AN ABSTRACT OF THE THESIS OF

Andrew Tristan Peery for the Degree of Master of Science in Oceanography
presented on March 21, 2008.
Title: Mapping Semi-Regular Autonomous Underwater Vehicle Glider Observations onto a Cross-Shelf Section

Abstract approved:

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Two Autonomous Underwater Vehicle Gliders have alternated continuous sampling of a 45-nautical mile transect line (the Newport Hydrographic Line) across the Oregon continental shelf since April, 2006. Strong currents (>25cm/s) push the gliders off their trajectories as they survey this transect line, preventing them from sampling the historically occupied stations exactly. Three methods were used to map the semi-regular glider data onto a cross-shelf line: (1) an algorithm that groups data by isobaths then block-averages the data, (2) an objective analysis that employs fixed along-isobath and cross-isobath correlation scales, and (3) a hybrid combination of the isobath-binning algorithm and objective analysis. To determine validity and accuracy, the mapping procedures are tested by comparison to moored observations at NH-10 on the Newport Line in 80m water depth while varying the spatial and temporal averaging scales. Isobath binning showed the best agreement with moored observations at the monthly timescale, while objective analysis showed the best agreement with moored observations at the weekly timescale. The hybrid method improved the agreement of the objective analysis at larger timescales.

Mapping Semi-Regular Autonomous Underwater Vehicle Glider Observations onto a Cross-Shelf Section

by
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A THESIS

Submitted to

Oregon State University

In partial fulfillment of
the requirements for the
degree of

Master of Science

Presented March 21, 2008
Commencement June 2008

Master of Science thesis of Andrew Tristan Peery presented on March 21, 2008.

APPROVED:

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Dean of the Graduate School

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.

Andrew Tristan Peery, Author

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1. Introduction

Autonomous Underwater Vehicle (AUV) gliders are independent buoyancy-driven ocean sampling devices. A glider contains a ballasting device that enables it to ascend and descend in the water column by changing the relative density of the glider. This device either pumps seawater in and out of a nosecone chamber or inflates and deflates an oil bladder (Webb et al, 2001; Eriksen et al, 2001). The wings and aerodynamic shape of the glider translate some of this vertical motion into horizontal motion, and the gliders traverse the ocean in a saw-tooth pattern as they profile the water column. The defining characteristics of buoyancy-driven gliders are long endurance (three weeks or more) and slow speeds (about 0.25 m/s); this is in contrast to propeller-driven AUVs that are characterized by short endurance (about 20 hours) and fast speeds (about 2.0 m/s) (Rudnick et al 2004). The energy efficiency of buoyancy propulsion gives gliders an operational range of 500 km or more (Rudnick et al, 2004). While at the surface, gliders determine their position via GPS, receive new instructions from land-based pilots and communicate near-real time data back to shore. Gliders are increasingly used in coastal oceanography, equipped with a wide variety of sensors, and will likely play a vital role in future ocean observation systems (Perry and Rudnick, 2003, Stommel,1989). Their main benefits are maneuverability, sustained presence, near-real-time data, and versatility of high-resolution sampling – all for a fraction of the cost of equivalent ship-based monitoring (Perry and Rudnick, 2003).

Complexities in navigation arise when using gliders in the coastal ocean. Gliders encounter strong flows that can be tidally-, wind-, or buoyancy-driven. Currents become strong, occasionally up to four times the speed of the glider, in which case the glider essentially becomes a drifter until it passes through the current. A result of the strong coastal currents is that the glider flight trajectories are often altered from the planned course. The nature of this monitoring method leads to semi-regularly-spaced, high-resolution observations. For example, a glider attempting to sample an east-west cross-shelf transect in the coastal ocean will be deflected north or south of the optimal transect line depending on the intensity, scale and duration of the along-shelf flow the glider encounters. While the glider will repetitively fly a certain transect during a deployment, it may not cross the same three-dimensional position twice. The challenge is to effectively use all of the glider data to accurately determine the water column properties along a defined cross-shelf transect whose exact sampling is unpredictably interrupted as the glider is swept off the line by the currents. Ideally, the gathered data set will be compared to and/or synthesized with other data, such as historical ship observations that were exactly on station, analysis of interannual variability data from external sources, or perhaps other autonomously collected data. Achievement of this goal relies largely on the ability to place this semi-regular data to a uniform transect.

While the coastal flows are strong, they flow mainly along isobaths (Kundu and Allen 1976). This framework provides a strategy to recast the semi-regular observations to a fixed cross-shelf transect. We assume that the flow is along-isobath, and so the water masses at the same isobath upstream, downstream, and directly on the transect line are the same water mass at different points in time. This assumption provides a method of spatially organizing the off-transect data by redistributing them onto the transect line according to isobath. Employing objective analysis (Bretherton et al, 1976; Denman and Freeland, 1985; Shearman et al, 1999) to weight the data by distance along- and cross-shelf from the transect line provides a statistically rigorous method for assessing average values and errors along the transect. The creation of a hybrid method that organizes data according to isobaths and then employs the objective analysis will explore the possibilities of spatially weighting isobath-organized data by distance away from the transect line. The calculations from these three methods are compared to moored observations from the 80m isobath to determine the validity of each method at three different time scales and three different spatial scales.

2. Background: OSU Glider Operations

Located at 44.65^{o}N is a transect line called the Newport Hydrographic (NH) Line that begins one nautical mile offshore and extends 45 nautical miles (roughly 80 km) offshore (Figure 1). Historically, the NH line was heavily sampled seasonally from 1961-1971 through The Next Ten Years in Oceanography (TENOC) program and again from 1997-2003 during the Northeast Pacific Long Term Observations Program (LTOP) (Huyer, 2006). During the TENOC period, the monitoring program consisted of bimonthly sampling of a string of stations from shore to approximately 300 km offshore along 44.65^{o}N. The physical data, temperature and salinity from the hydrographic casts, are the foundation of the TENOC data set (Huyer, 2006). The breadth of the NH line time series over the TENOC period prompted the inclusion of the NH line in later process-oriented research efforts (e.g. research programs – plankton studies 1970-72 Peterson and Miller, 1975; plankton studies 1990-92 Fessenden 1995; PISCO). The NH line time-series continued sporadically in this manner until the advent of the Global Ocean Ecosystems Dynamics' (GLOBEC) LTOP study which resumed bimonthly sampling along the NH line from 1997 to 2003. The GLOBEC sampling regime shortened the length of the transect line from 300 km to 160 km offshore, decreased the station spacing to 5 nautical miles, and increased the amount of biological and chemical observations (Huyer 2006).

In 2006, AUV gliders commenced sampling along the NH line as part of a National Science Foundation (NSF) project to study shelf circulation and the subsequent impact on coastal ecosystems. A goal of the glider observing system is to quantify the year-round, time-dependent along- and cross-shelf fluxes of water and the material they contain. Newly collected glider data will eventually be compared with historical data from the Newport Line to quantify changes in circulation patterns at varying temporal scales.

In implementation, two Oregon State gliders alternate continuous monitoring of 45 nautical miles (~80 km) of the NH Line (Figure 1). The data examined in this paper span the period from April 2006 to November 2007, which is a subset of the ongoing glider operations along the NH Line. During this subset, the gliders were in the ocean for 432 days, flew a combined distance of 11,097 kilometers while completing 171 transects along the NH line, and recorded 56,053 water column profiles. Oregon State University deploys Webb Research Corporation Slocum Electric Coastal Gliders with 200 m depth capabilities and whose endurance is approximately three weeks. The Oregon State glider's suite of sensors comprises a SeaBird-41 CTD, an optical Anderaa dissolved oxygen sensor , and a WetLabs EcoTriplet Fluorometer with chlorophyll fluorescence, CDOM fluorescence, and single-wavelength backscatter (Figure 2). The CTD samples once every second and the EcoTriplet and the

Anderaa dissolved oxygen sensor sample once every 4 seconds, leading to a vertical resolution of <1m at a dive rate of about 15 cm/s. The glider flies a saw-tooth pattern from the surface to a few meters above the seafloor (determined by acoustic altimeter) or 200 meters maximum depth, whichever is shallower. Every surface communication event, routinely scheduled at 6 hour intervals, results in a transmission of a condensed data set comprised only of upward profile data that is sub-sampled once every 16 seconds. These telemetered sub-sampled data are observations recorded since the last communication event, which provides consistent near-real-time data of the ocean conditions. The full data set is downloaded upon recovery.

The strength of the along-shelf flow on the Oregon coast is largely dependent on the strength of the wind, and fluctuates accordingly (Kosro 2005, Huyer 1983), so the glider may experience different flow regimes each time it crosses the continental shelf, usually 6 times during a three-week deployment. The strongest currents typically occur in the along-isobath direction, and as the glider crosses the shelf east-west, these currents (Huyer 1978) push the glider north and south of its desired trajectory (Figure 1), in addition to wind-driven coastal flows, surface waves can potentially affect glider flight. From April 2006 to November 2007, 59% of data collected were within 5 km of the Newport Line and 84% of data collected were within 10 km.

As the gliders traverse the NH line longitudinally over the sampling period, their tracks differ in the magnitude of latitudinal variation (Figure 3). The longitude remains relatively stable, as the glider travels to and from the same offshore point, while the latitude changes throughout the year according to the predominant currents. The mean deviation from the latitude of the NH Line is 5.37 km with a standard deviation of 4.87 km. The percentage of discretized latitudinal variation of the glider by month (Figure 4) shows the seasonality of the strength of the currents on the continental shelf; the glider maintains the latitude of the NH Line more consistently during the summer months of June-September 2006. When strong winds are forecast, gliders are assigned waypoints further north or south of the NH line latitude (44.65^{o}N) in anticipation of transverse displacement from the NH Line due to strong currents (Figure 5). While these incorporated transverse displacements are not directly caused by current drift, they are a good indication of the strength of the coastal jet flows encountered at a particular time of the year. In May 2006, early September 2006, and March 2007 the gliders experienced the most southward (upwelling-favorable) flow (Table 1). April, May, and October through November of 2006 exhibit the most northward flow. The northern positions of April and May 2006 incorporate the farthest north jet-crossing waypoints. The timeseries is less continuous between

November 2006 and April 2007 because wave conditions on the Oregon coast prevent the glider-deploying vessel (the R/V ELAKHA) from operating within safety constraints.

The north-south component of the wind (v) and the significant wave height (Figure 6) were measured using NOAA Buoy 46050, located at 44.62 N 124.53 W (Figure 1). The NOAA Buoy 46050 anemometer provided no data from April-August 2006. A nearby meteorological station, C-MAN Station NWPO3 located onshore approximately 35 km away, recorded consistent wind data for this period. To populate the missing wind data at Buoy 46050, a regression analysis was performed on the north-south wind component (v) from the 2005 calendar year at both stations. The resulting multiplier and intercept, 0.7721 and 0.0986 respectively, were applied to the April-August 2006 NWPO3 data to approximate the missing north-south wind component (v) at Buoy 46050. The regression statistics were consistent with previous studies of the wind relation at these two stations (Kirincich and Barth, 2005).

A comparison of the absolute transverse distance from the NH Line according to wind speed (Figure 7) with the absolute transverse distance from the NH Line according to significant wave height (Figure 8) reveals wind to be a stronger influence than waves. As the wind speed increases to greater than 15 m/s, the percentage of data collected within 5 km of the NH Line is almost halved. In contrast, the percentage of data collected within 5 km of the NH Line differs by only 10-15% as significant wave height increases from 1 to 5 m. It appears the higher the waves, the better the glider adheres to the NH Line, but one possible reason is that there are much fewer data collected with 5 m wave conditions during this time period.

It is apparent the wind and wave strengths have seasonality associated with them, and the glider experiences changes in north-south deviation from the NH Line in accordance with these conditions. The wind that drives the currents is the most formidable meteorological obstacle to maintaining the NH Line latitude. Certain weather conditions are unavoidable, as are glider observations being pushed off the line, so determining a method to retain data integrity is imperative.

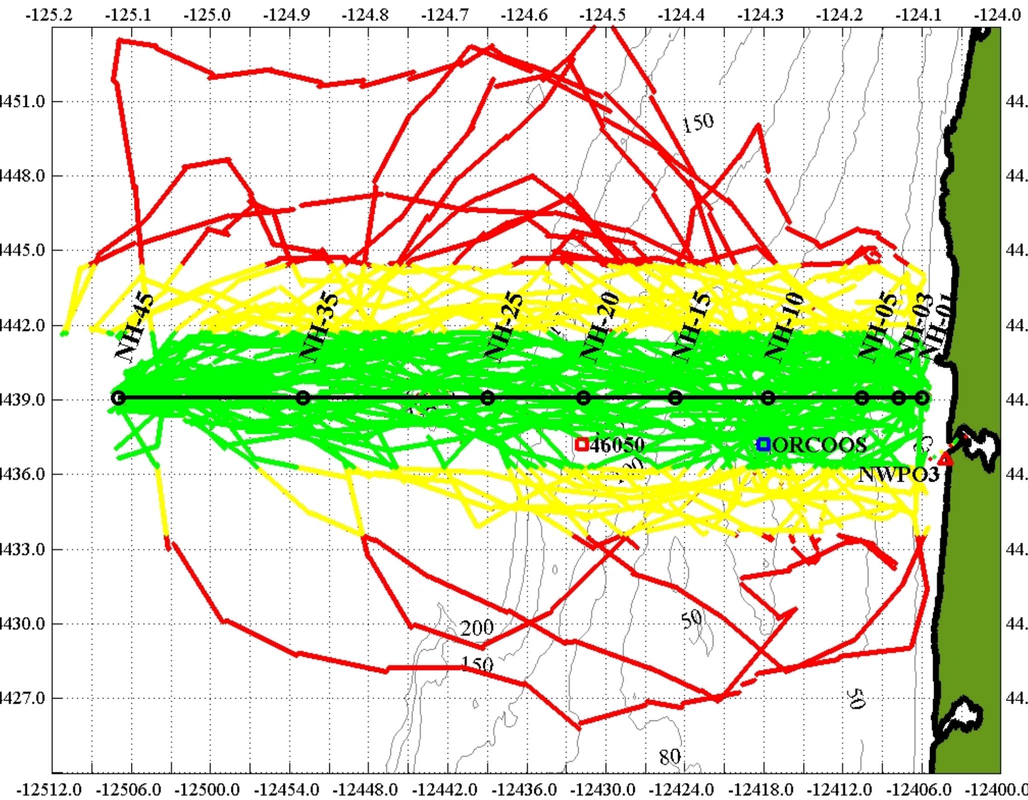

Figure 1. Glider flight paths from April 2006 – November 2007. Green indicates data within 5km of the NH line, yellow indicates data between 5km and 10km, and red indicates data collected further than 10km from the NH Line. Also illustrated are NOAA Buoy 46050, the C-MAN station NWP-03, and the OrCOOS mooring.

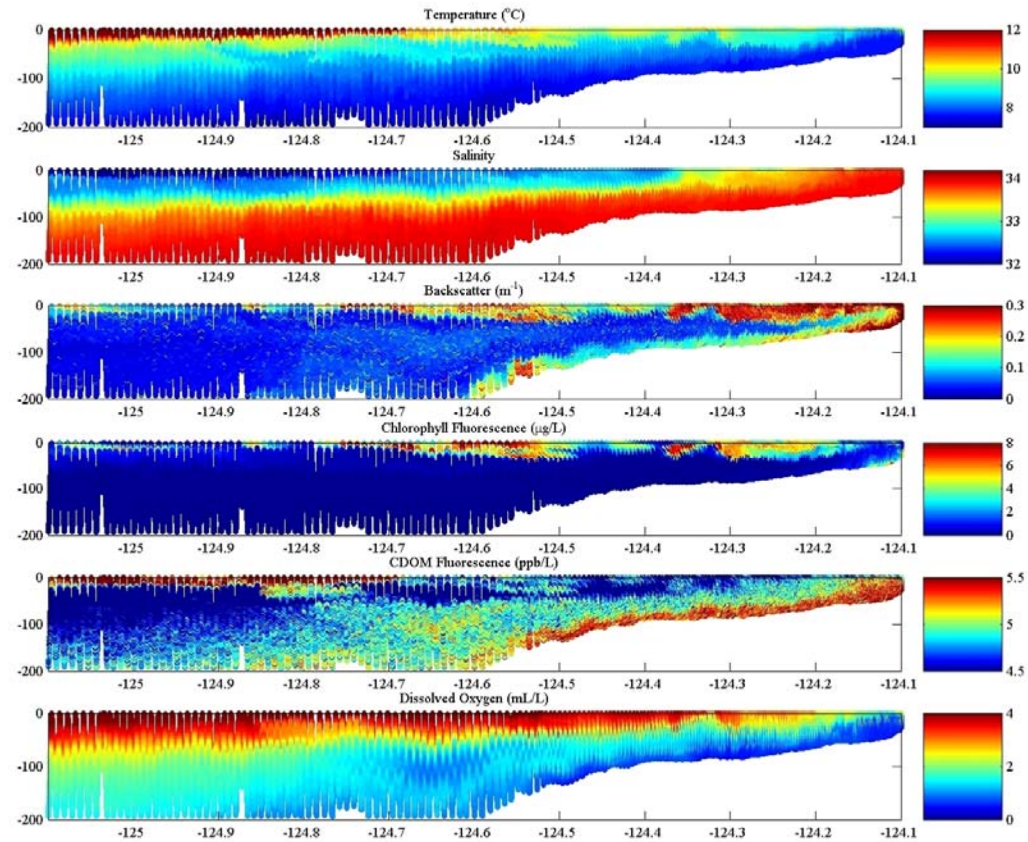

Figure 2. A glider transect of the NH Line from August 5-8, 2006 depicting all scientific parameters (temperature, salinity, backscatter, chlorophyll, CDOM, and dissolved oxygen).

