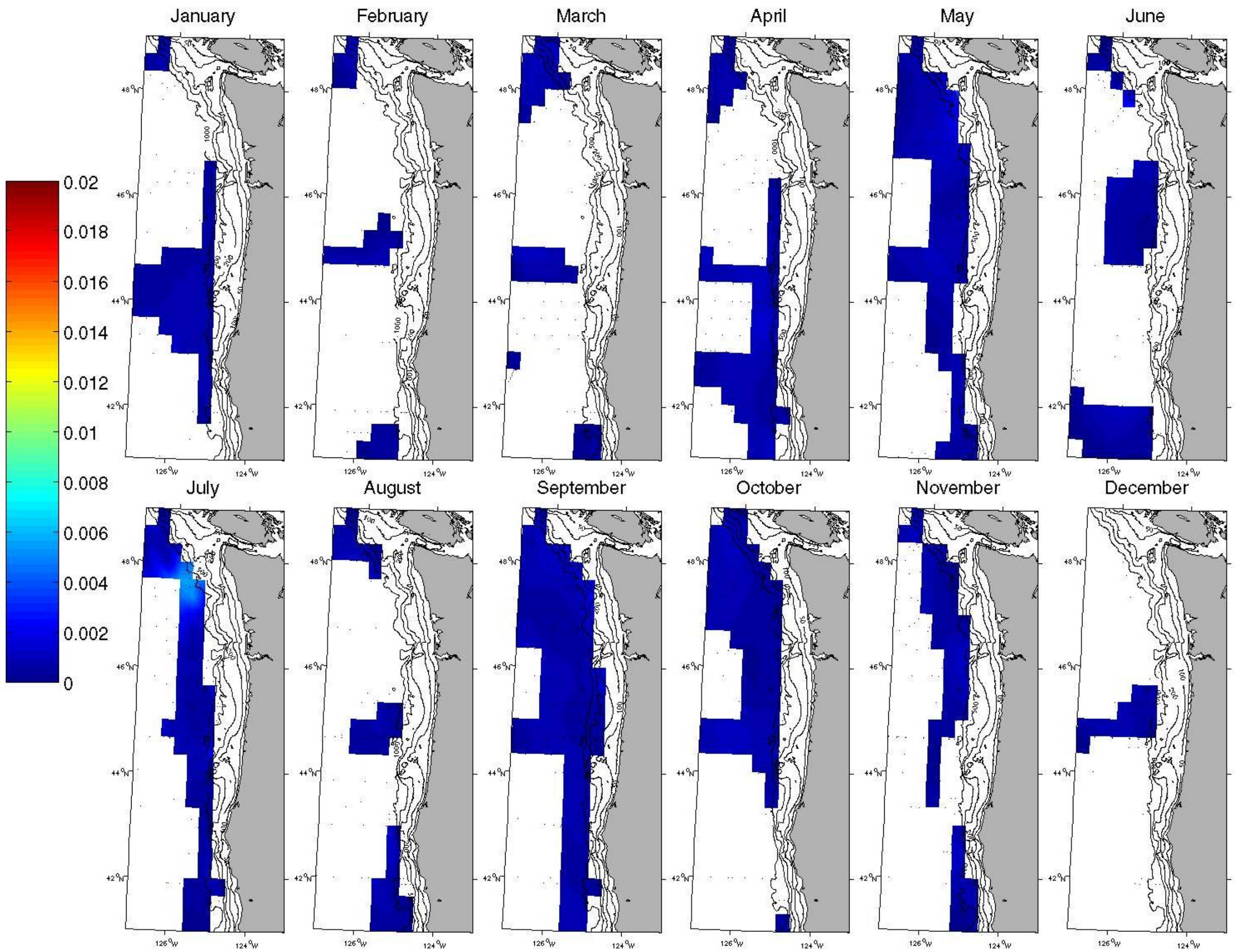

Figure 12-10 Climatological monthly coefficient of variations for salinity at 500m off the Washington and Oregon coasts from CTD cast observations (1930-2004).