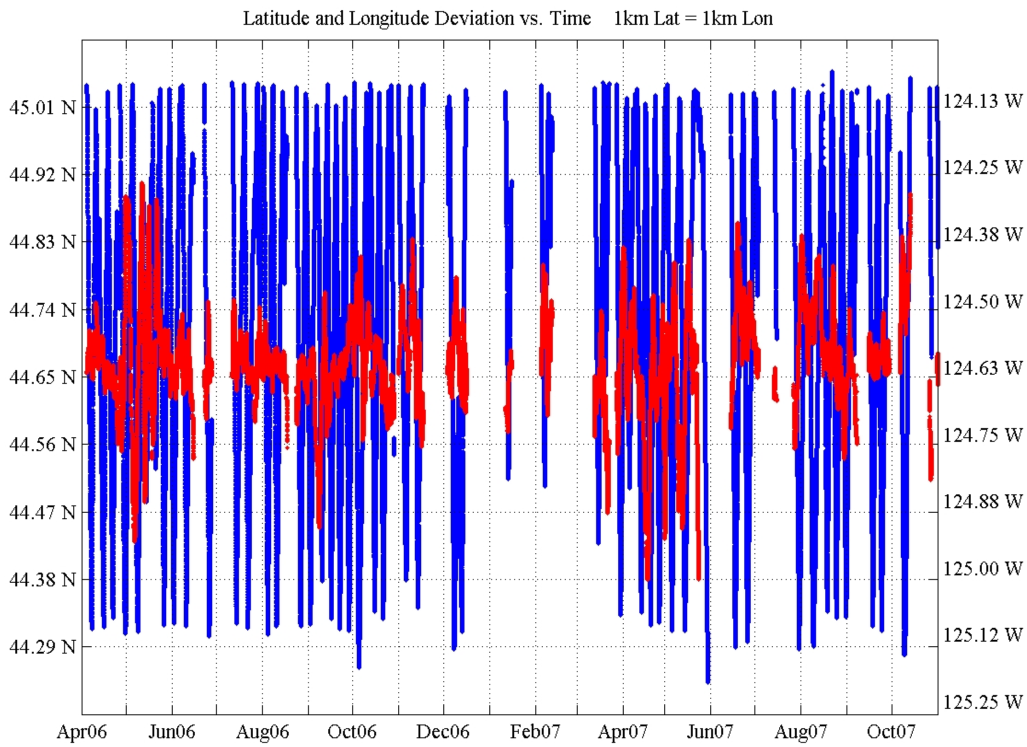

Figure 3. Longitudinal (blue) and latitudinal (red) variation according to time from April 2006 to November 2007 shows the variability of glider position.

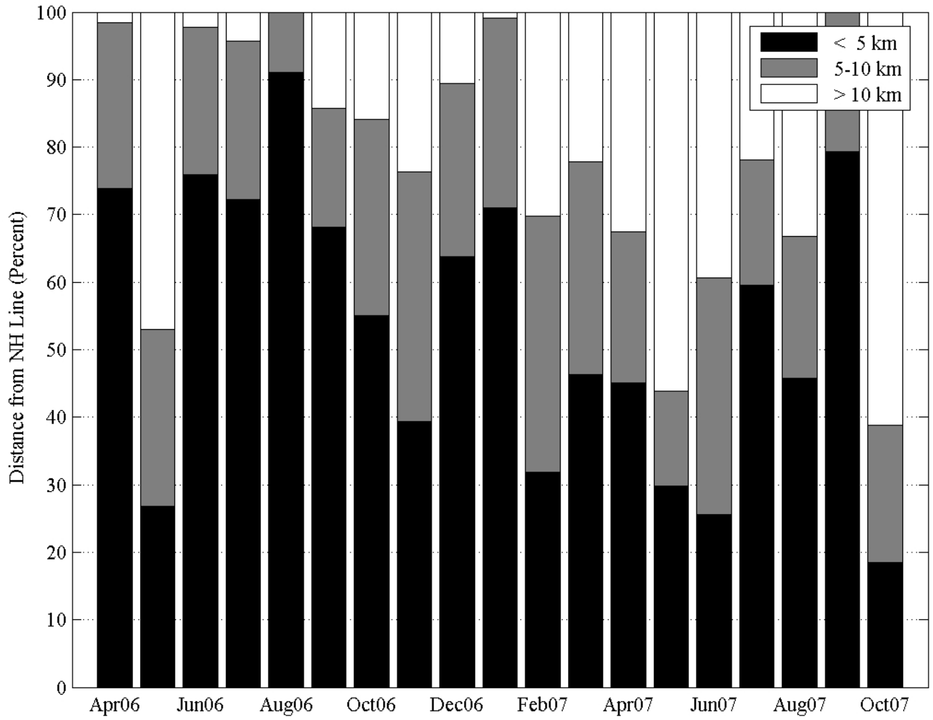

Figure 4. Percent of glider observations within 5km (black), 5-10km (grey), and greater than 10km (white) from the NH Line by month.

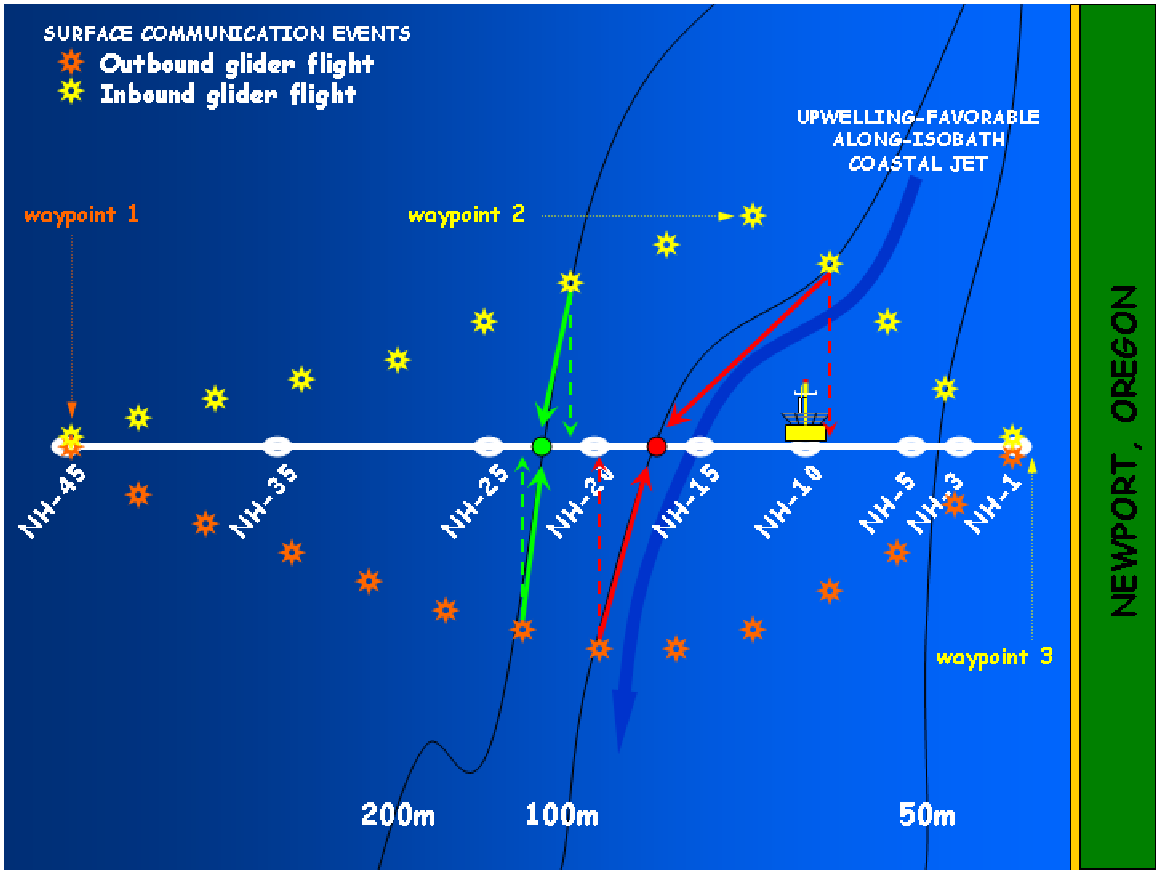

Figure 5. Cartoon depicting a typical outbound/inbound glider flight along the NH Line during upwelling-favorable winds. Glider waypoints are adjusted north or south to compensate for north/south drift caused by strong alongshore currents (waypoint 2). Dashed lines (red and green) indicate where data would be mapped if data were mapped according to longitude. Organizing by isobaths maps the data to the NH Line (red and green solid lines) at the location where the isobath at which the data were collected crosses the NH Line.

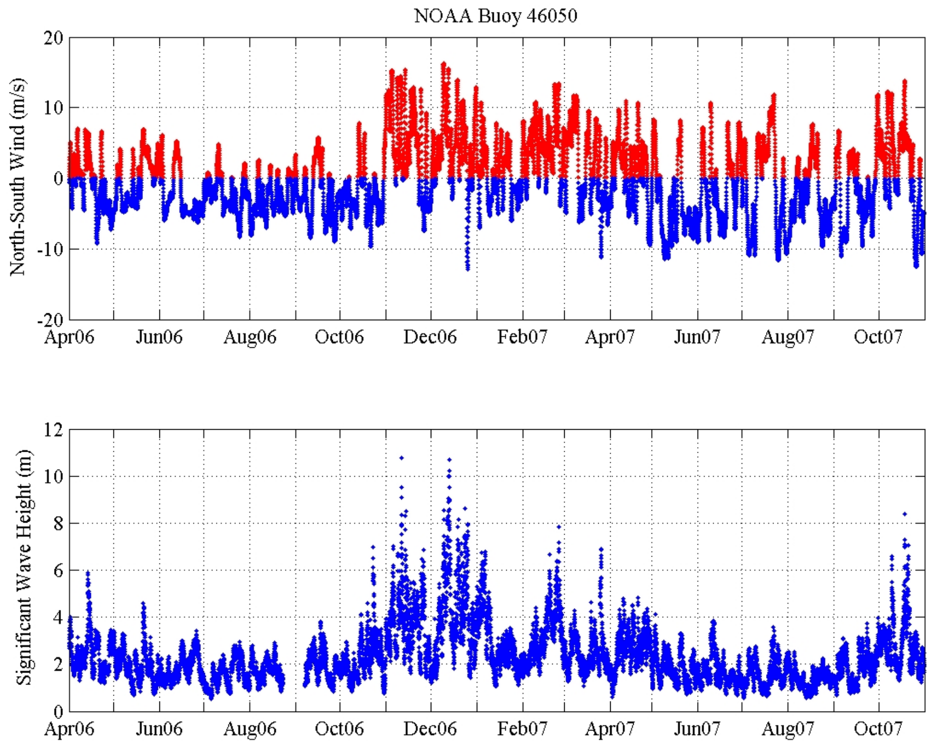

Figure 6. NOAA Buoy 46050 north/south wind speed (top panel) and significant wave height (bottom panel) for the sample period. Wind data from April 2006 to September 2006 were regressed from C-MAN station NWP-03, there were no wave data available from the buoy for a period in early September 2006.

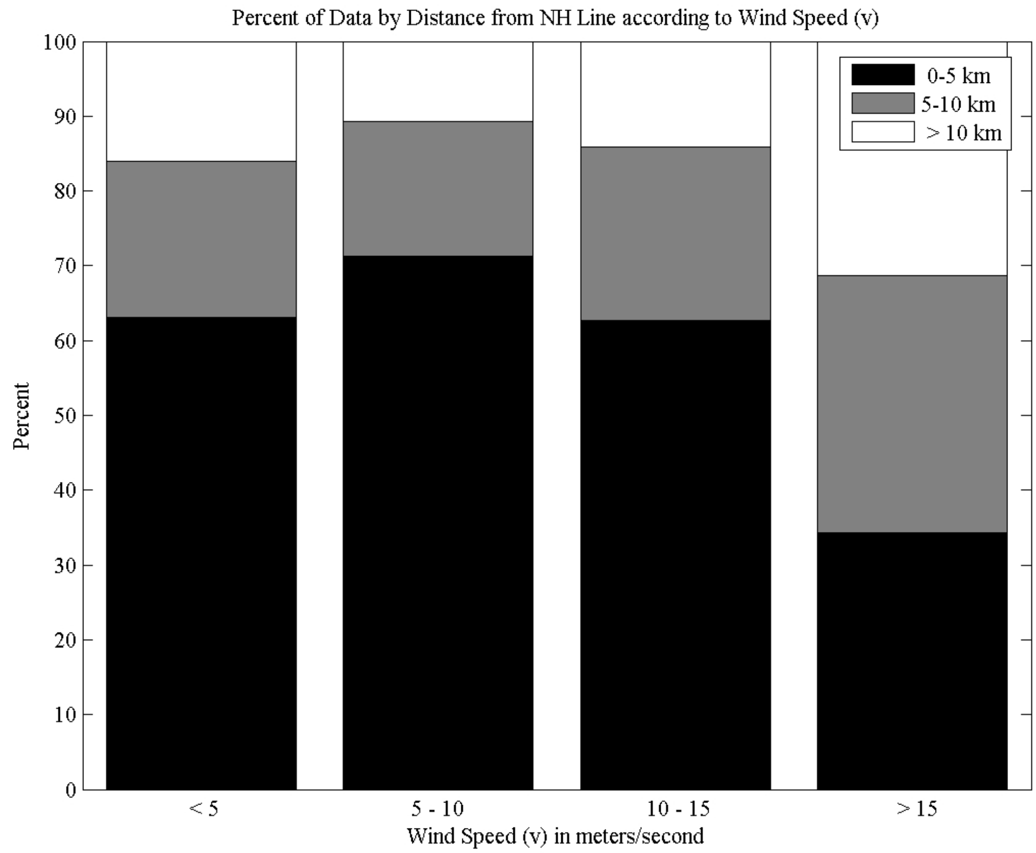

Figure 7. Percent of data collected within 5km (black), 5-10km (grey), and greater than 10km (white) from the NH Line as a function of north/south wind speed from NOAA Buoy 46050.

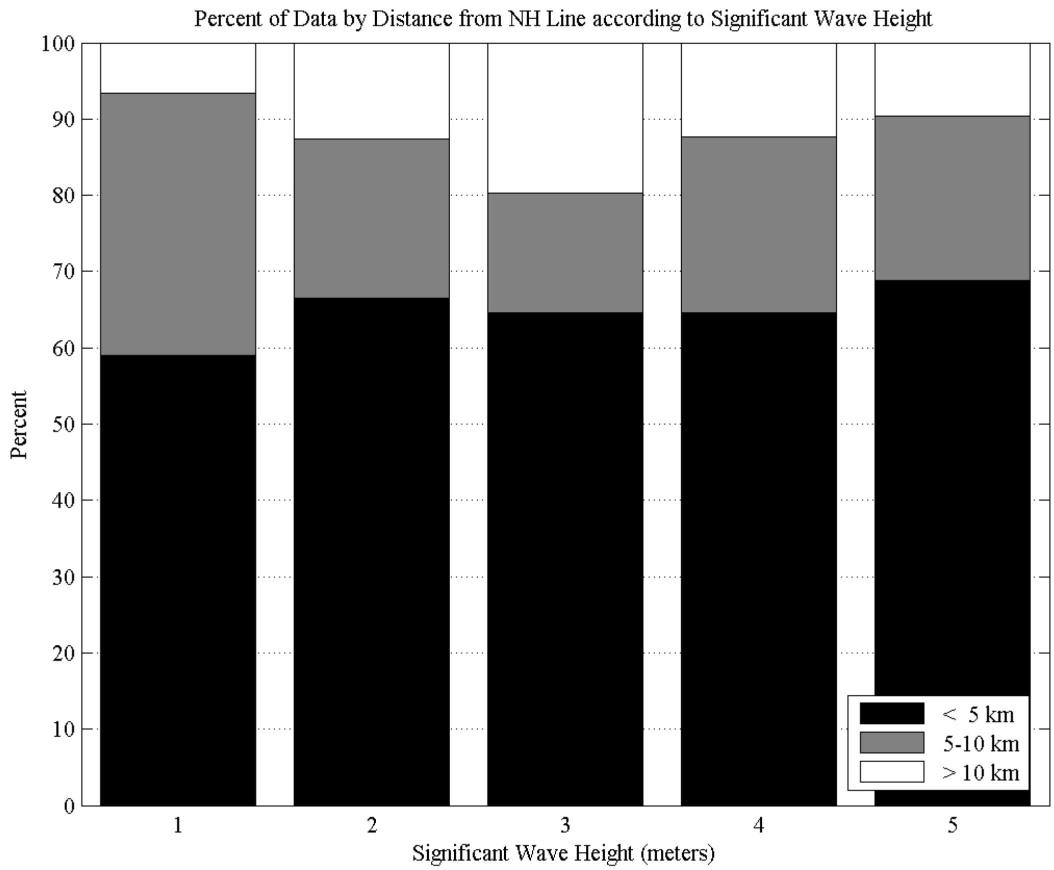

Figure 8. Percent of data collected within 5km (black), 5-10km (grey), and greater than 10km (white) from the NH Line as a function of significant wave height from NOAA Buoy 46050.

Table 1. Absolute mean distance and absolute standard deviation of mean distance of latitudinal disposition from the NH Line in kilometers for months with most north/south drift.

Month	Abs. Mean (km)	Abs. St. Dev. (km)
April 2006	3.86	4.06
May 2006	15.05	7.93
early Sept 2006	4.69	4.92
Oct-Nov 2006	6.00	4.69
March 2007	5.72	4.30

3. Methods

A gridded section (a composite of one or more complete glider flights inbound or outbound) for any parameter along the NH Line capitalizes on the entire data set by employing all glider-collected data - including observations north and south of the NH Line. As transverse distance from the NH Line increases, however, so does the possibility of introducing errors from averaging spatially dissimilar water parcels. The slope is narrower and steeper north of the NH Line and wider and shallower south of the NH Line; if flow is along-isobath then binning the entire data field strictly by longitude creates situations where unlike water is combined, introducing error (Figure 5). Additionally, coastal circulation is primarily along-isobath (Kundu and Allen 1976, Winant et al 1987, Kosro 1987, Lentz and Chapman 1989) and the isobaths along much of the NH Line are oriented diagonally to the coastline, preventing simple meridional averaging. There were three methods developed to assimilate all glider-collected data parameters into averaged sections. The first is a binning procedure to map off-transect glider data to the NH Line according to corresponding isobaths and then block average the bins. The second is to objectively map using separate along-isobath and cross-isobath correlation scales. The third is a hybrid combination of the first two methods.