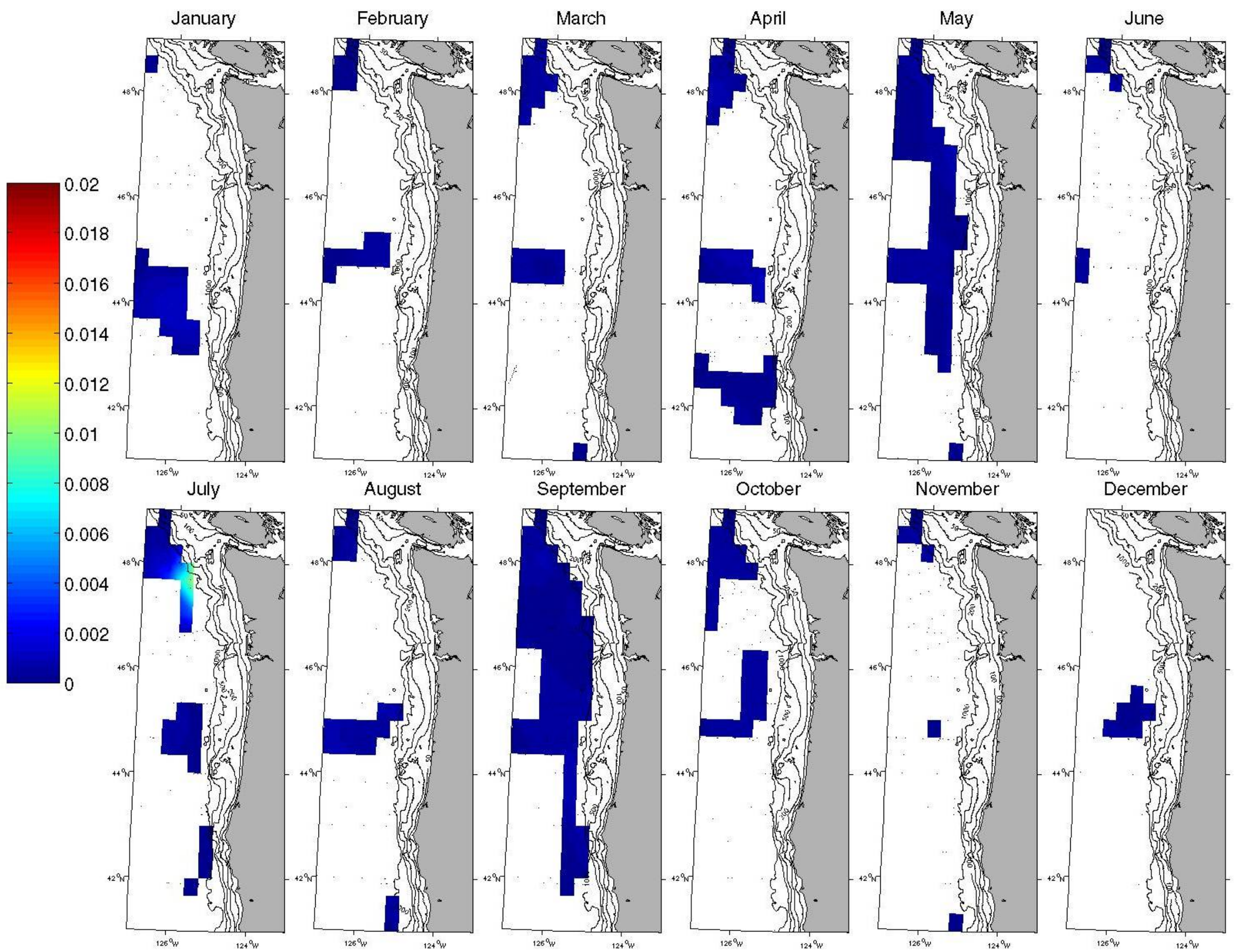

Figure 12-11 Climatological monthly coefficient of variations for salinity at 1000m off the Washington and Oregon coasts from CTD cast observations (1930-2004).