3.1. Isobath Binning and Block-Averaging

Binning according to isobath requires that the bathymetric profile along the NH Line first be established. Archived, consolidated bathymetry data compiled by Eric D'Asaro (personal communication via Steve Pierce and more recently available as part of the National Geophysical Data Center Coastal Relief Model (http://www.ngdc.noaa.gov/mgg/coastal)) spanning the Oregon continental shelf from 123.9^{o}W (the coastline) to 125.5^{o}W (128 km offshore) and from 41.5^{o}N to 46.0^{o}N (500 km north/south) at 300 m resolution were used to extract the bottom depths along the NH Line at 2 km resolution. This profile was smoothed to remove small (>4 km) features (Figure 9).

The NH-Line is divided into a row of uniformly-sized collection bins beginning at NH-01 and extending roughly 80 kilometers offshore. Each bin represents a portion of the NH-Line in the cross-shelf direction, and has a specific bottom depth associated with it. Data collected away from the NH-Line are mapped to the NH-Line by matching the bottom-depth from where the off-transect observation was recorded to the collection bin that contains its matching bottom-depth along the NH Line. The bins are populated in this manner until all off-transect data for a specified time period (e.g., weekly, two-weekly or monthly) reside in a bin on the NH-Line.

Not all data are binned by matching isobaths in this method. First, data collected within 4 km of the NH Line latitudinally are considered direct readings on the line and are mapped simply by longitude instead of by matching bottom-depths (Figures 10 and 11). This distance was determined from a sensitivity analysis that varied the distance data were mapped directly to the NH line by longitude (2km, 4km, and 8km distances). When using a "swath" distance of 2km from the NH Line, 25% of the data were mapped directly to the line by longitude which provided insufficient coverage. The 8km swath distance contained almost 70% of the data record and averaged multiple isobaths together according to longitude. The 4km swath had a good combination of both these extremes by including an ample portion of the data record and not including and averaging too many isobaths together per longitudinal bin. In the April 2006-November 2007 timeframe, 44% of all glider observations are considered a direct reading on the NH Line because they were recorded within 4km (Figure 4). Observations farther than 4 km north or south of the line are considered off-transect, and mapped to the NH Line according to matching isobaths.

Gliders possess an altimeter in their nosecone which allows them to sense the distance to the seafloor, when they are within about 30 m from the bottom; at the end of their descent they record a bottom depth at their nadir. During the rest of their flight or when the bottom depth is substantially deeper than 200 m, there is no bottom depth measured therefore an interpolated bottom depth is calculated from the glider's x, y position, using the gridded bathymetry. A glider cannot communicate with satellites while underwater and therefore cannot obtain a GPS location. GPS locations of the glider within the water column are determined in this analysis through a linear interpolation of satellite-provided GPS locations from glider communication events at the surface.

Data are binned in a certain order to eliminate cross-population. Once a temporal increment (monthly, fortnightly, or weekly) and spatial collection bin size (2 km, 1 km, and 500 m) are determined, the data are binned. All data are collected, and placed into bins in the following order (Figure 11). First, all observations within 4 km of the NH Line are binned directly to the line according to their longitudinal (approximately cross-shelf) position. Next, the offshore data (defined as west of NH-25) north and south of the line are binned according to their longitude. Because along-isobath flow is assumed to be restricted to the continental shelf (<300 m depth), and since the deeper isobaths are oriented north-south (orthogonal) to the NH Line, the offshore data are binned according to longitude. The inshore data (east of NH-25) to the north of the line begin the isobath-binning procedure and are placed according to the matching isobath along the NH Line. Inshore data south of the NH Line introduce the dilemma of Stonewall Bank, discussed in detail in the next subsection, and are binned according to isobath from 124.10^{o}W (NH-01) to 124.21^{o}W (just past NH-05). From here, the data on the western edge of Stonewall Bank (see below) proceeding offshore to NH-25 are binned by isobath to the NH Line between 124.43^{o}W (NH-15) to 124.65^{o}W (NH-25).

The remaining data are considered to be on Stonewall Bank. Stonewall Bank, the seamount located at 124.40^{o}W, poses a challenge; it is a prominent feature of the continental shelf and too large to ignore or smooth (Figure 9). It juts above 80 m depth, creating a zone between 124.275^{o}W and 124.425^{o}W where three locations exist with depths between 79 m and 88 m. North of Stonewall Bank, the shelf slope steadily decreases, so the dilemma is how and where to appropriately populate data along the NH Line from a presumed along-isobath shelf flow that may bifurcate somewhere north of the NH Line. The data north of the NH line deeper than 79 m are mapped to the bins west of Stonewall Bank, the data shallower and inshore (north or south) of Stonewall Bank are mapped by isobath to the bins on the eastern side of the "bowl" (from the coastline to 124.35^{o}W), and the bins on the western side of the "bowl" are populated by readings considered directly on the line or directly above Stonewall Bank. The data south of the NH Line collected above Stonewall Bank are binned last, and mapped according to isobath along the western slope of the valley that Stonewall Bank creates (124.35^{o}W – 124.40^{o}W). Data too far south of the NH Line and on Stonewall Bank comprise less than 1% of the total data record and are removed from the data set (Figure 11). The other seamount present in the profile at 124.7^{o}W (Figure 9) is much smaller than Stonewall Bank in area although it appears much larger when viewed as a cross section. It happens to fall directly along the NH Line (Figure 10) although in the "offshore" area. The effect this seamount has on shelf circulation is considered minimal and its presence is ignored as it has been historically (Huyer 2006). Once the binning procedure is complete, simple bin averages are used to compute gridded glider sections of temperature (Figure 12) for each bin size and timescale.

3.2 Objective Analysis

Another method, an objective analysis (Bretherton et al 1976), was applied to the semi-regularly spaced glider data. Objective analysis is a gridding technique that allows smoothing with differing along-isobath and cross-isobath scales. It also has the added benefit of its results being continuously differentiable and it has a straight-forward error calculation. In this application, it is essentially a spatially-weighted interpolation of non-uniformly distributed data points (glider observations) to a uniform grid (the NH Line). The uniform grid is the same as used for the isobath binning procedure. For each node, the entire data field is weighted with values ranging from 0 to 1 to interpolate the value at each particular grid point, with the data closest to the grid point receiving the highest weighting. Data collected farther than the correlation distances are weighted to zero and essentially excluded from the analysis. Correlation scales are different in the cross-shelf and along-shelf direction. The data closest to the grid points will receive the highest weighting, as determined by the covariance function

$$C = e^{-\left[\left(\frac{dx}{a_x}\right)^2 + \left(\frac{dy}{a_y}\right)^2\right]} \cos\left[\left(\frac{\pi}{2}\right)\sqrt{\left(\frac{dx}{b_x}\right)^2 + \left(\frac{dy}{b_y}\right)^2}\,\right] \tag{1}$$

where dx, dy are the longitudinal and latitudinal separations, and a_x, a_y are the decay scales in the cross-shelf and along-shelf directions, and b_x, b_y are the zero crossings in the cross-shelf and along-shelf directions. A value of 0.1 (10% of variance) was used for random measurement noise.

Glider temperature observations were autocorrelated in space to estimate the values for a_x, a_y, b_x, and b_y. To determine the cross-shelf correlation scales, the temperature record at 10 m depth was divided into weekly timeframes. A glider will usually complete an offshore/inshore transect in about a week which falls within the dominant 2-10 day weather-band variability of the Oregon shelf (Huyer 1983, Austin and Barth 2002). The objective analysis treats the temperature record that occurs during this time span as synoptic. All data were initially autocorrelated at depths of 10m, 20m, and 30m to determine any differences in decay scales with depth. The results were similar, and most differences appeared driven by the smaller ranges of temperature associated with deeper waters. The decision to use the decay scales at 10m was justified because this depth encompassed the most variability (standard deviation of 1.95 ^{o}C). These weekly temperature records at 10 m depth are detrended in the cross-shelf direction (Figure 13) and then autocorrelated according to separation distance. Cross-shelf temperature trends (gradients) removed were on the order of 0.01 ^{o}C/km. The weekly autocorrelations are then averaged to arrive at one universal temperature correlation vs. distance in the cross-shelf direction (Figure 14). The along-shelf correlation scales were determined in a similar fashion using data from glider north-south transits to a southern monitoring line 100 km from the NH Line. The zero-crossings (b_x, b_y) and decay-scales (ax, ay) were fitted using a least squares analysis. The values calculated using this analysis were a_x=2 km, a_y=7.5 km, b_x=4 km, and b_y=15 km. These values define an elliptical shape that surrounds every grid point. All the data within the ellipse are weighted to determine the value at the grid point. Data that fall outside the ellipse are weighted to zero, and essentially eliminated from the spatially-weighted interpolation (Figure 15). The correlation scales are larger in the along-shelf direction, incorporating the dominance of the along-shelf flow into this method. Cross-shelf correlations scales are small compared to other estimates in the coastal ocean (Dever 2004, Denman and Freeland 1985). This is due to the large variability in temperature in the cross-shelf direction due to sharp fronts, associated with near shore upwelling (e.g. the sharp front at ~15 km in May (Figure 13)). Another reason for the small cross-shelf correlation scale is the extremely high spatial resolution of glider observations (as small as 200 m at the inshore end) – past observations have not resolved features on such spatial scales.

The glider data are objectively analyzed at three temporal resolutions- monthly, fortnightly, and weekly. The positions of each recorded data point are converted to distance (kilometers) away from NH-01 so that all distance scales are in kilometers. The objective analysis is a two-dimensional interpolation; mapping data in the x, y plane. To obtain a three-dimensional analysis, the horizontal objective analysis is performed for depth intervals of 2 meters, and stacked together vertically to create an objectively analyzed section of glider data (Figure 12).

Objective analysis also provides error estimates that are calculated according to the geometric distribution of data to the interpolated grid point. In this case, the error estimates reflect the spatial proximity of the glider observations within the covariance ellipse to the location of the grid point along the NH Line (Figure 16). Error estimates below 0.1 (10% of the data variance) are considered to indicate a good geometric distribution of data within the ellipse. A high error estimate does not necessarily mean poor agreement with the temperature values at the OrCOOS mooring, nor does a low error estimate mandate the opposite. It is a valuable statistical calculation quantifying the confidence level associated with the interpolation at any particular grid point.

A major limitation of the objective analysis method is the along-shelf and cross-shelf directions are only approximations to the orientation of the isobaths, fixed to the north-south and east-west directions, when in reality isobaths follow a non-orthogonal, curvilinear path (Figure 1). This results in potentially giving undue weight in the OA to water parcels from differing isobaths.

3.3 Hybrid Method

A third method, a hybrid method combining elements of the isobath binning procedure and the objective analysis, was applied to the data. This method employs the spatial organization of the isobath binning procedure then applies the objective analysis, using the already determined covariance function (1) and correlation scales. The goal of this method is twofold, (1) to eliminate the objective analysis' tendency to include data collected from unlike water by strictly defining the data field to be of similar isobath, and (2) to improve the orientation of the axis angle of the objective analysis' ellipse in relation to orientation of isobaths along the NH Line.

The ellipse that is defined by the along-shelf and cross-shelf correlation scales in the objective analysis includes data from non-like isobaths when estimating the temperature value at each grid point. It includes data collected at deeper isobaths from the north and shallower isobaths from the south as well as including more data in the cross-shelf direction. In addition to the inclusion of these data, the objective analysis weights them in a spatially uniform manner when the isobaths are not oriented to the NH Line orthogonally or uniformly. The potential exists for data that are equidistant from the NH Line to be weighted identically even though their individual isobaths may differ vastly from the isobath of the NH Line grid point.

Isobaths do not cross the NH Line at perpendicular angles, or at one uniform angle. Depending on the longitudinal position on the NH Line, isobaths may cross at a variety of angles. This creates a problem for the objective analysis whose along-isobath and cross-isobath directions remain fixed in the x and y direction. The premise behind the hybrid method is that the angle of isobath orientation is intrinsic in the selection of data when organizing according to isobaths and that applying a spatially-weighted analysis to these binned data will produce better results than the objective analysis alone (Figure 17).

In application, the binning procedure occurs as described in Section 3.1. The bins along the NH Line are supplemented by off-transect data in defined bin sizes (2km, 1km, 500m), and then objectively analyzed using the same correlation function determined and described in Section 3.2 at 2 meter vertical depth bins. This analysis produced error estimates and was performed at monthly, fortnightly, and weekly timescales.

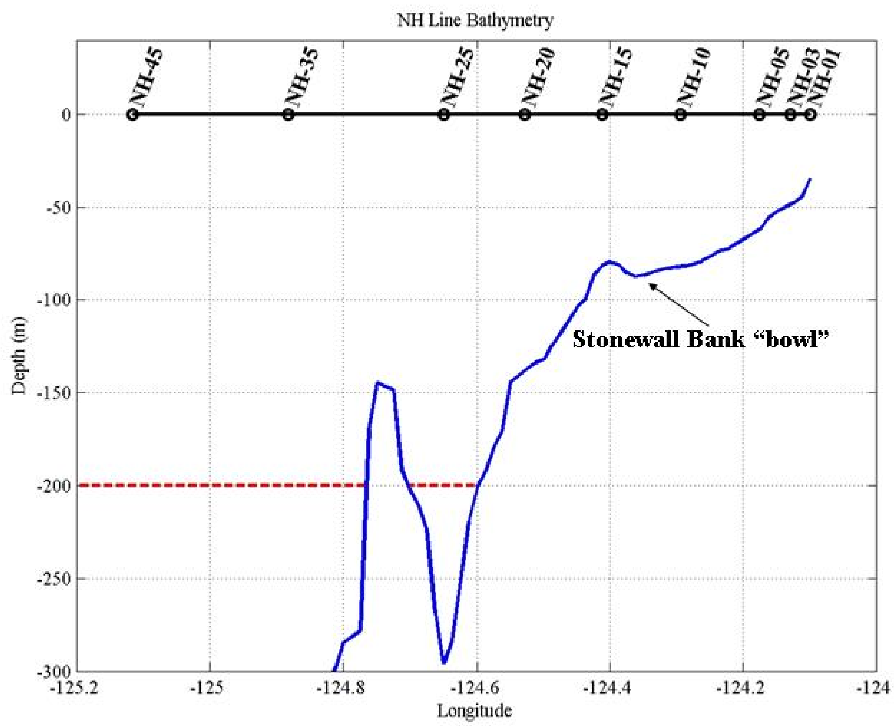

Figure 9. Bathymetry in meters along the NH Line. Stonewall Bank is the peak located at -124.4 W Longitude. The valley to the east of the bank is the "bowl" that causes complications in mapping by isobaths. The ridge at 124.7 W is ignored.

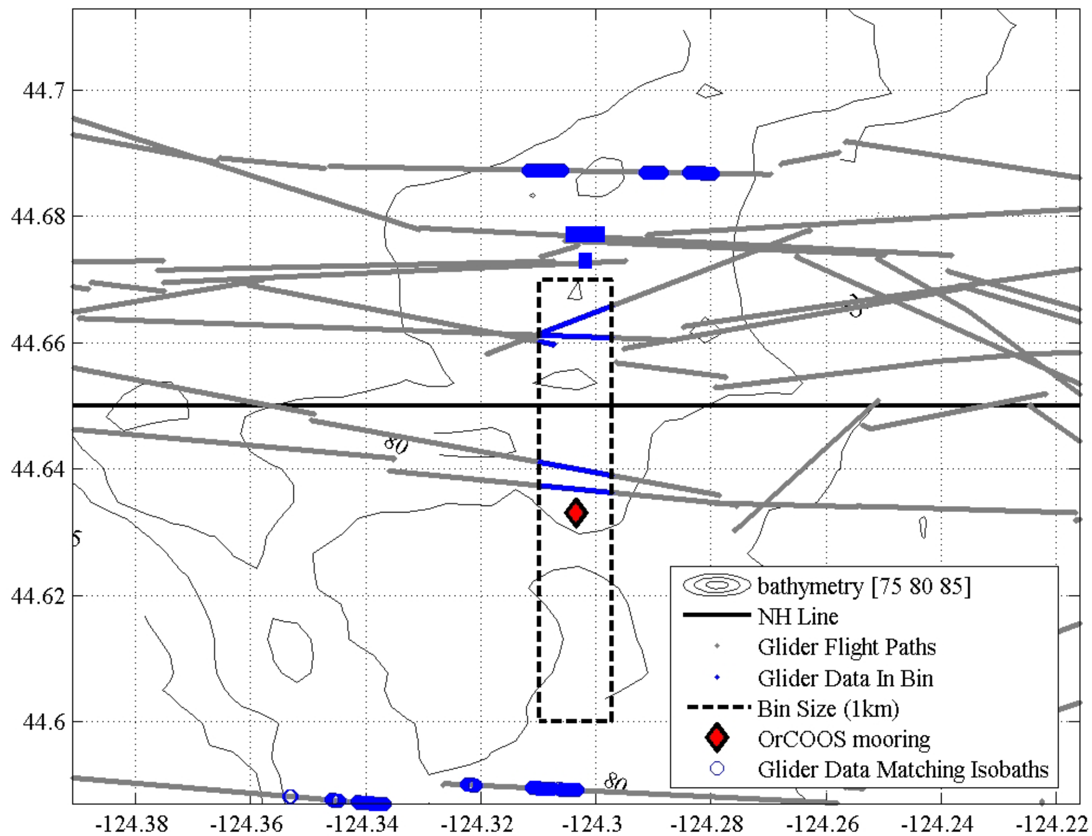

Figure 10. An example of how data are organized using the isobath binning algorithm at a single bin along the NH-Line, here it is centered at the OrCOOS mooring (red diamond). The grey lines are glider track for the month of August 2006. All data recorded within the dashed box (1 km bin size in width, 8 km in length because of the NH "swath") are considered a direct reading, and the data is supplemented by data recorded at identical isobaths outside of the dashed box.