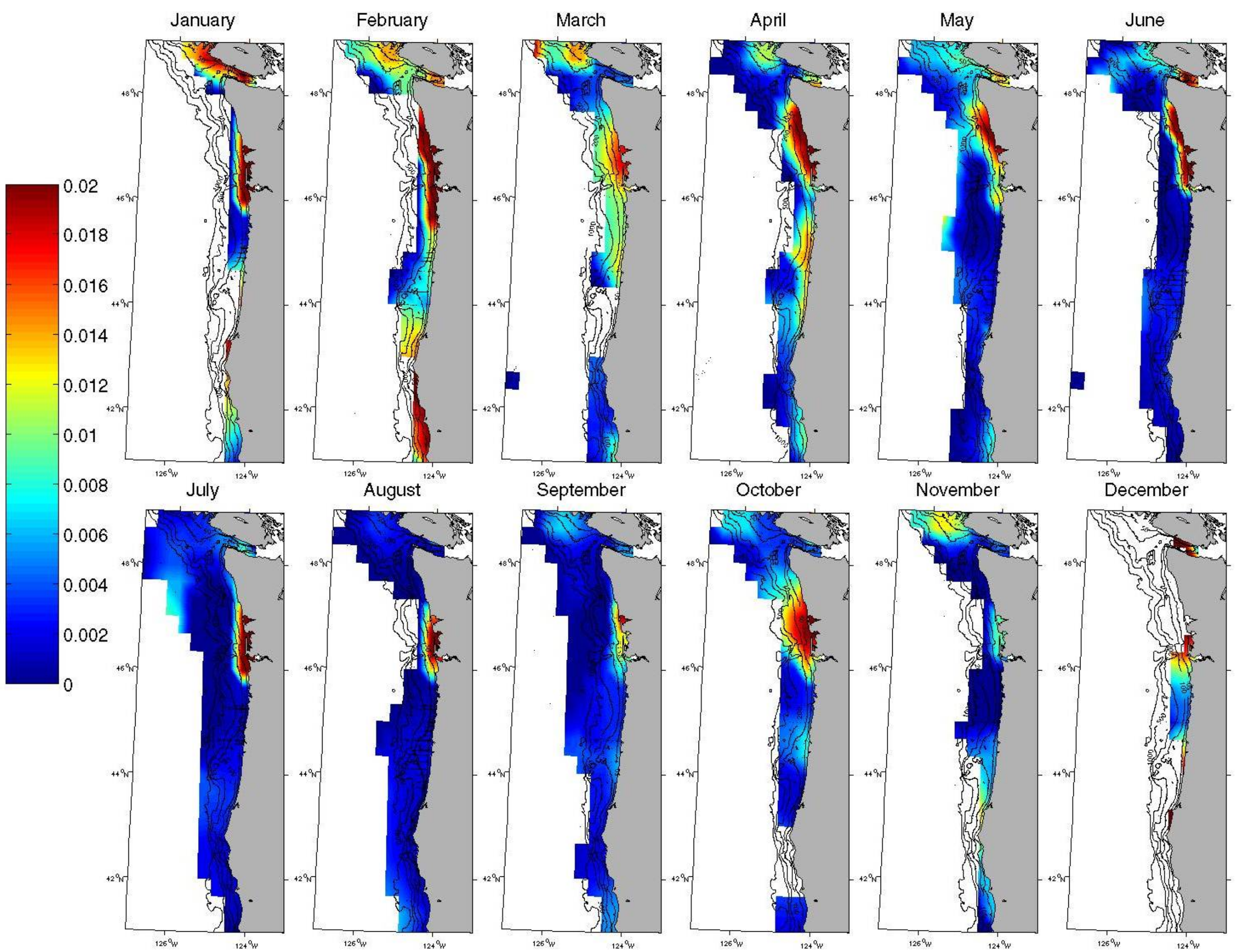

Figure 12-12 Climatological monthly coefficient of variations for salinity at the bottom off the Washington and Oregon coasts from CTD cast observations (1930-2004).

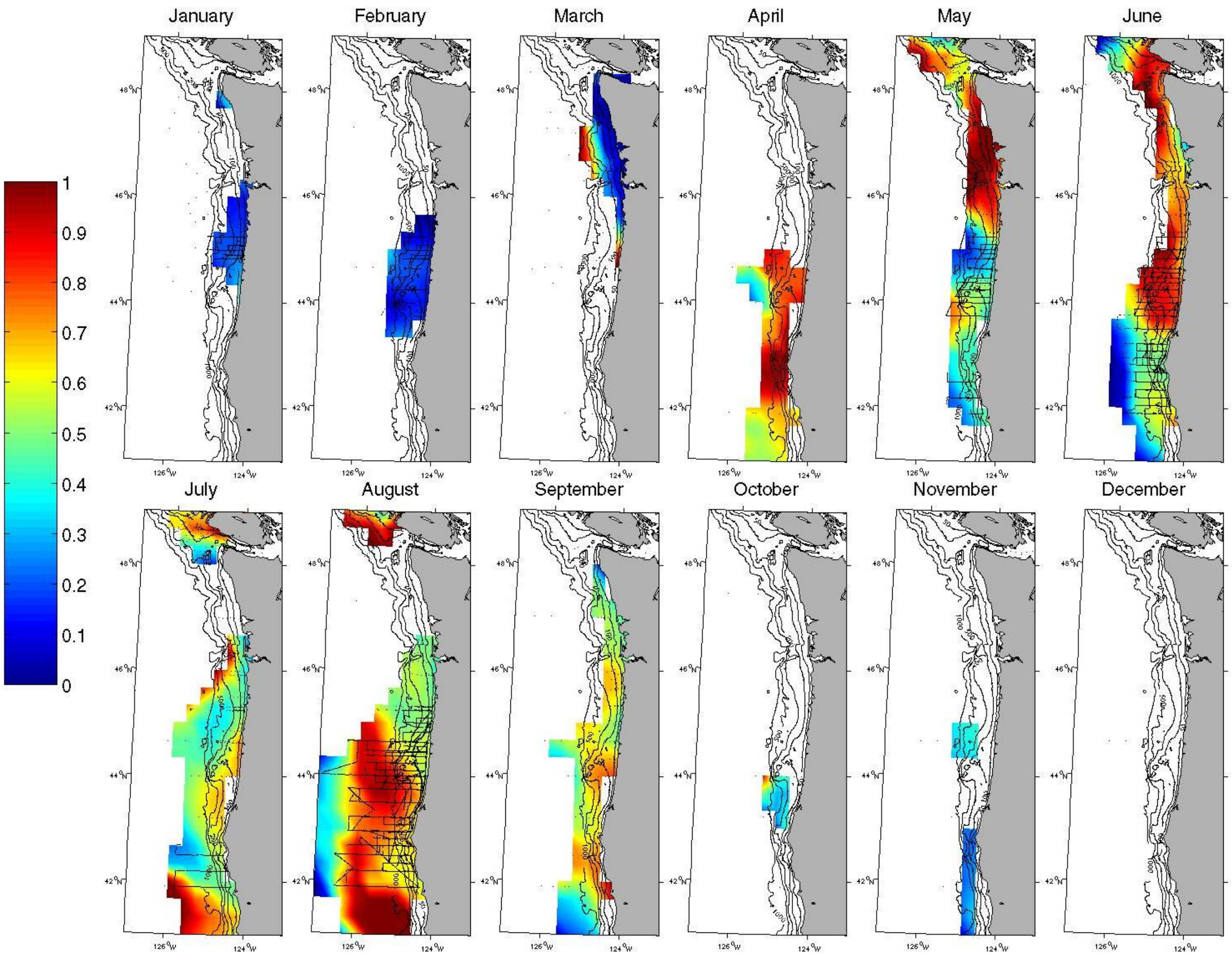

Figure 12-13 Climatological monthly coefficient of variations for Chlorophyll-a at the surface off the Washington and Oregon coast from fluorometers and Niskin bottle samples (1950-2004).

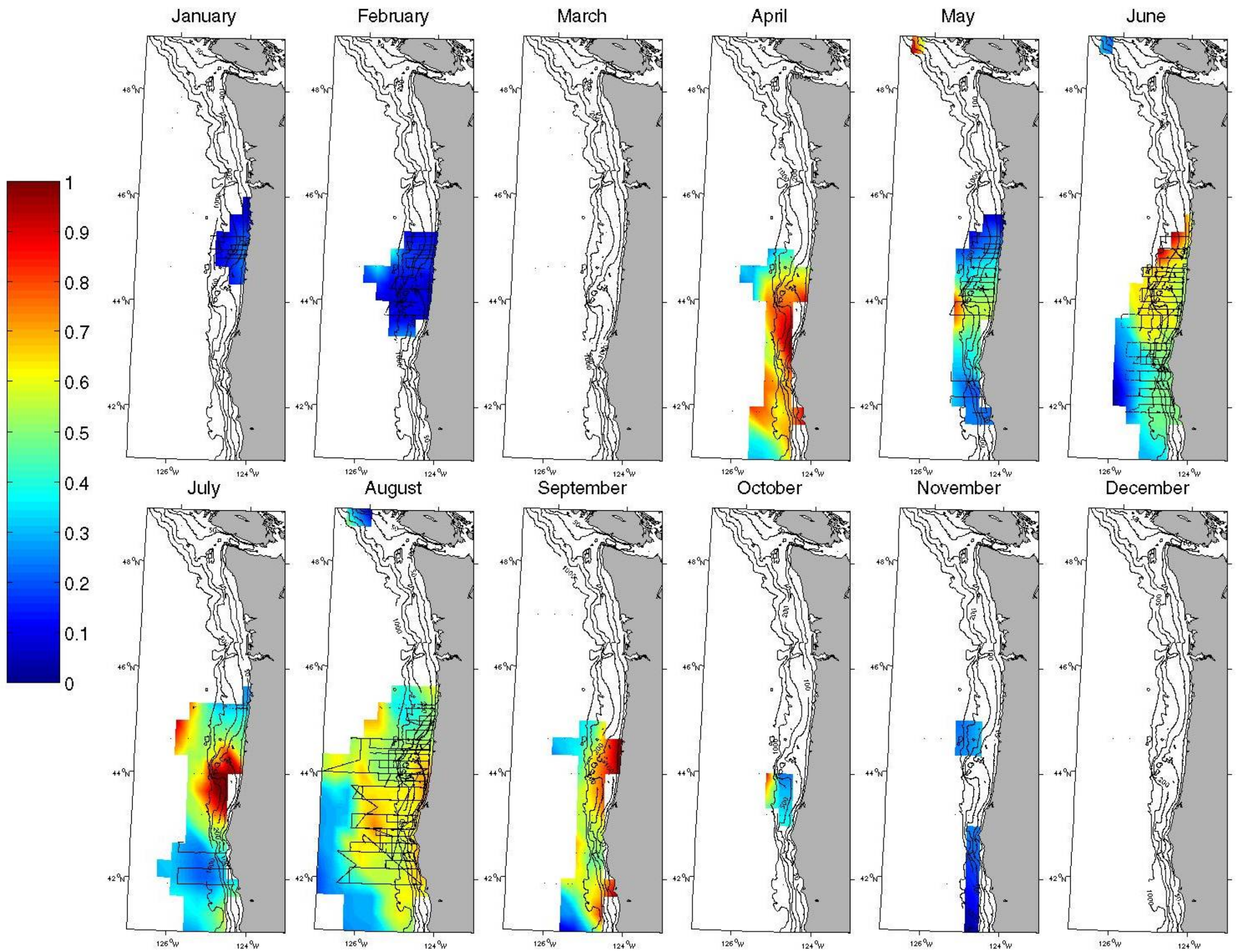

Figure 12-14 Climatological monthly coefficient of variations for Chlorophyll-a at 20-30 m off the Washington and Oregon coast from fluorometers and Niskin bottle samples (1950-2004).