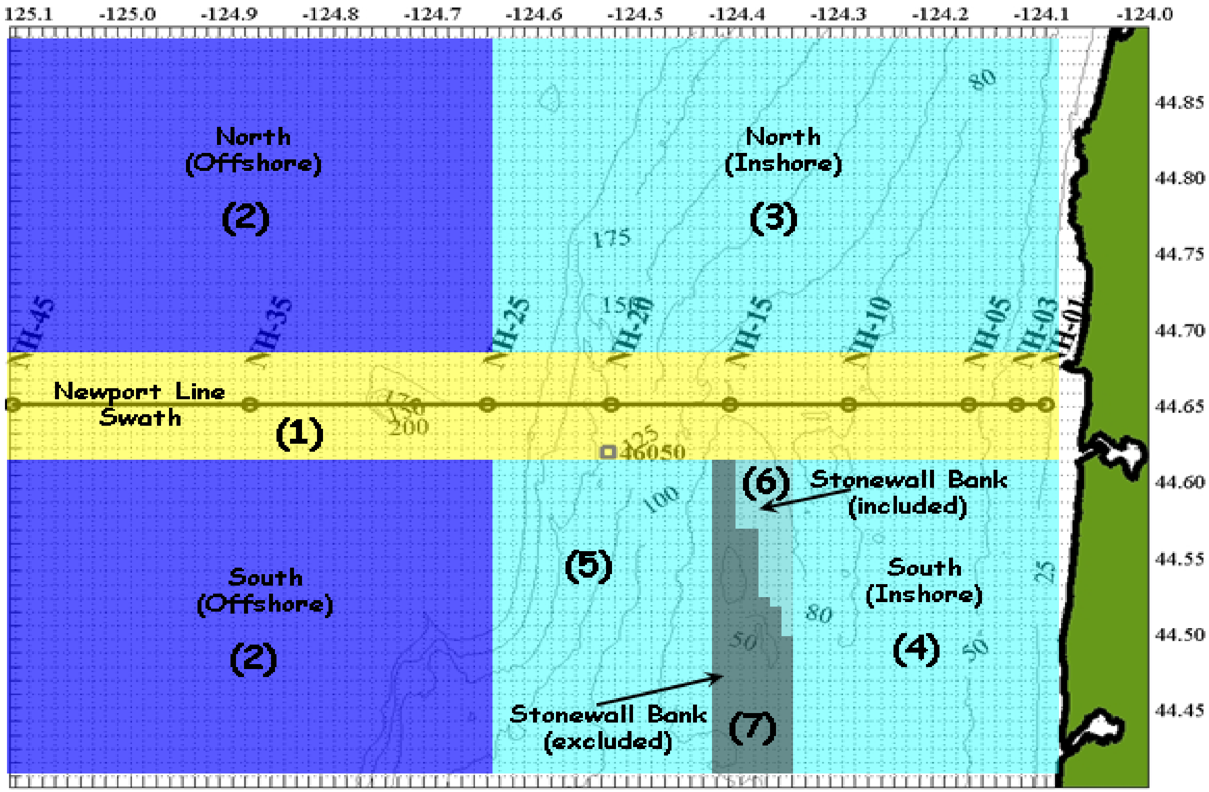

Figure 11. The sampling region of the NH Line divided into 1km x 1km bins. The yellow bar indicates the 8km wide NH swath that is binned to the NH Line according to longitude. The regions are numbered according to the order the glider observations are mapped to the NH Line when using the isobath-binning method.

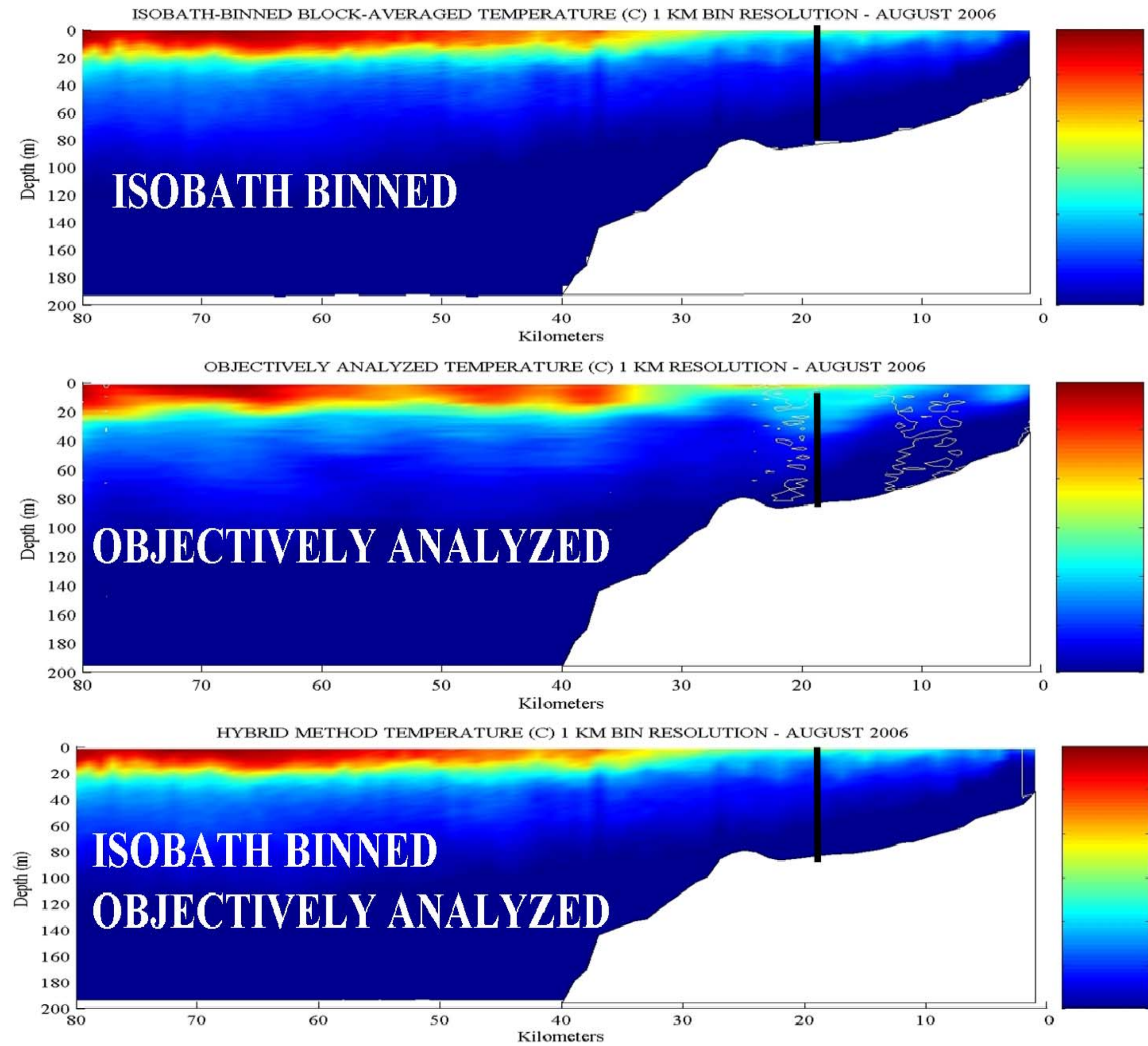

Figure 12. Gridded glider sections of temperature for the month of August 2006. Top panel is the isobath binning method, the middle panel is the objective analysis (white contour represents 0.1 error estimate – inshore data within the contour are <0.1, and offshore data outside the contour are >0.1), the lower panel is the hybrid method (white contour represents 0.1 error estimate – inshore data within the contour are <0.1, and offshore data outside the contour are >0.1). Black column represents location of OrCOOS mooring.

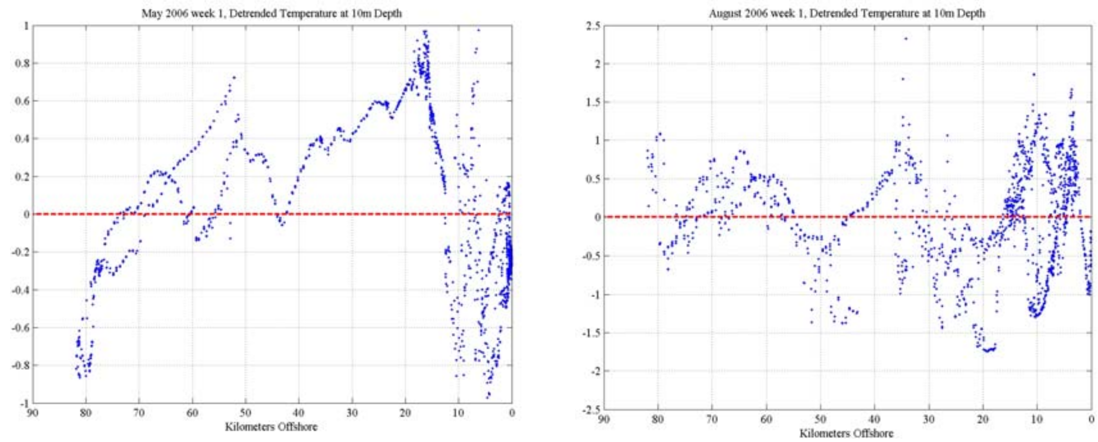

Figure 13. Detrended cross-shelf temperature variability for the first week in May 2006 (left panel) when the cross-shelf temperature gradient was 0.04°C/km and the first week of August 2006 (right panel) when the cross-shelf gradient was 0.07°C/km.

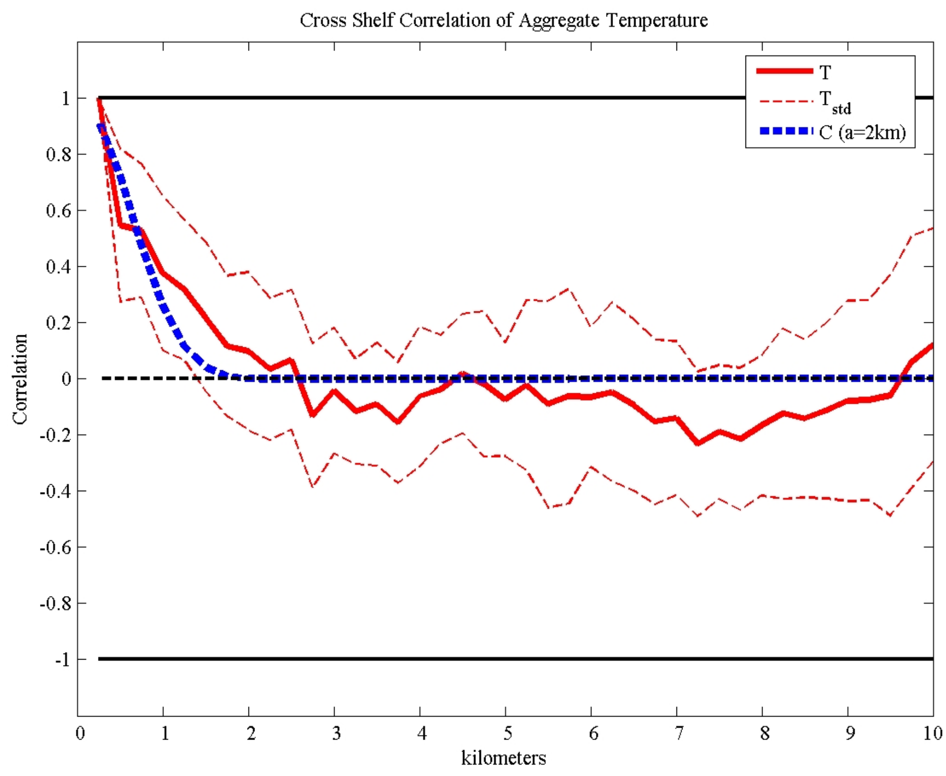

Figure 14. Cross-shelf correlation scale (blue solid line) determined at 10m depth from temperature (red solid line), standard deviation of temperature is shown as a red dashed line.

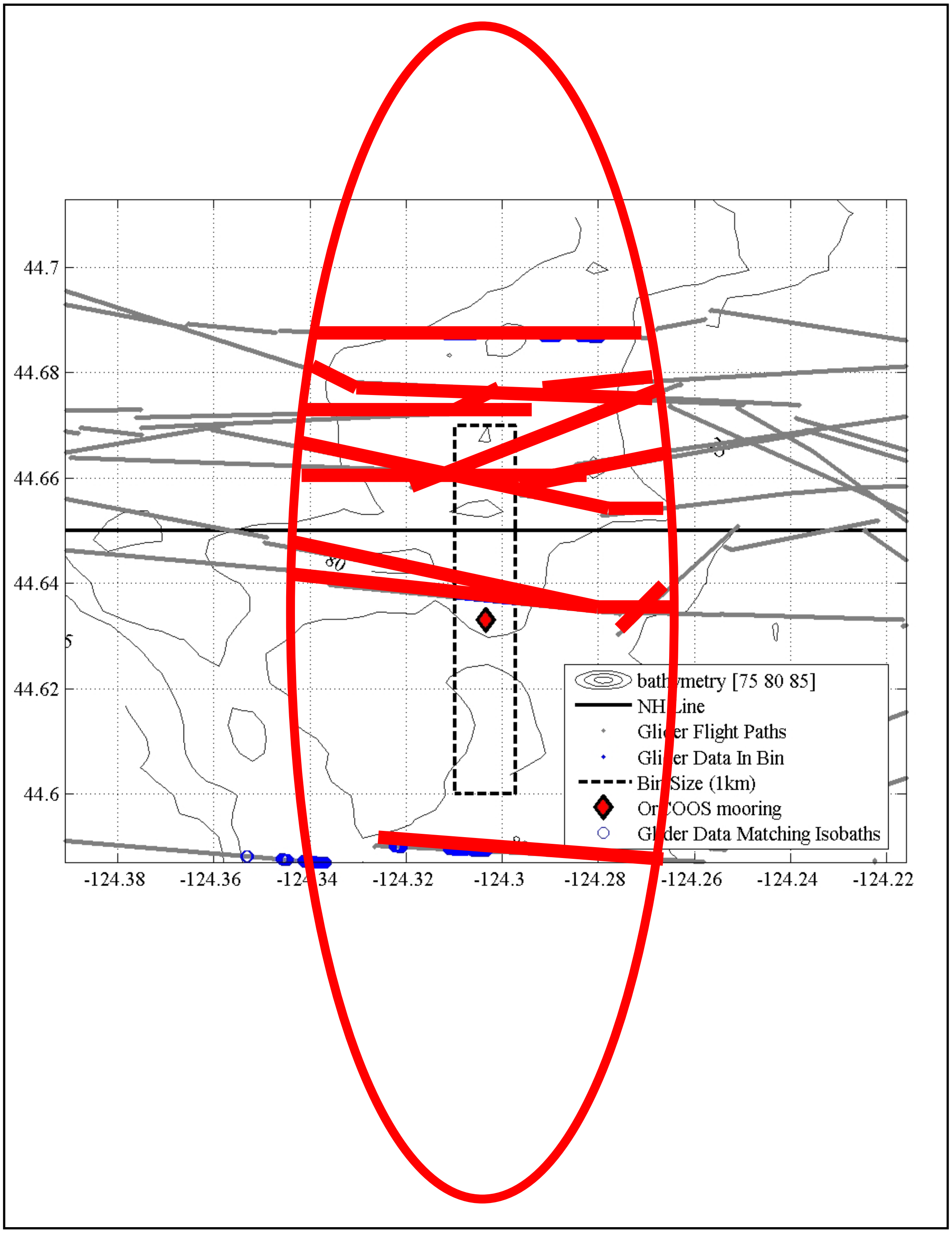

Figure 15. Similar to Figure 10, the red objective analysis "ellipse" is defined by the cross-shelf and along-shelf correlation scales. Data within the ellipse are weighted by the correlation function with a value of 1 at the center to 0 at the ellipse edges. This ellipse is centered at the OrCOOS mooring (red diamond). The dashed box indicates the size of the isobath-binning method's 1 km bin size.

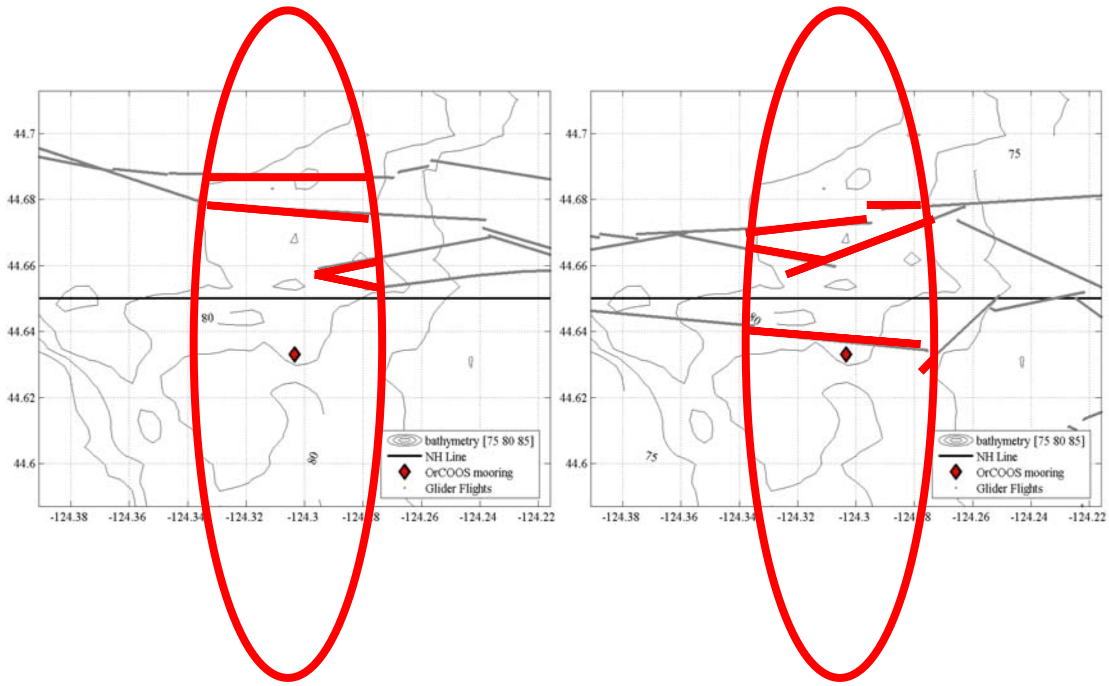

Figure 16. Error estimates from weekly August 2006 data demonstrating the geometric distribution of data. Left panel is the first week in August, has error estimate of 0.6. Right panel is the third week in August, has error estimate of 0.1.