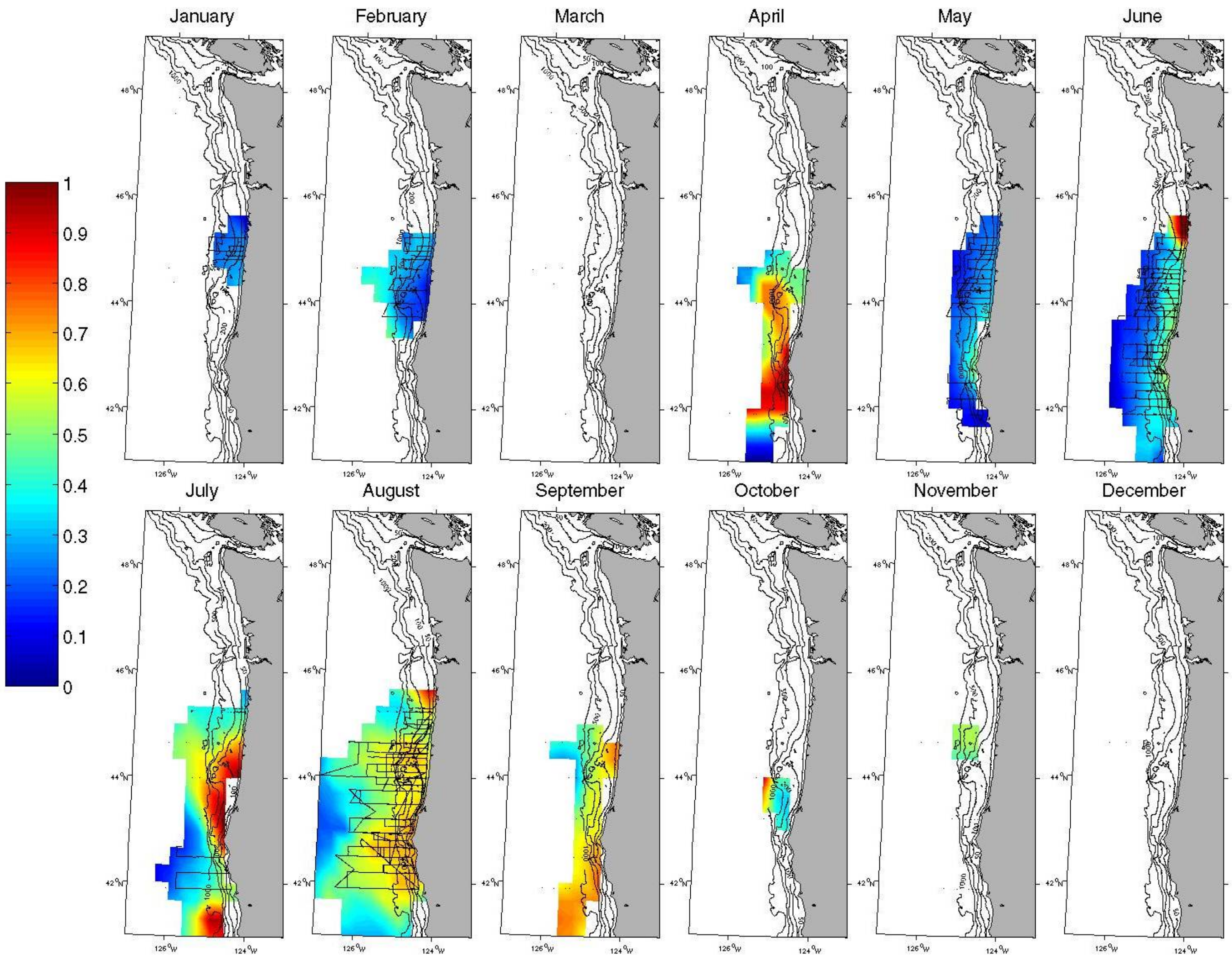

Figure 12-15 Climatological monthly coefficient of variations for Chlorophyll-a at 40-50 m off the Washington and Oregon coast from fluorometers and Niskin bottle samples (1950-2004).

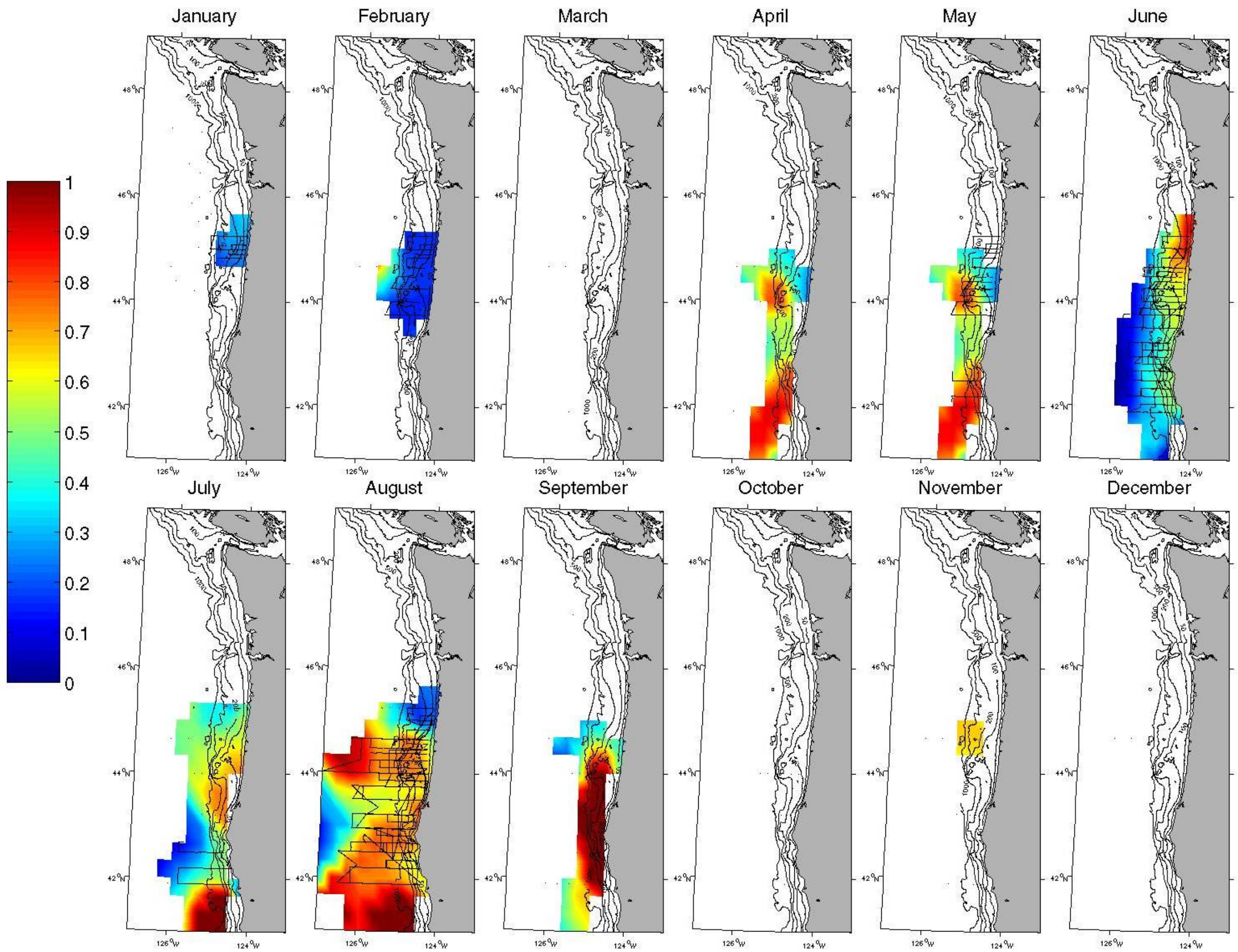

Figure 12-16 Climatological monthly coefficient of variations for Chlorophyll-a at 60-70 m off the Washington and Oregon coast from fluorometers and Niskin bottle samples (1950-2004).