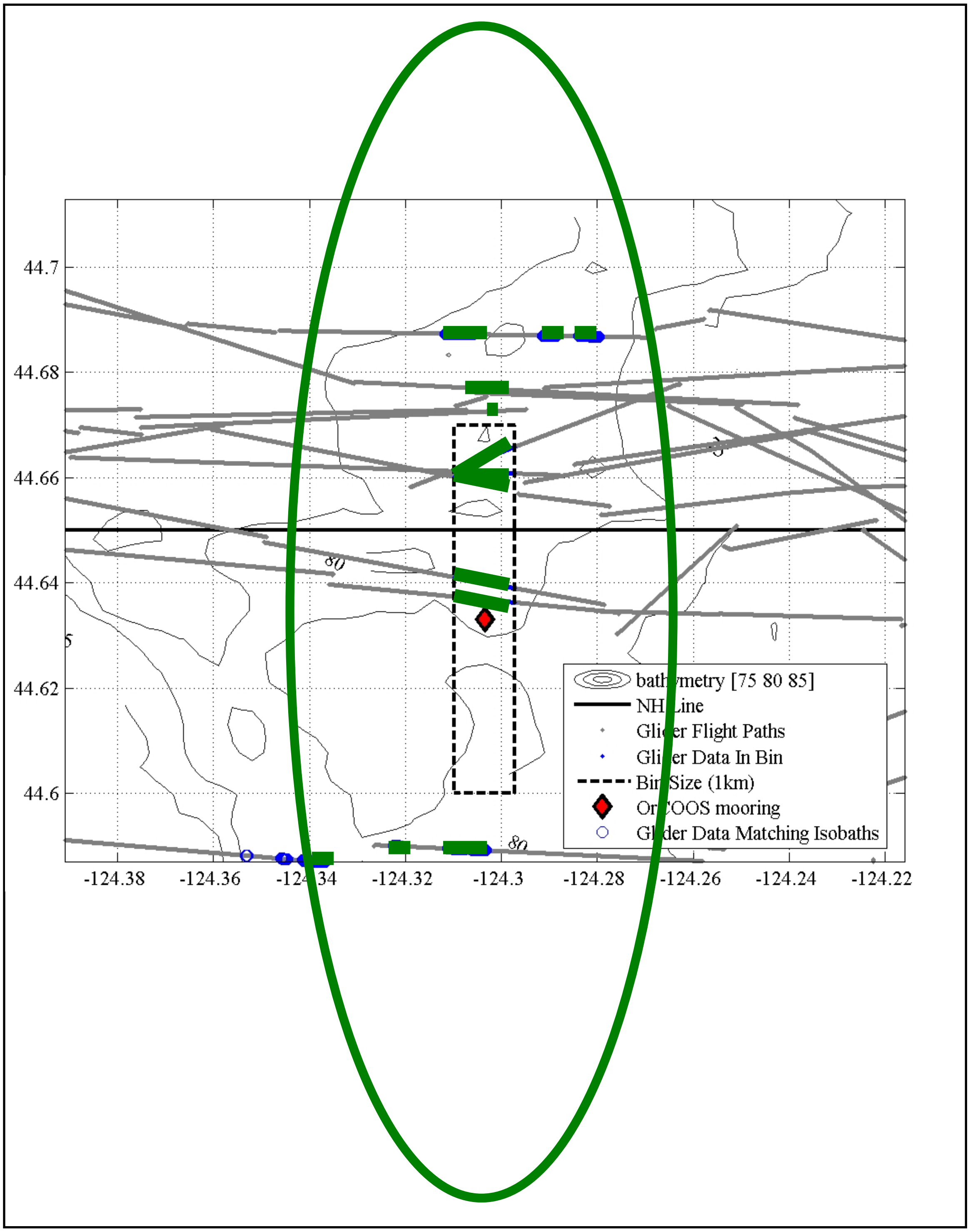

Figure 17. Similar to Figures 10 and 15, the hybrid method's green "ellipse" is overlaid onto the isobath-binning method. All data within the dashed box are considered a direct reading at the OrCOOS mooring (red diamond) and are supplemented with data recorded at identical isobaths. These data are weighted by the correlation function with a value of 1 at the center of the ellipse to 0 at the edges of the ellipse.

4. Results

Glider observations on the Oregon continental shelf along the NH Line are frequent although non-uniform in time and space. Applying the best method for grouping the semi-regular observations to the uniform grid of the NH Line is essential to accurately assessing the ocean conditions for many reasons, but mainly to know that the method applied will successfully capture the desired phenomena of concern. Three methods were applied to the glider data collected on the Oregon shelf, a block-average isobath-binning method, an objective mapping method, and a hybrid combination of the two. The results of the three methods are examined individually to determine validity, compared individually to the OrCOOS mooring to determine accuracy, and then contrasted to each other to examine inconsistencies or similarities.

The OrCOOS mooring is located at 44^{o}37.98'N, 124^{o}18.21'W (approximately NH-10) in 80m of water (http://agate.coas.oregonstate.edu) and deploys 13 sensors spanning the water column at depths of 4, 6, 8, 10, 15, 20, 25, 30, 40 50, 60, 70, and 73 meters. Seabird SBE-37 CTDs (conductivity-temperature-depth sensors) are located at 10, 20, 30, and 60 meters depth, and Seabird SBE-39 CTs (conductivity-temperature sensors) are located at all other depth locations, with the exception of the 73 m depth location which deploys a Seabird SBE 16plus-IM. The OrCOOS mooring has occupied this location since July 20th, 2006 and provides a timeseries (Figure 18) for comparison to glider data collected along the NH Line. Temperature data from the instruments along the mooring are temporally averaged to match the timescale resolution (monthly, fortnightly, weekly) of any particular glider analysis. Months that contained less than three weeks of glider data were excluded from the analyses, as were months that contained no OrCOOS data. Similarly, if data were collected for less than 75% of the fortnightly and weekly time periods, those periods were excluded from analysis. The temporally averaged mooring profile was compared to a profile extracted from a gridded glider section calculated at the exact location of the OrCOOS mooring. Comparisons between the mooring and all methods of glider mapping analyses are discussed below.

Gliders travel underwater at a horizontal speed of approximately 0.25 m/s, which equates to roughly 1 km/hr. At bin sizes of 1km, this means it takes the gliders about 1 hour to pass through a 1 km bin centered at NH-10 (the OrCOOS mooring location). In a month, the gliders traverse the NH-Line somewhere around 10 times, which means they spend less than half a day (total) collecting data in the vicinity of the OrCOOS mooring, which records temperature data every 60 seconds. The effort is made here to use the mapped glider data as a ”virtual” mooring even though the gliders spend a fraction of the mooring’s time collecting data at NH-10. These mapped glider-section profiles at NH-10 are compared to the OrCOOS mooring’s profiles to determine the validity of each method’s ability to accurately portray the ocean temperature.

4.1 Root Mean Squared Analysis

To statistically determine which method most accurately depicted the observations of the OrCOOS mooring, a root mean square (rms) analysis of the difference between the temperature profiles of each method (isobath-binned, objective analysis, and hybrid method) to the temperature profile of the OrCOOS mooring at the depths of every OrCOOS sensor was used for all timescales (Table 2). Therefore, a single rms result represents the difference between the profiles over the entire water column (Figure 19), and is a measure of the absolute departure of each method's profile from the OrCOOS profile. All methods compare closely with the OrCOOS observations – average rms differences range from 0.32-0.85 ^{o}C, approximately 27-71% of the total standard deviation. The analysis with the lowest average rms (0.32^{o}C) across all months was the 1 km isobath-binned block-averaged analysis at the monthly resolution, and it was closely followed by the same method/timescale at 2 km bin resolution. When each method's monthly rms value was averaged over the data record, the isobath-binning method had the closest agreement with the OrCOOS mooring at the monthly timescale. At the fortnightly timescale, the isobath binning method and the objective analysis have agreement with the OrCOOS mooring less than or equal to 0.50 ^{o}C. At the weekly timescale, the objective analysis and the isobath binning at 2 km bin resolution have the closest overall agreement with the OrCOOS method (0.45 ^{o}C). When comparing the rms results of an individually calculated timescale (i.e. all three methods compared during the first week of August instead of the average performance of the weekly timescale of each method across the data record), the objective analysis did have better agreement to the OrCOOS mooring than the isobath binning method occasionally, most often in the weekly timescales, sometimes at the fortnightly timescale, but never at the monthly timescale. The hybrid method, when averaged across all timeframes, never had the closest agreement to the mooring, however it had closer agreement to the mooring than the objective analysis at the fortnightly timescale (40%). It is important to note that the variability in rms differences is small (compared to the natural variability in the temperature field), and the significance of these comparisons is undetermined, however the consistently lower rms values for the IB method at monthly timescales is compelling.

An rms value provides a method for quantifying the absolute departure of each method's profile from the OrCOOS profile, but it does not indicate from where the disagreement stems or if it is spread over the entire water column. To determine where the methods had the most agreement/disagreement with the mooring, the difference at each depth was examined through box and whisker plots (Figures 20-22). These boxplots represent the residuals of the entire data record per timescale at each depth. The median is indicated with a red line, and data that falls within the blue box represent the breadth of the second and third quartile, and comprise half of the data record. The whiskers indicate the first and fourth quartile, and any red marks outside these quartiles are outliers that are defined as 1.5 times the variance of the second and third quartile.

The isobath binning method had three different bin sizes (2 km, 1 km, and 500 m) and three different timescales (monthly, fortnightly, and weekly). At the monthly timescale, there were a few similarities between all three bin sizes, 1) below 15m depth, the isobath binning method almost always calculated temperature warmer than the mooring, 2) below 30m depth, almost all data are within 0.5 ^{o}C agreement with the mooring, 3) in the upper 10 m of the water column, the medians are very close to zero which indicates that the method calculates temperature warmer than the mooring as many times as it calculates temperature cooler than the mooring, and 4) the most variance in the profile was at 15 m depth. The 2 km and 500 m bin sizes had more variance at 25 m depth than the 1 km bin size. Below 30 meters depth in the 2 km bin size, there were two outliers outside of 0.5 ^{o}C agreement with the mooring at 40 m and 50 m. In the upper 10 m, in the 1 km bin size, 50% of all data fell within 0.5^{o}C agreement with the mooring, while in the 500 m bin size, almost all data fell within 0.5^{o}C agreement.

At the fortnightly timescale, there were a few similarities between all three bin sizes: 1) the medians are all within 0.5^{o}C of agreement with the mooring, 2) the greatest variance is located at 15 m depth (at 500 m, the variance is greater than 2.0^{o}C, and in the 2 km bin size, the variance is greater than 2.5^{o}C), 3) below 30m, most of the data fall within 0.5^{o}C, with at least two outliers at every depth, except at 70 m and 73 m which have only one (more outliers associated at depths below 30 m in the 2 km and 500 m bin sizes), and 4) at depth below 30 m, this method almost always calculated temperature warmer than the mooring with few exceptions. In the 2 km and 1 km bin sizes, the variance at 15 m depth was greater than 2.5^{o}C. In the upper 10 m, the 2 km bin size had 50% of data fall within 0.5^{o}C of agreement with the mooring, the variance was greater than 2^{o}C everywhere, and there was one rms value that was colder than the mooring by 1.5^{o}C everywhere. In the upper 10 m at the 1 km bin size, the data variance was at least 2.0 °C everywhere, and in the 500 m bin size, there was less variance than the 1 km bin size, with 50% of the data surrounding the median within 0.5^{o}C agreement with the mooring, but there were more outliers.

At the weekly timescale, there were a few similarities between all three bin sizes: 1) below 50m, most data within 0.5^{o}C (outliers in all bin sizes at 70m), 2) in the upper 10 m, the medians were closest to zero of entire water column at this timescale with outliers warmer than 2.0^{o}C from mooring at 4m depth in all bin sizes (with an outlier colder than mooring by greater than 2.0^{o}C at 6m in the 500 m bin size), 3) in the upper 10 m, this method calculates temperature colder than mooring almost half the time, and 4) most variability was located at 15 m and 20 m with at least one rms value at 15 m and 20 m greater than 2.0^{o}C warmer than mooring. In the 2 km bin size and the 1 km bin size at 15 m and 20 m depth, the variance was greater than 2.5^{o}C, and in the 500 m bin size the variance at 15 m depth was almost 3.0^{o}C. In the 2 km bin size, 50% of the data surrounding the median had less than 0.5^{o}C agreement with the mooring at depths of 30m and lower. In the 1 km bin size, most of the data fell within 0.5^{o}C agreement with the mooring below 40 m depth. In the upper 10 m in the 500 m bin size, the variance was roughly 2.0^{o}C.

The objective analysis calculated temperature directly at the OrCOOS mooring and does not involve specified bin sizes (the smoothing is achieved through the correlation scales), but was analyzed at three timescales (monthly, fortnightly, and weekly). At the monthly timescale, within the upper 10 m, the median was always colder than the mooring, with a variance greater than or equal to 3.0^{o}C at all depths. At depths 15 m to 30 m, the medians were close to zero with a data variance of 1.5^{o}C or greater. At depths 40 m and below 50% of the data surrounding the median were less than 0.5^{o}C warmer than the mooring (with an outlier at 40 m depth greater than 1.0^{o}C).

At the fortnightly timescale, within the upper 10 m, the medians were close to zero, and the 2nd and 3rd quartiles had less variance than the monthly timescale. In the upper 10 m, there were rms values colder than the mooring by more than 2.0^{o}C at every depth, and rms values warmer than the mooring by 2.0^{o}C at 4m depth. At 30 m depth, there were two outliers warmer than the mooring and two colder, with one outlier warmer than the mooring by greater than 2.0^{o}C. At 25 m depth and below, the 2ns and 3rd quartile had less than 0.5^{o}C agreement with the mooring, with two warmer outliers at all these depths with the exception of 70 m and 73 m which only had one outlier warmer.

At the weekly timescale, the medians were close to zero at all depths with the largest departure in agreement with the mooring at depths of 25 m and 40m. There were fewer outliers with depth associated with this timescale than the previous two, and when they were present, they were closer to the data ranges than the other timescales. In the upper 10 m, 50% of data was within 0.5^{o}C of agreement with the mooring, except at 10 m, which was just over 0.5^{o}C agreement, and the data variance at these depths hovers around 2.0^{o}C. There were four outliers at 4 m depth, three calculated temperature colder than the mooring by greater than 1.0^{o}C, and one calculated temperature warmer than the mooring by greater than 1.0^{o}C. At 15m depth and below, 50% of all data was within 0.5^{o}C agreement with the mooring, and at 25 m and below, the data ranges, excluding outliers, are less than 1.0^{o}C.

The hybrid method employed three bin sizes (2 km, 1 km, and 500 m) at three different timescales. At the monthly timescale, there were a few similarities with all three bin sizes: 1) at 40 m depth and below, all data were within 0.5^{o}C agreement with the mooring with an outlier at

40m greater than 1.5^{o}C warmer than mooring, and 2) the agreement with the mooring increases with depth. Characteristics of the 2 km bin size are that the temperature variance is largest (>3.0^{o}C) at 8 m and 10 m, and in the upper 10 m, the medians were close to zero and 50% of the data closest to the median were within 1.0^{o}C agreement with the mooring. In the 1 km bin size, the most temperature variance was at 4 m depth (almost 3.0^{o}C), and the medians at all depths are close to zero (excepting 15 m depth location, which was still within 0.5^{o}C). At 30 m depth and below, all data were within 0.5^{o}C of agreement with the mooring, with outliers at 40 m and 70 m that were greater than 1.0^{o}C warmer than the mooring. In the upper 15 m, the greatest departures in temperature from the mooring appear to be when the hybrid method calculates temperatures warmer than the mooring. In the 500 m bin sizes, at 15 m and below, the medians are close to zero, with the largest separation from the mooring at 40 m. The greatest variance is at 4 m, 6 m, and 15 m depth, with one value greater than 2.0^{o}C warmer than the mooring at 4m. In the upper 15 meters, 50% of the data is within 1.0^{o}C agreement with the mooring, and the largest separations from the mooring appear to be when the temperatures are calculated warmer than the mooring.

At the fortnightly timescale, the hybrid method had much variance when compared to the mooring. There was one similarity between all bin sizes: there were multiple depth locations with temperature variance greater than 3.0^{o}C. The 2 km bin size had less variance at this timescale than the other two bin sizes, and between 40 m and 70 m, it had agreement within 0.5^{o}C of the mooring with the exception of one outlier at each depth greater than 1.0^{o}C warmer than the mooring. In the 2 km and 1 km bin sizes, the medians were close to zero, and at least within 0.5^{o}C agreement with the mooring at all depths, and at 40 m depth and below, both of these bin sizes calculated temperature warmer than the mooring.

At the weekly timescale, there were a few similarities between all bin sizes: 1) in the upper 10 m, the medians were all close to zero, 2) at 30 m depth and below, all data was within 1.0^{o}C agreement with the mooring (excepting a small number of outliers) – in the 1 km bin size, all data was within 0.5^{o}C agreement, 3) below 25 m, the hybrid method had a tendency to calculate temperature warmer than the mooring, and 4) at 50 m and below, the data ranges are the smallest. In the 2 km and 1 km bin sizes, the greatest variance (>3.0^{o}C) is at 15 m depth, while the greatest variance in the 500 m bin size was located at 4 m depth (~3.0^{o}C). In the 1 km bin size, in the upper 10 m, 50% of the data congregated around median was within 0.5^{o}C agreement with the mooring, and there were rms values greater than 1.0^{o}C at all depths

In summation, all three methods compare closely to the observations at the OrCOOS mooring, with overall rms values that are small compared to the total temperature standard deviation. The isobath binning method indicates the most deviation for this method is located at

15 m depth, and the smallest deviation is below 40 m depth. This method had the closest agreement with the mooring of all methods in the upper 10 m of the water column, and had a tendency to calculate temperature warmer than the mooring at depths below 15 m. The monthly timescale has the closest agreement with the mooring at all depth locations as indicated by the lowest overall rms values for this timescale, and the medians at almost all depths and timescales were close to zero (Figure 20).

In the objective analysis method, examining the variability of residuals with depth indicates that agreement with the OrCOOS mooring appears to be strongest below 25 meters depth across all timescales, with more than 90% of all data below this depth agreeing with the mooring within 1^{o}C. At the timescale with the closest agreement to the mooring, the weekly timescale, the objective analysis appears to have the greatest variability in the upper 15 meters (Figure 21). The medians at all depths are very close to zero, indicating the rest of the data cluster around these readings that are close in agreement with the mooring. As the timescales get longer the box representing the second and third quartiles (50% of the data) get larger, indicating more variability. In the monthly timescale, the results are the same – below 25 meters, the agreement is less than 1^{o}C (with one outlier), and the greatest variability is in the upper 15 meters. The variability in the upper 15 meters at this timescale is larger than at the weekly timescale, leading to the lower overall rms value at the weekly timescale. The objective analysis has the most disagreement with the mooring profile in the upper 15 meters, often calculating temperature cooler than the mooring, with the most variability at 15 meters.

The results of the hybrid method were ambiguous. The depths below 20 meters have good agreement with the mooring profile, and the largest disagreement is in the upper 15 meters. Similar to the isobath binning method, the most variability is usually at 15 meters - the approximate location of the mixed layer – and it appears the greatest departures in temperature from the mooring occur when the hybrid method calculated temperature warmer than the mooring. There are more outliers associated with the objective analysis, but the overall difference between rms analyses over the entire profile seems to indicate the objective analysis has closer agreement with the mooring than the hybrid method does (Figures 21, 22). The areas where the hybrid method experiences the most difficulty seems to be similar to the objective analysis; the upper 20 meters. At the fortnightly timescale, bin size does not seem to make much difference in the overall rms values, with all bin sizes experiencing large variance and hovering around an overall rms of 0.70^{o}C, and in the monthly timescale, the 500 m and 1 km bin sizes hover around 0.65^{o}C.

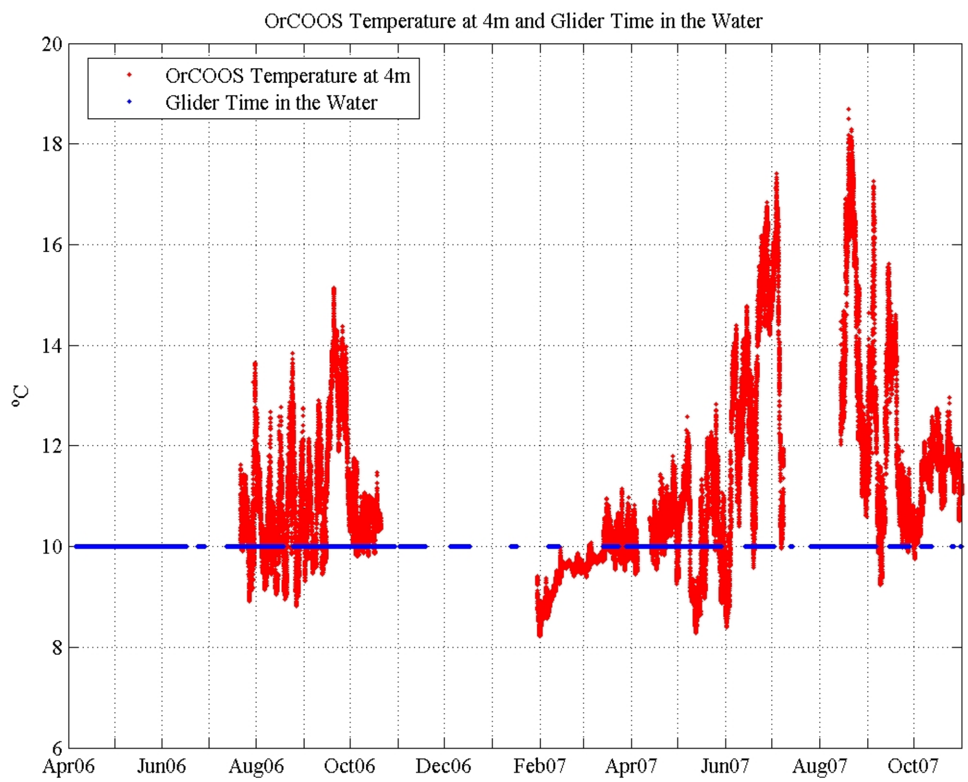

Figure 18. Timeseries of OrCOOS mooring temperature at 4m depth (red) and the time record of glider deployment in the ocean (blue).

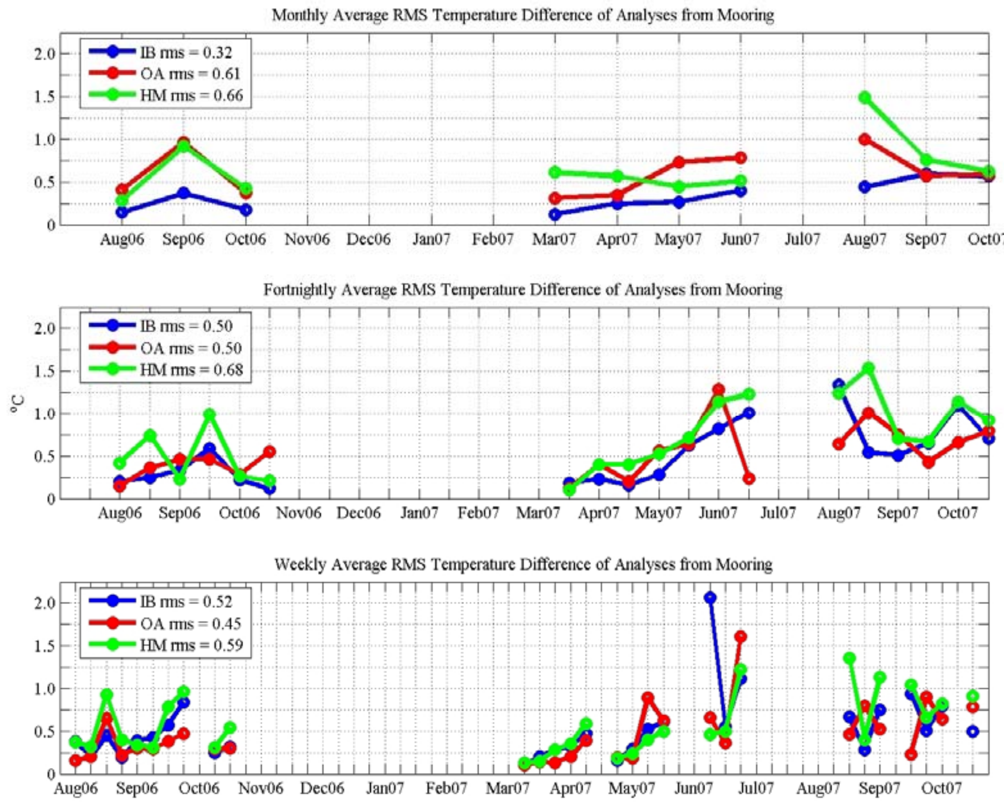

Figure 19. Overall RMS temperature values (^{o}C) for all profiles from all three methods at the 1 km bin size for all three timescales, monthly (top panel), fortnightly (middle panel), and weekly (bottom panel) . Legend indicates the mean RMS temperature value per method at each timescale.

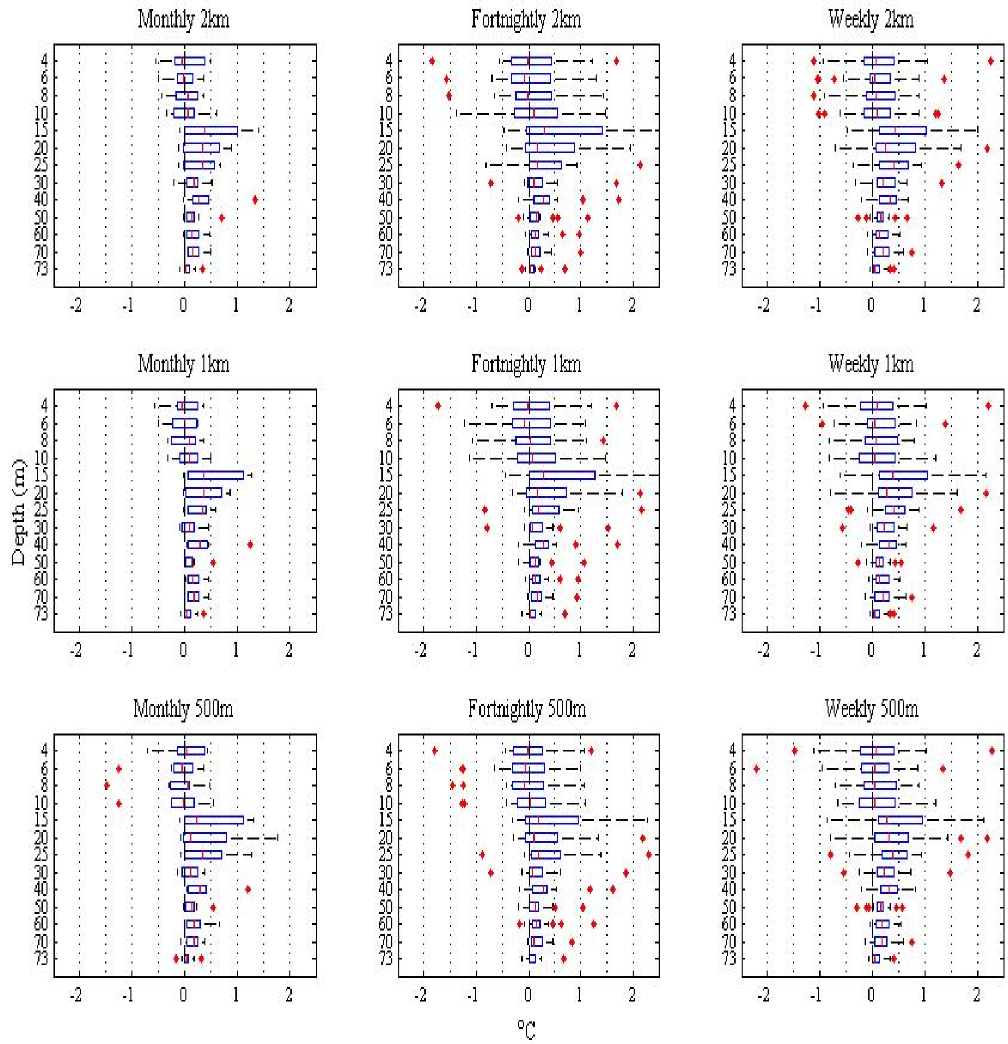

Figure 20. Box and whisker plots of the temperature residuals for all timescales and bin sizes for the data record according to depth. Residuals are the Isobath Binning method (IB) subtracted from the OrCOOS mooring (OR) at the monthly timescale. Red lines are medians, blue box represents 50% of the data, and the red dots are outliers.

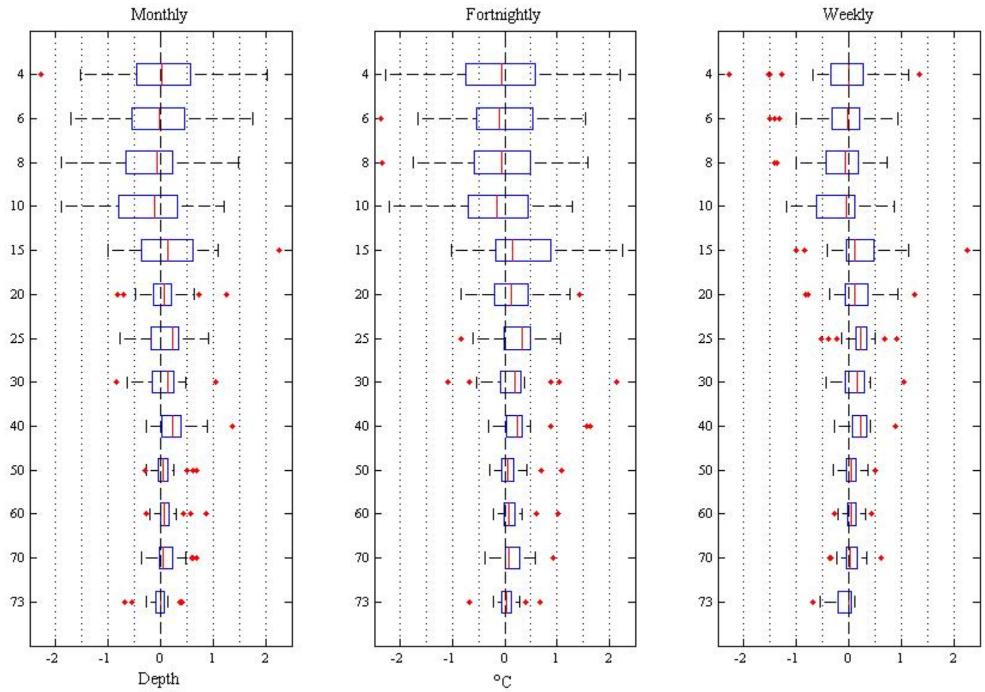

Figure 21. Box and whisker plots of all temperature residuals for all timescales for the data record according to depth. Residuals are the Objective Analysis method (OA) subtracted from the OrCOOS mooring (OR) at the monthly timescale. Red lines are medians, blue box represents 50% of the data, and the red dots are outliers.

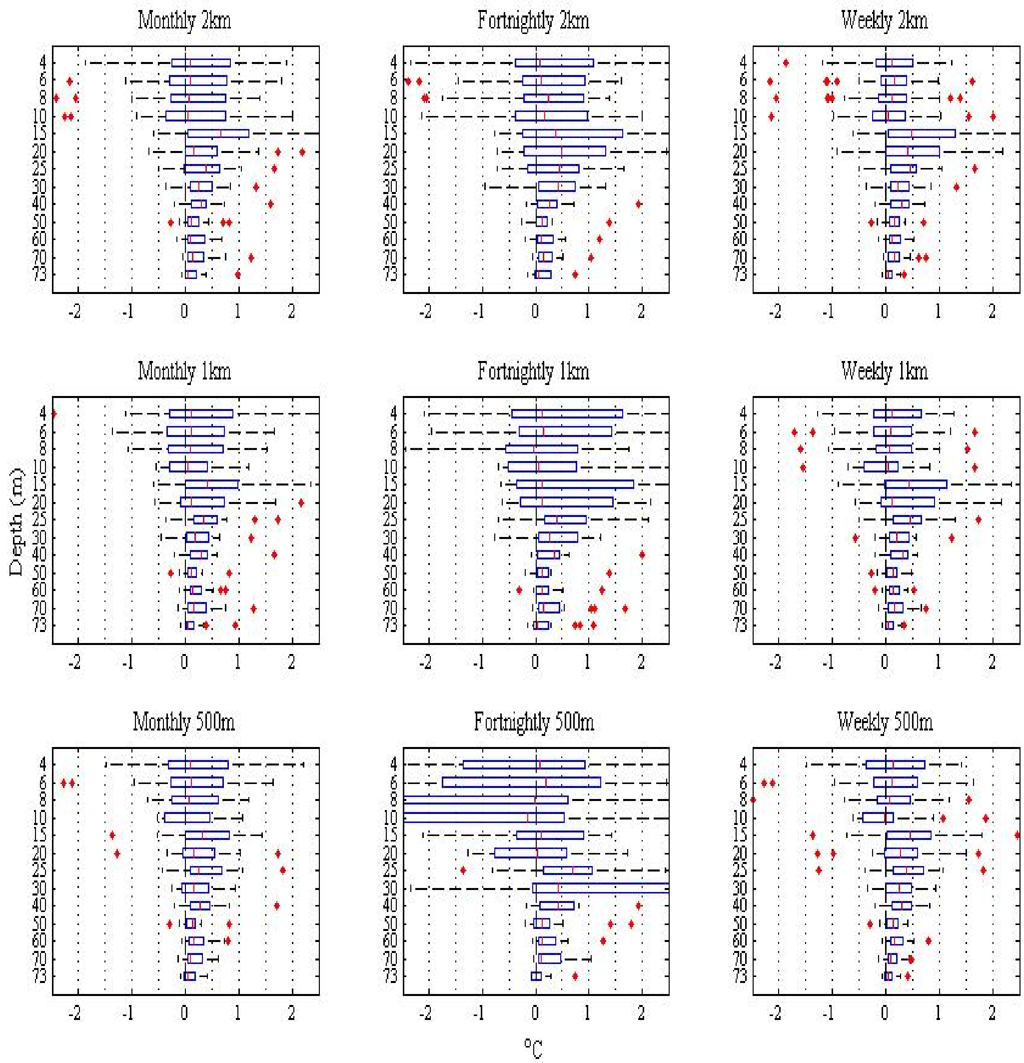

Figure 22. Box and whisker plot of the temperature residuals for all timescales and bin sizes for the data record according to depth. Residuals are the Hybrid Method (HM) subtracted from the OrCOOS mooring (OR) at the monthly timescale. Red lines are medians, blue box represents 50% of the data, and the red dots are outliers.