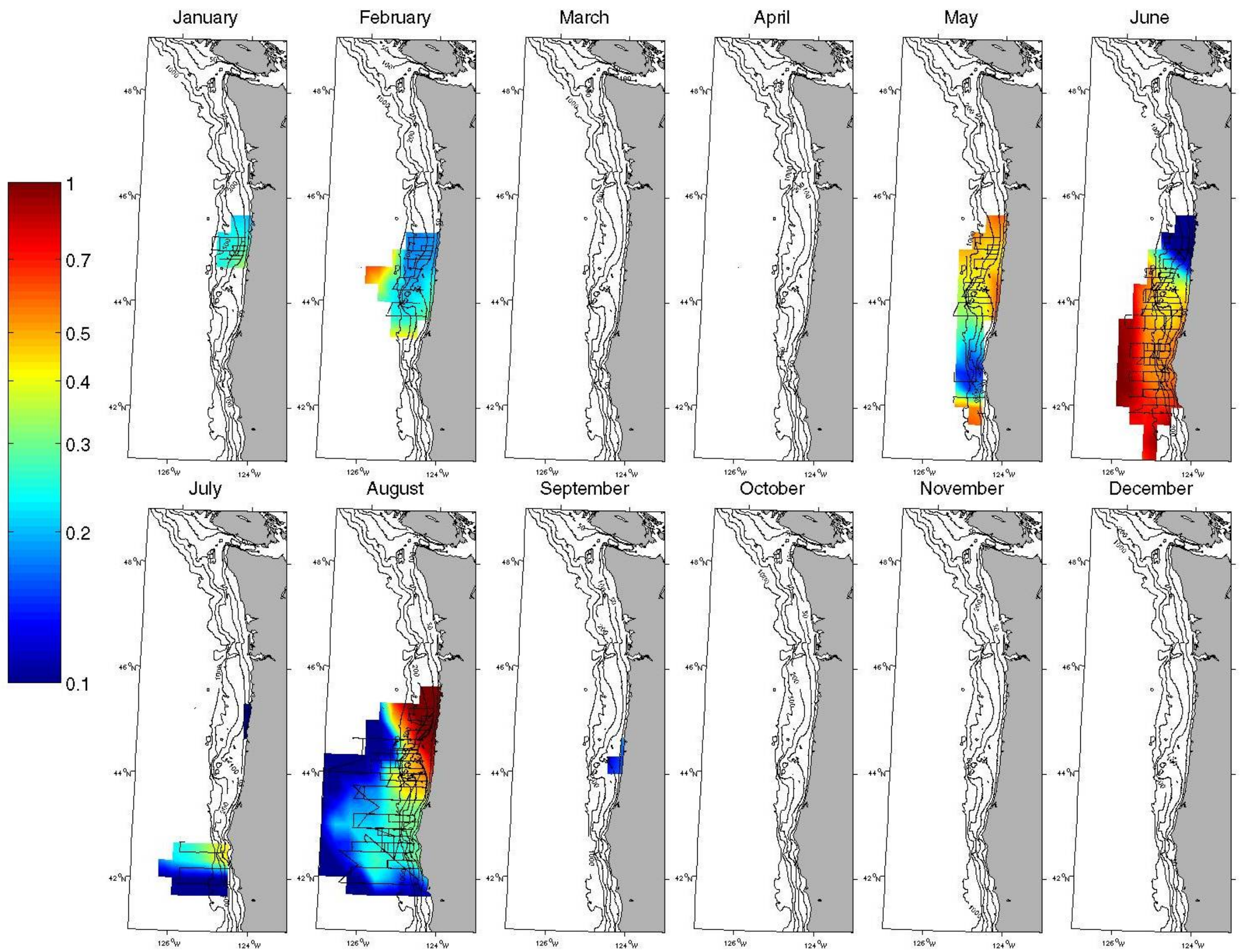

Figure 12-17 Climatological monthly coefficient of variations for Chlorophyll-a at 80-90 m off the Washington and Oregon coast from fluorometers and Niskin bottle samples (1950-2004).

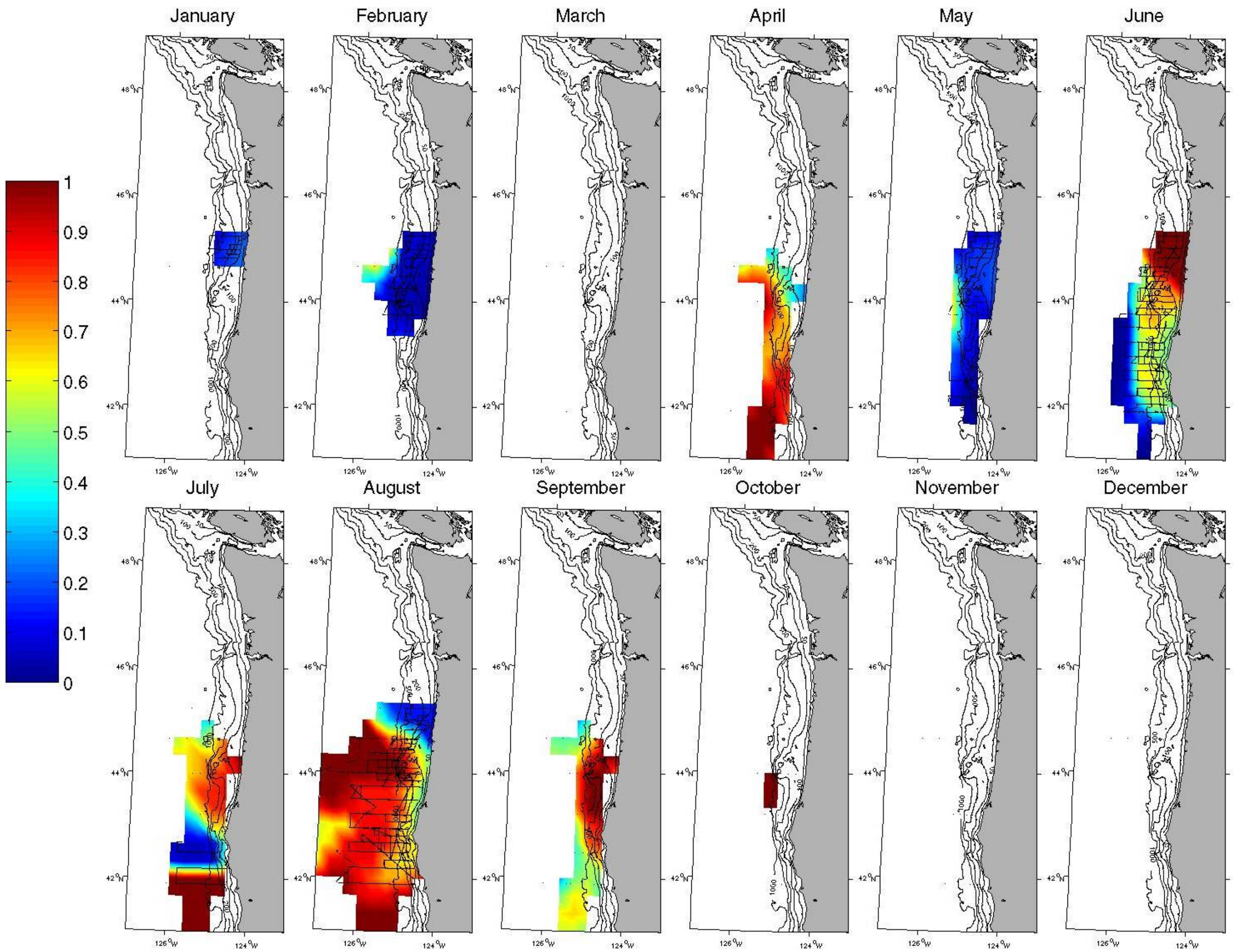

Figure 12-18 Climatological monthly coefficient of variations for Chlorophyll-a at 100-110 m off the Washington and Oregon coast from fluorometers and Niskin bottle samples (1950-2004).