TABLE 2
Root Mean Square of the difference between OrCOOS Mooring Temperature and Isobath Binned Temperature, Objectively Analyzed Temperature, and Hybrid Method Temperature

MONTHLY	AVERAGE
500m Bin Resolution - 4km swath	0.38
1 km Bin Resolution - 4km swath	0.32
2 km Bin Resolution - 4km swath	0.33
Objective Analysis (x=2, y=7.5)	0.61
Hybrid Method 500m (x=2,y=7.5)	0.64
Hybrid Method 1km (x=2,y=7.5)	0.66
Hybrid Method 2km (x=2,y=7.5)	0.77

FORTNIGHTLY	AVERAGE
500m Bin Resolution - 4km swath	0.47
1 km Bin Resolution - 4km swath	0.50
2 km Bin Resolution - 4km swath	0.50
Objective Analysis (x=2, y=7.5)	0.50
Hybrid Method 500m (x=2,y=7.5)	0.69
Hybrid Method 1km (x=2,y=7.5)	0.68
Hybrid Method 2km (x=2,y=7.5)	0.70

WEEKLY	AVERAGE
500m Bin Resolution - 4km swath	0.49
1 km Bin Resolution - 4km swath	0.52
2 km Bin Resolution - 4km swath	0.45
Objective Analysis (x=2, y=7.5)	0.45
Hybrid Method 500m (x=2,y=7.5)	0.68
Hybrid Method 1km (x=2,y=7.5)	0.59
Hybrid Method 2km (x=2,y=7.5)	0.85

5. Discussion

5.1 Block-Average Isobath-Binning Method

Intrinsically, a block average of a coarser resolution leads to smoother results than finer resolution averages because there are more data points per block. Finer resolution will enable distinction of smaller-scale phenomena normally glossed over with coarser resolution. The challenge is to determine which time resolution and which spatial resolution work best in conjunction to produce the desired effect of accurately portraying the ocean phenomena of concern. Large storms lasting a few days may assimilate into a monthly-averaged timeframe, while a weekly interval may showcase the reaction of the ocean to such an event.

It is important to determine whether or not the isobath-binning helps or hinders the block-averaging process in a quantifiable manner. To determine the validity of using the isobath binning method, two separate block-averaged analyses were performed per timescale/bin resolution, the first analysis included all data points that fell within the bins as determined by isobaths (Figure 11), and the second analysis included only data points determined to be an observation "directly" on the NH Line ("directly" means within 4 km north and south of the line, and mapped strictly by longitude to the NH Line, as discussed in Section 3). The results imply there is better agreement between the glider observations and the mooring observations when the glider data points that fall directly on the NH Line are supplemented by glider data mapped to the NH Line by corresponding isobaths (Figure 23).

The binning procedure is only as strong as its ability to correctly and uniformly place off-transect glider observations along the NH Line. Certain behaviors became apparent when applying this technique to the full data set, such as how to correctly compensate for Stonewall Bank, steep gradients collecting large amounts of data, and making the resolution (bin sizes) too fine. It is also possible that northern data maps to the NH Line in this method with more agreement than southern data. The bathymetry south of the NH Line contains strong features such as Stonewall Bank and Heceta Head that create a more complex environment than the simply sloping continental shelf north of the NH Line. It is possible that these seafloor formations complicate the current flow when it heads northward (downwelling favorable events) and that the along-isobath flow constraint is much stronger when flowing southward from simple bathymetry to complex bathymetry (upwelling favorable events).

Sometimes in the bin-averaged sections, there are areas containing no data above Stonewall Bank. This is usually because 1) there were no data collected that were considered directly on the NH Line at this longitude, and/or 2) the data at these isobaths were mapped either inshore or offshore of Stonewall Bank (recall the multiple locations of the same isobaths at Stonewall Bank). As mentioned previously, Stonewall Bank is an imposing structure on the continental shelf, and its effect on the coastal flow is difficult to resolve uniformly across a variety of timescales. In these binning analyses, Stonewall Bank is handled last, leading to a possible reason the data is sparser in this area of the gridded glider section; the area of the Stonewall Bank "bowl" (Figure 9) tends to have the least populated bins of the gridded glider transect.

Bins with a steep gradient tend to collect more than the average distribution of data. These steep gradients provide a larger window of isobaths into which off-transect glider data may match and are therefore highly populated (Figure 24). The bins with the steepest gradients create a visible vertical banding effect in the gridded glider sections. Perhaps creating a smaller bin resolution in these steep gradient areas would reduce the banding effect without distorting the rest of the gridded section. For the most part, these bins with larger populations do not appear to introduce error in any noticeable way within the bins – the data seem to average smoothly and merge into the large scale mean ocean structure. A probable reason for this is that the rest of the bins are still highly populated due to the voluminous nature of the glider observations. It seems the isobath binning and block-averaging needs are met by the high frequency of glider data on the whole, but it is difficult to map around these distinctive steep-gradient bins. When the resolution becomes finer, such as the 500 m bins, these columns of irregularity tend to decrease as the bin size decreases but bins with shallow gradients become sparse as their bathymetric window becomes smaller.

Sawtooth patterns, a glider's vertical flight trajectory in the water column, are visible within the bins at the finest resolutions. A glider usually takes one week to travel to the end of the NH Line and back, so a temporal scale of a week represents two, perhaps three, glider transects. These sawtooth patterns emerge because the time scales are small enough to allow only a small number of transects across any particular longitude, and the spatial resolution is fine enough that the entire upward or downward profile of a glider is not contained within the same vertical bin column. Given the 26^{o} rise/dive angle of a glider's profile, the distance between a glider's position after one downward profile and one upward profile is roughly four times the water depth. In 125 meters of water, the 500 meter bin size is just large enough to contain one downward and upward profile. Data often do not populate all the bins in the section at this resolution, as sometimes a portion of either the upward or downward profile is collected off-transect and matches isobaths with a different bin than the rest of the profile. This situation occurs most often at smaller timescales.

Across the time period spanning April 2006 – November 2007 the isobath binning method appears to have the closest overall agreement with the OrCOOS mooring. The bin size with the closest agreement changes depending on the timeframe, (1 km closest at monthly, 500 m closest at fortnightly, 2 km best at weekly) but the differences are all within 0.07^{o}C of each other at all timeframes. The agreements between the isobath binning method at all bin sizes and the OrCOOS mooring profile are closest at the monthly timescale (Table 2).

5.2 Objective Analysis

The objective analysis is a powerful tool to apply to data. It spatially weights data according to the provided range of data with a predetermined correlation function. It is used in many oceanographic applications (e.g. World Ocean Atlas). Complexities do arise when using it in a coastal application such as the continental shelf of Oregon.

The first complexity of the objective analysis is determining the proper spatial correlation scales of the data, which in this example were the correlation scales of temperature data in the along-shelf and cross-shelf direction. On the continental shelf off Oregon, upwelling, downwelling, and transitional regimes exist in the ocean and effectively shift the longitudinal location of the temperature front and thermocline along the NH Line. Determining a valid universal correlation scale for temperature across these different regimes proves difficult as this temporal change in ocean temperature structure is translated into spatial variability. The cross-shelf correlation scales are small (2 km) and these varying regimes and the frequency of variability they introduce when averaged across a timespan as long as a year are a possible cause of these small correlation scales. Another possible reason is that the high spatial and temporal resolution of a glider encapsulates more temperature variation in the ocean than previously recorded. An alternate approach to calculating the correlation scales could be to group the data record into upwelling, downwelling, and transitional regimes by some criteria (such as wind direction) and determine the temperature correlation scales specific to each regime. Perhaps these new correlation scales might change compared to the universal one calculated in this analysis, fit each regime more specifically, and enable the objective analysis profiles to more closely match the OrCOOS mooring profile.

Another complexity of the objective analysis is the orientation of the correlation "ellipse" to the NH Line. The correlation "ellipse" is the resulting data-inclusive footprint that occurs when combining the along- and cross-shelf correlation scales. It is elliptical in shape because the along-shelf scales are longer than the cross-shelf scales, and it is oriented orthogonally to the NH Line simply because the along- and cross-shelf scales were defined in Cartesian space. The isobaths of the continental shelf do not cross the NH Line at an orthogonal angle, nor do they cross at a uniform angle. The along-shelf correlation scale now becomes a factor as it sometimes reaches past the extent of the identical isobaths and includes data collected from deeper isobaths (as the footprint stretches north) and from shallower isobaths (as the footprint stretches south) than the one at the NH Line, depending upon the longitudinal position along the NH Line. This introduces the averaging of unlike water with equal weighting, and even though this water is at the lesser-weighted extents of the ellipse, the data are still included in this analysis, where they are excluded in the isobath-binning analysis.

Error estimates are calculated when using objective analysis, and quantifies how the data are geometrically distributed within the ellipse. In the comparison with the OrCOOS mooring, error estimates that are equal to or less than 0.1 are considered a good geometric distribution of data within the ellipse (Figure 16). At the monthly timescale, 60% of the months had an error estimate less than 0.1, and of these months, only 50% had an overall rms value of less than 0.5^{o}C. The remaining months with error estimates greater than 0.1 (40% at the monthly timescale) had overall rms values of less than 0.5^{o}C of the mooring 25% of the time. These percentages are similar for the fortnightly and weekly timescales, which illustrates that spatial distribution is not the only important factor in the objective analysis. The other factor involved is temperature variability across time. In these analyses, all data within a timeframe are considered synoptic, but obviously are not. Within a given timeframe, if a glider passes close to the mooring during an anomalous event, and passes a farther distance away from the mooring during more representative ocean conditions during the given timeframe, the objective analysis will weight the anomalous event heavier than the rest of the data since it was observed with the closest proximity to the mooring. These error estimates are useful, but do not always indicate the level of agreement with a fixed mooring.

5.3 Hybrid Method

The hybrid method maps data to the NH Line by matching isobaths from the data field to the NH Line bathymetry. Once mapped into bins, the same correlation function used in the objective analysis is applied to the data in the bins. The premise of this combination was to devise a method which oriented the objective analysis' ellipse along the angle of the isobaths as they intersect the NH Line. It was assumed that excluding all data that didn't match the isobaths of the bin along the NH Line would intrinsically orient the ellipse along this bathymetric angle. The hybrid method includes much less data than the objective analysis (Figures 15, 17), and produced different results from the block-average isobath binning method since the data are weighted according to the correlation scales defined in the objective analysis. In the isobath binning method, the along-shelf correlation scales are essentially infinite, as all data are weighted equally in the block-average. In the hybrid method, this is not the case. The hybrid method displayed traits of both methods – there is indication that at the monthly timescale, in the upper 10 m of the water column, the hybrid method is an improvement upon the objective analysis' agreement with the OrCOOS mooring, as the hybrid method displays ranges of data more closely associated with the isobath-binning profiles at these depths. Perhaps this indicates the objective analysis includes too much data. On the other hand, the fortnightly and weekly timescales had ambiguous results. While there were certain periods over all timescales that an individual hybrid method profile had closer agreement with the mooring than an individual objective analysis profile, these instances represent a minority of the data set (20% weekly, 25% fortnightly, 30% monthly), they are probably attributed to the ability of the isobath-binning method to agree with the mooring at larger timescales in the upper 10 m – locations where the objective analysis had the most disagreement with the mooring. The hybrid method profiles individually had closer agreement with the mooring than the isobath binning method profiles less frequently (15% at the weekly and fortnightly timescales, and none (0%) at the monthly timescales).

Error estimates are also calculated in the hybrid method, since it employs the objective analysis. The results of the error estimates are similar to those of the objective analysis. At the monthly timescale across all bin sizes, the hybrid method has error estimates of less than or equal to 0.1 for 60% of the time, and out of those months, only 30% of them have an overall rms value of less than or equal to 0.5 ^{o}C. Of the remaining months that have an error estimate above 0.1, 75% of them have an overall rms value of less than 0.5 ^{o}C. The results are similar for the fortnightly timescale – 40% of the data have an error estimate at or below 0.1, and of that 40%, only 30% are within 0.5 ^{o}C of agreement with the mooring. Only 10% of the profiles have an error estimate that is less than or equal to 0.1 at the weekly timescale. These error estimates are different from the error estimates of the objective analysis, but again must be understood for what they are, a representation of the geometric distribution of data within the correlation ellipse. When the hybrid method excludes non-matching isobath data, it potentially removes data close to the mooring, which would improve the distribution of data for the error estimate calculation. The focus should be on the agreement of the hybrid method to the mooring, however, and the error estimate is only a tool to help quantify that agreement by assessing spatial distribution, not temperature patterns in the ocean.

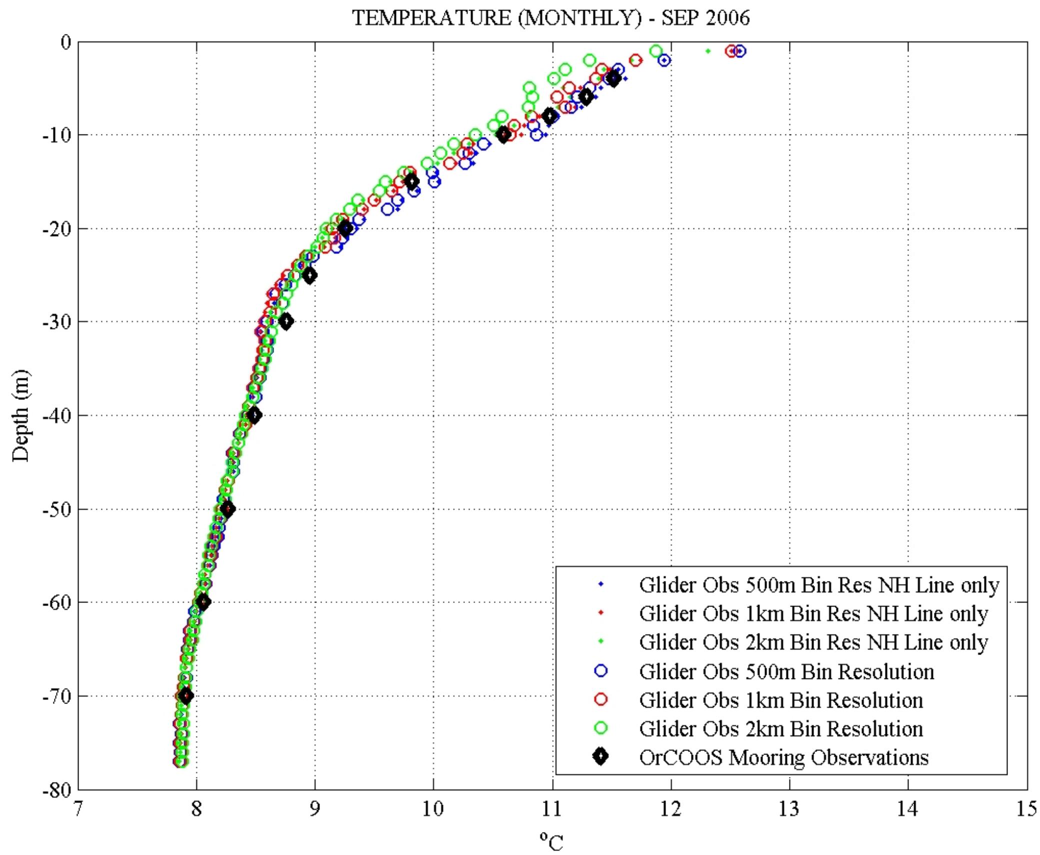

Figure 23. Comparison of OrCOOS mooring profile in the month of September 2006 to the Isobath binning procedure and the glider observations mapped directly to the NH Line according to longitude.

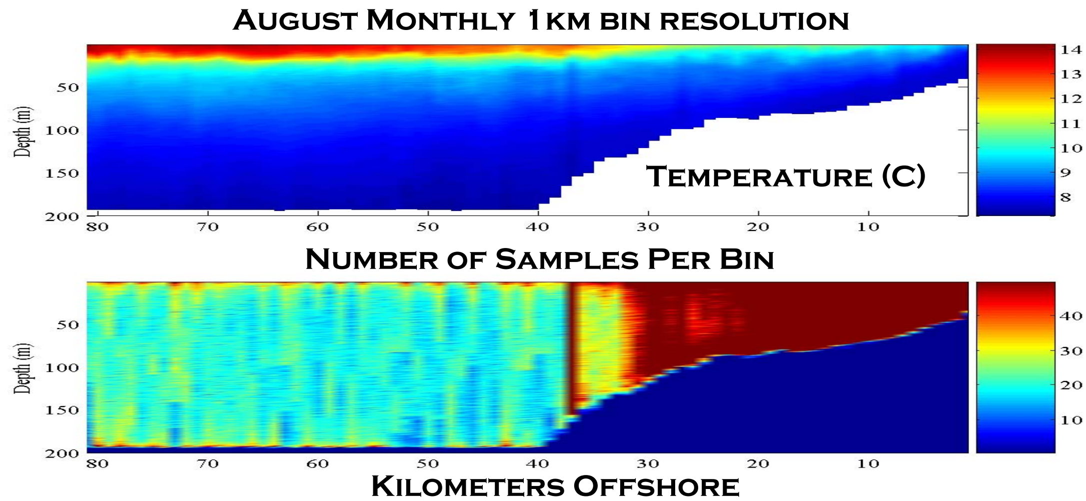

Figure 24. Gridded glider section of temperature for the month of August 2006 using the isobath binning method (top panel) and the number of samples per bin (bottom panel).