13 APPENDIX 5 – VERTICAL SECTION OF VELOCITY

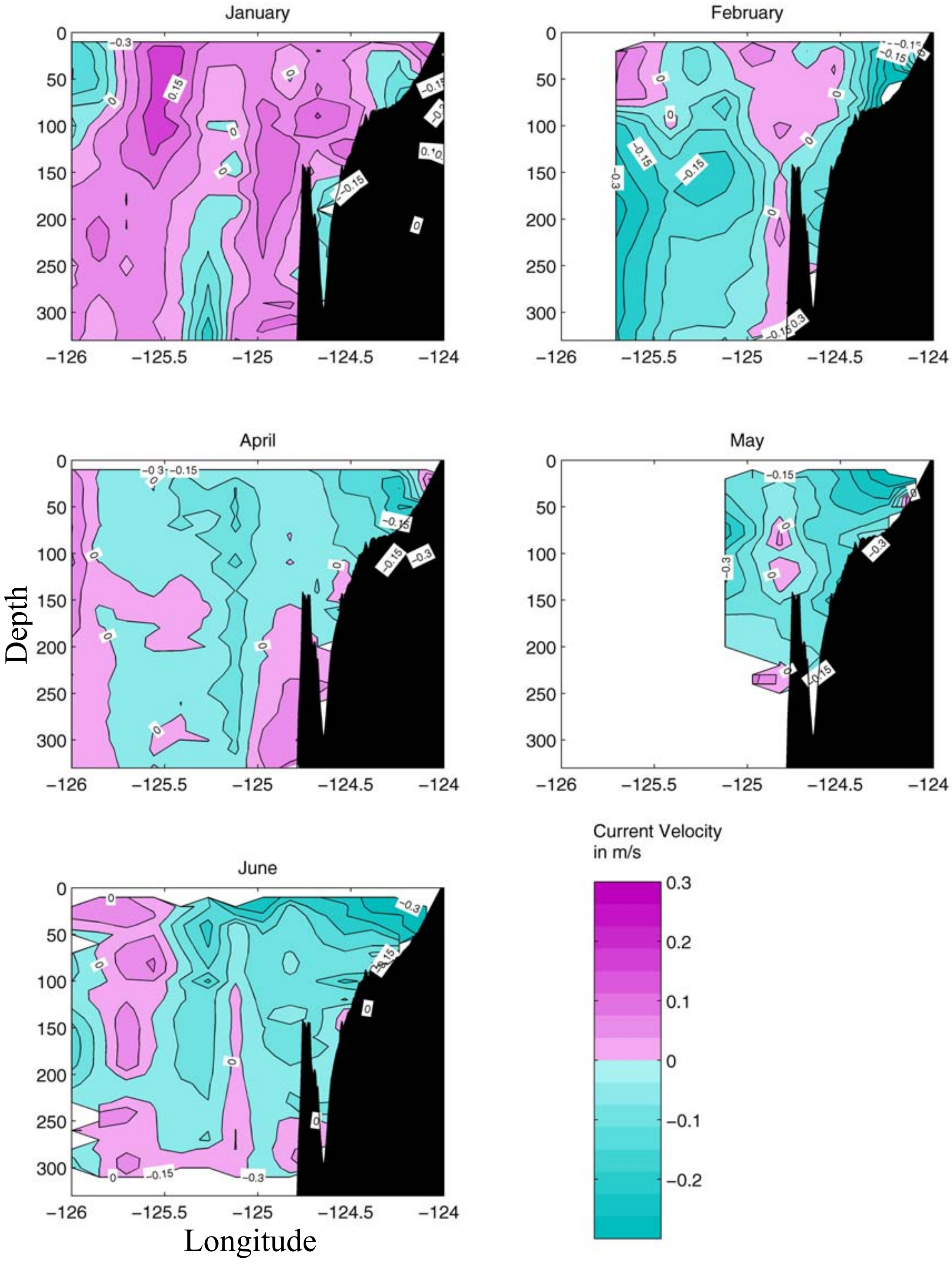

Figure 13-1 Vertical sections of climatological monthly means for current velocity at the Newport Hygrologic Line (North-South Component) from shipboard ADCP observations (from 1991-2004).

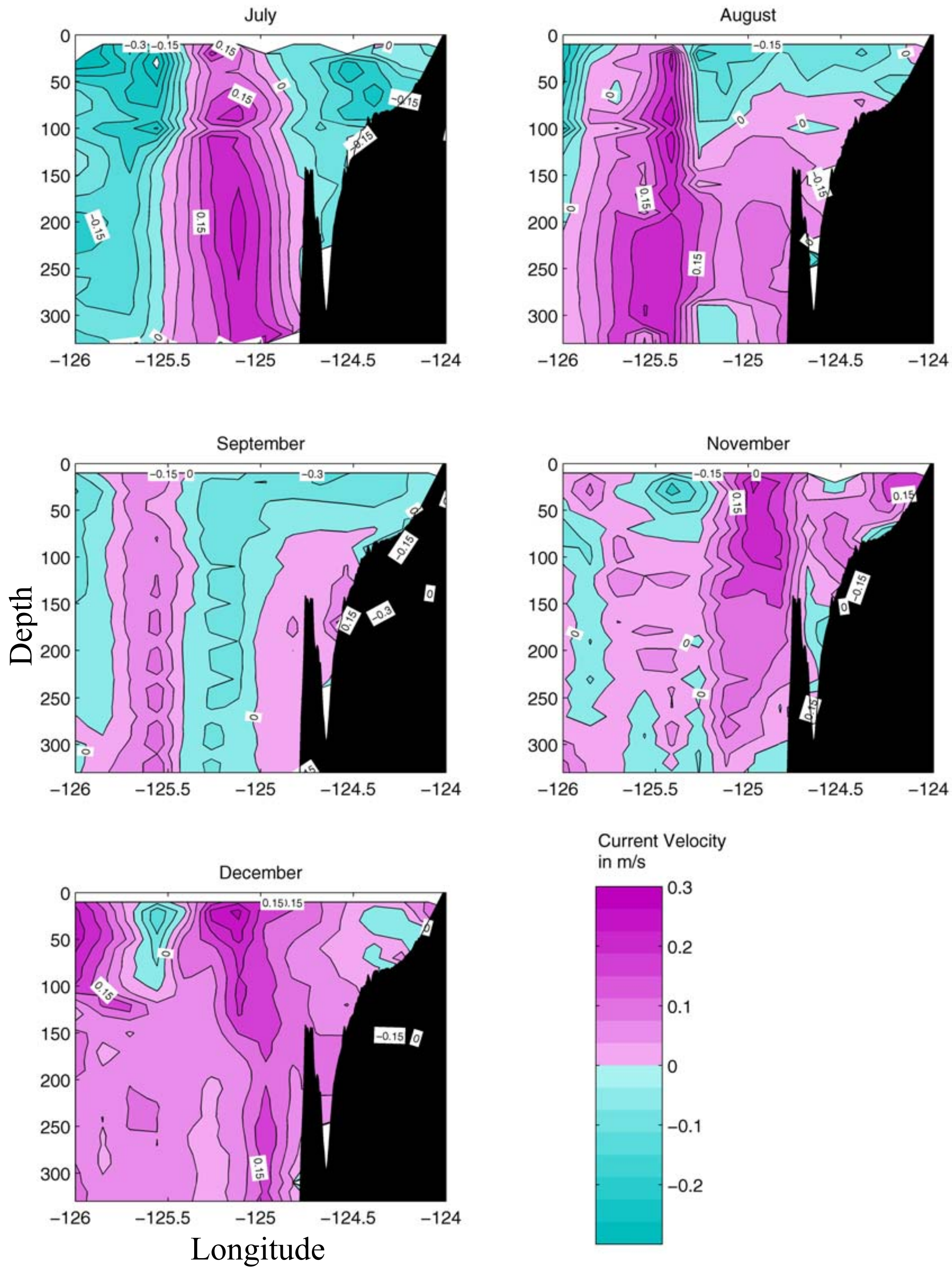

Figure 13-2 Vertical sections of of climatological monthly means for current velocity at the Newport Hygrologic Line (North-South Component) from shipboard ADCP observations (from 1991-2004).