6. Conclusions

Three methods were analyzed to evaluate their ability to successfully map a large number of non-uniformly collected data to a uniform grid. The first was a block-averaging method that binned data to the uniform grid according to the isobath at which the data were collected, the second was an objective analysis, which used a covariance function with separate along- and cross-isobath length scales estimated from the observations, to spatially weight the irregularly spaced data prior to averaging, and the third was a hybrid method that binned data to a uniform grid by similar isobaths and then spatially weighted the data using a covariance function. The results of these methods were compared to the OrCOOS mooring, which resides at 80 m depth along the NH Line to test accuracy of the mapping calculations. While each method has advantages and disadvantages, all compared closely with the mooring observations.

The isobath-binning method performed the best across all temporal variations, and was an improvement upon simply binning by longitude. The timescale/bin resolution with the closest agreement to the OrCOOS mooring was the monthly timescale with 1 km bin size. All bin sizes performed closely at this timescale, and quantified the surface waters (upper 10 m) with the closest agreement to the mooring of all timescales and analysis methods. In general, this method seemed to calculate temperature close to but warmer than the mooring at lower depths, with the most variability at 15 m, the depth of the mixed layer and thermocline. It appears the along-isobath flow of water is a strong constraint, and a good method by which to map off-transect data collected on the Oregon continental shelf. The disadvantages of this method are the accumulations of data into bins with steep gradients, and the liability of correctly placing data collected directly over Stonewall Bank.

The objective analysis provided a statistically rigorous method of spatially-weighting the data and had good agreement with the mooring at the shorter timescales, having its best overall agreement with the mooring at the fortnightly and weekly timescales. Perhaps the drop in number of glider passes at the mooring location (NH-10) that comes with a smaller timescale minimizes the inclusion of data collected far north or south of the NH Line, minimizing inclusion of unlike isobath data. There were more extreme values in this method than the isobath binning, mostly in the surface waters of the mixed layer and thermocline (the depths where the objective analysis had the most variance). This method frequently over-predicted temperature in the upper 10 m compared to the OrCOOS mooring. Improvements could potentially come from using multiple covariance functions with depth. Perhaps seasonality plays a larger role in cross-shelf correlations than assumed in this analysis (upwelling, downwelling regimes) and specifying correlation scales according to upwelling/downwelling might lead to closer mooring agreement. The isobaths along the Oregon coastline are irregular, and perhaps the uniform ellipse defined by the correlation function is not uniformly accurate along the continental shelf. The objective analysis seemed to smooth the data well, it seemed to have the most difficulties accurately quantifying the coastal jet and the surface waters which is perhaps a construct of the correlation scales including too much unlike water.

The hybrid method, binning by isobath with an along-shelf and cross-shelf covariance function, did not turn out to be the best of both worlds. The results are ambiguous, but seem to shed some insight about the other two methods. For instance, when dealing with a strong current, or areas with complex bathymetry, following the constraint of along-isobath flow appears to be a powerful method by which to spatially organize the data. In this analysis, with a focused characteristic such as the coastal jet and a shifting temperature front, the objective analysis smoothed the data in the surface waters too much. In the hybrid method, the isobath-binning step seemed to improve (by exclusion of data from unlike isobaths) the objective analysis' large temperature variances that were encountered at the shallower depths. The disadvantage of this fact is that sometimes the orientation of the isobaths to the NH Line placed the off-transect data outside of the correlation ellipse and therefore out of range (too far northeast) for the spatial-weighting of the orthogonally–oriented correlation ellipse. Perhaps improvement upon the correlation scales in the objective analysis might also help the hybrid method to have better agreement with the mooring. Perhaps shifting to an isobath-oriented grid would be more successful than overlaying the objective analysis' correlation ellipse to the isobath-binned data.

It appears that the statistically sound choice for a larger timescale is to use the isobath binning method with a bin size of 1 km. For shorter timescales, either the objective analysis or the isobath binning is adequate for the entire water column; if the surface waters/mixed layer is the focus, then the isobath-binning method might be preferable, or if a statistical evaluation of data distribution is desired, then the objective analysis might be preferable.

Future steps for gliders are numerous. Using the methods described here to map a gridded glider section, it is now possible to compare the ongoing glider observations to the historical record along the NH Line. The historical record has a much coarser sampling resolution, and must be interpolated to obtain the same resolution as the gliders (Figure 25). Operationally, these historical observations can be compared immediately to incoming glider data to produce real-time anomaly plots of hydrographic and biological data. Scientifically, these gridded glider sections of density can be taken a step further to compute geostrophic velocities and transports, calculate heat budgets, create boundary conditions for numerical models, and calculate dynamic height and hence sea surface elevation in the near-shore areas that satellites cannot resolve.

In all of these ideas, given the size and nature of the glider data sets, it is important to think about correct placement of these off-transect observations in order to take full advantage of historical records and concurrently sampling moored observations. Technology has progressed much since the inception of the NH Line, the days of TENOC and one hydrographic cast at a station. Gliders are cutting-edge technology providing outstanding data resolution, but it is imperative not to sacrifice accuracy and spatial organization is a keystone.

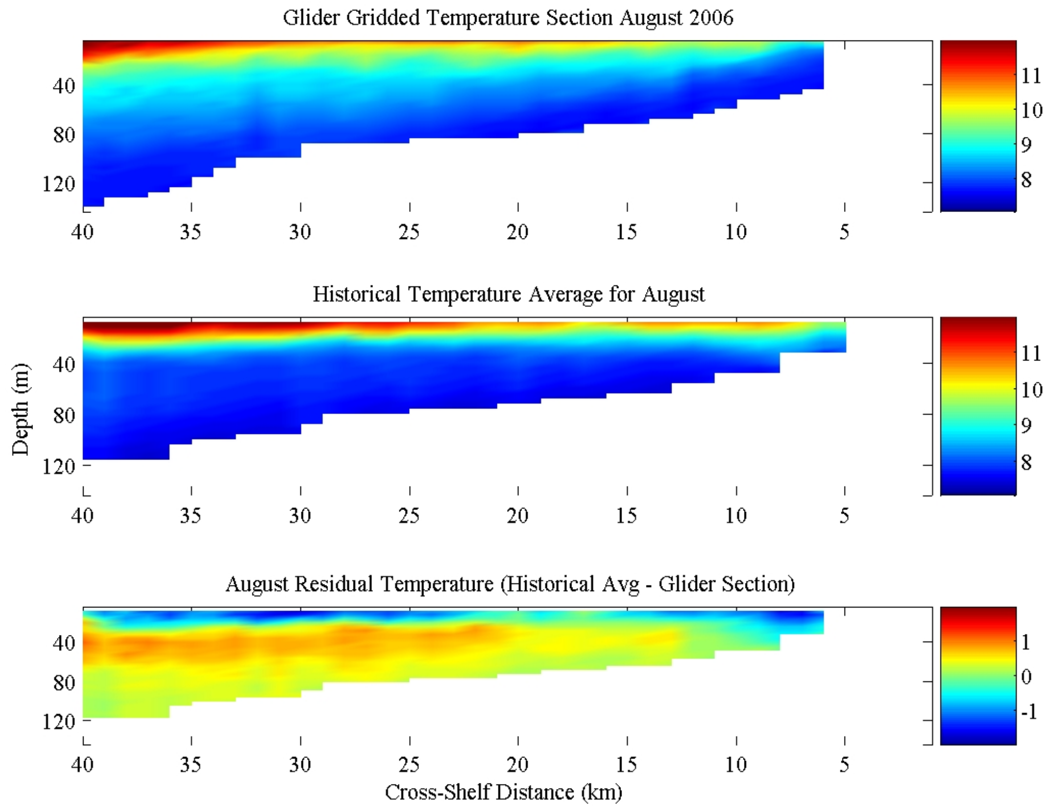

Figure 25. A gridded glider section of temperature (^oC) for the month of August 2006 (top panel) compared with an interpolated section of historically averaged temperature (^oC) for the month of August from 1961-2004 (middle panel) which when subtracted from one another produces a section of anomalous temperature (^oC) (bottom panel).

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APPENDICES

APPENDIX A – MATLAB CODE

ISOBATH BINNING STEP 1 (1 km bin resolution)

IB_step1_m_1km.m

This is the master file for the isobath binning method. This file will load the data, call the script that bins the data by isobath, and then call the script that averages the bins by depth.

```
%% load glider dbd data
beginning=datevec(now);
load oregon_bathy.mat;
load glider_transect_line.mat;
yearday=[
     datenum(2006,4,1);  datenum(2006,5,1); datenum(2006,6,1);  datenum(2006,7,1);...
     datenum(2006,8,1); datenum(2006,9,1); datenum(2006,10,1); datenum(2006,11,1);...
     datenum(2006,12,1); datenum(2007,1,1); datenum(2007,2,1); datenum(2007,3,1);...
    datenum(2007,4,1); datenum(2007,5,1); datenum(2007,6,1); datenum(2007,7,1);...
    datenum(2007,8,1); datenum(2007,9,1); datenum(2007,10,1;) datenum(2007,11,1);
    ];

 dataname=[
      'DBD_0604';
      'DBD_0605'; 'DBD_0606'; 'DBD_0607'; 'DBD_0608'; 'DBD_0609'; 'DBD_0610';...
      'DBD_0611'; 'DBD_0612'; 'DBD_0701'; 'DBD_0702'; 'DBD_0703'; 'DBD_0704';...
      'DBD_0705'; 'DBD_0706'; 'DBD_0707'; 'DBD_0708'; 'DBD_0709'; 'DBD_0710';...
      'DBD_0711'];

matname=[
      'raw_IB_m_1km_0604';  'raw_IB_m_1km_0605'; 'raw_IB_m_1km_0606';…
'raw_IB_m_1km_0607'; 'raw_IB_m_1km_0608'; 'raw_IB_m_1km_0609';…
'raw_IB_m_1km_0610'; 'raw_IB_m_1km_0611'; 'raw_IB_m_1km_0612'; …
'raw_IB_m_1km_0701'; 'raw_IB_m_1km_0702'; 'raw_IB_m_1km_0703'; …
'raw_IB_m_1km_0704'; 'raw_IB_m_1km_0705'; 'raw_IB_m_1km_0706'; …
'raw_IB_m_1km_0707'; 'raw_IB_m_1km_0708'; 'raw_IB_m_1km_0709'; …
'raw_IB_m_1km_0710'; 'raw_IB_m_1km_0711'];

for kk=1:length(yearday)-1
```

```
    eval(['load ' dataname(kk,:)])
    %% nan the data that's too far west
    goodlon=find(Lon>=-124.4);
    g=[ Julday(goodlon), Lat(goodlon), Lon(goodlon),...
        Pressure(goodlon), BottomDepth(goodlon),...
        Temp(goodlon), Salinity(goodlon), Sigmat(goodlon)];
    IB_step2_m_1km;
    eval(['save ',matname(kk,:),' T Tswath'])
    clear date g T Tswath
    disp(kk)
    datevec(now)
end

disp('Step 2 of 3 complete')
datevec(now)
IB_step3_m_1km;
disp('Step 3 of 3 complete, total runtime was...')
runtime=datevec(now)-beginning
```

ISOBATH BINNING STEP 2 (1 km bin resolution)

IB_step2_m_1km.m

This is the script that bins the data by isobath.

```
% % at Lat 45, km per degree Latitude=111.135  0.0090
% % at Lat 45, km per degree Longitude=78.715  0.0125
scrn=('step 2 begins')
datevec(now)
load oregon_bathy.mat;
% g=g(date,:);

%% DISCARD BAD OFFSHORE DATA READINGS
%% nan the data that's too shallow
off=find(g(:,3)<=nh_lon(35)); bad=find(g(off,6)<100); %-124.52 & 80m
g(off(bad),6)=nan; clear bad;
off=find(g(:,3)<=nh_lon(40)); bad=find(g(off,6)<195); %-124.77 & 195m
% g(off(bad),6)=nan; clear bad;
g(off(bad),6)=200; clear bad;
tooshall=find(g(:,6)<25); g(tooshall,6)=nan;

%%INTERPOLATE FOR THE BOTTOM DEPTH
 %get rid of nans
qn=find(isnan(g(:,6))); qnn=find(~isnan(g(:,6)));
g(qn,6)=interp1(g(qnn,1),g(qnn,6),g(qn,1));
 %derive depth from gps according to oregon_bathy
goodgps=find(~isnan(g(:,3)));
zi=interp2(lon_or_bathy,lat_or_bathy,bot_or_bathy,g(goodgps,3),g(goodgps,2),'linear');
g=[g,ones(length(g),1)*nan]; %adds new depth using oregon bathymetry - column 21
g(goodgps,14)=zi;
qn=find(isnan(g(:,14))); qnn=find(~isnan(g(:,14)));
g(qn,14)=interp1(g(qnn,1),g(qnn,14),g(qn,1));
```

```
%% SET THE BINSIZE (lats lons of 1km each)
% 0.0125 is 1 km decimal degrees longitude at 45N
% 0.009  is 1 km decimal degrees latitude  at 45N
xtix=[-124.1000:-0.0125:-125.1167]; xtix=((round(xtix*1000))/1000)'; xtix=flipud(xtix);
y1=[44.65:0.009:44.9020]; y2=[44.65-0.018:-0.009:44.4]; ytix=[y2,y1]; ytix=sortrows(ytix');
ytix=((round(ytix*1000))/1000);

%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%
T=cell(1,83); %% this is the binned Transect matrix
load glider_transect_line
nhd2=nh_depth(1:1:end); nhl2=nh_lon(1:1:end);

% STEP 1 find all data within 4km of nhline
nh_swath=find(g(:,2)>=44.614 & g(:,2)<44.686);
for ii=1:(length(nhl2)-1)
   bn=find(g(nh_swath,3)<=nhl2(ii) & g(nh_swath,3)>nhl2(ii+1));
   T{ii}=[T{ii};g(nh_swath(bn),:)];
   g(nh_swath(bn),:)=nan; clear bn;
end

% STEP 2 take all of the northern data
north=find(g(:,2)>44.65);
%start inshore to bottom of stonewall bank bowl
%bin by interpolated bottom depth from oregon_bathy
%according to nhd2
for ii=1:21
% for ii=1:10
   inshore=find(g(north,14)>=nhd2(ii) & g(north,14)<nhd2(ii+1));
   T{ii}=[T{ii};g(north(inshore),:)];
   g(north(inshore),:)=nan; clear inshore
end
```

```
%take all the offshore readings and bin them according to longitude
%this should leave only the middle regions of the northern flights
for ii=45:81
% for ii=23:40
    offshore=find(g(north,3)<=nhl2(ii) & g(north,3)>nhl2(ii+1));
    T{ii}=[T{ii};g(north(offshore),:)];
    g(north(offshore),:)=nan; clear offshore
end

%the rest should all be less than 300m bottom depth and easily
%binned into the rest of the nh line...
for ii=22:44
% for ii=11:22
    midground=find(g(north,14)>nhd2(ii) & g(north,14)<nhd2(ii+1));
    T{ii}=[T{ii};g(north(midground),:)];
    g(north(midground),:)=nan; clear midground
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%          END NORTHERN HALF           %%%%
%%%%         BEGIN SOUTHERN HALF          %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

south=find(g(:,2)<44.65);
for ii=1:21
% for ii=1:10
    inshore=find(g(south,14)>=nhd2(ii) & g(south,14)<nhd2(ii+1));
    T{ii}=[T{ii};g(south(inshore),:)];
    g(south(inshore),:)=nan; clear inshore
end

for ii=45:81
% for ii=23:40
    offshore=find(g(south,3)<=nhl2(ii) & g(south,3)>nhl2(ii+1));
```

```
    T{ii}=[T{ii};g(south(offshore),:)];
    g(south(offshore),:)=nan; clear offshore
end

% find all lons west of -124.4250 (nhl2(27)) east of -124.65 (nhl2(45))
% bin, nan the lats and lons
ston=find(g(:,3)<=-124.425 & g(:,3)>-124.65);
for ii=27:45
% for ii=14:22
    bn=find(g(ston,14)>=nhd2(ii) & g(ston,14)<nhd2(ii+1));
    T{ii}=[T{ii};g(ston(bn),:)];
    g(ston(bn),:)=nan; clear bn;
end

% find all lons inbetween nh10 and nh15
% find all data on stonewall bank, reserve in S matrix for later
% nan the data from this area
S=[];
bowl=find(g(:,3)<=-124.3000 & g(:,3)>-124.4250); %nh10 to nh15
bad1=find(g(bowl,3)<-124.350 & g(bowl,2)<44.497);
S=[S;g(bowl(bad1),:)]; g(bowl(bad1),:)=nan;
bad2=find(g(bowl,3)<-124.3625 & g(bowl,2)<44.515);
S=[S;g(bowl(bad2),:)]; g(bowl(bad2),:)=nan;
bad3=find(g(bowl,3)<-124.3750 & g(bowl,2)<44.524);
S=[S;g(bowl(bad3),:)]; g(bowl(bad3),:)=nan;
bad4=find(g(bowl,3)<-124.3875 & g(bowl,2)<44.569);
S=[S;g(bowl(bad4),:)]; g(bowl(bad4),:)=nan;
bad5=find(g(bowl,3)<-124.4125 & g(bowl,2)<44.614);
S=[S;g(bowl(bad5),:)]; g(bowl(bad5),:)=nan;
clear bad1 bad2 bad3 bad4 bad5

%% ...the remainder should be just the right (northeastern) bowl
% % % IMPORTANT this could also be binned by longitude
% % %     as this is the last piece of the puzzle fitting
```

```
% % %     into the bin model

for ii=21:27
% for ii=10:14
    bn=find(g(bowl,14)>=nhd2(ii) & g(bowl,14)<nhd2(ii+1));
    T{ii}=[T{ii};g(bowl(bn),:)];
    g(bowl(bn),:)=nan; clear bn;
end

shallow=find(g(:,14)<nhd2(1) & g(:,6)>=20);
% T(2:83)=T(1:82);
% T{1}=g(shallow,:);
datevec(now)

for jj=1:length(T)
    temp=T{ii};over=find(temp(:,4)>nhd2(ii+1));
    temp(over,:)=nan; T{ii}=temp; clear temp
end
```

ISOBATH BINNING STEP 3 (1 km bin resolution)

IB_step3_m_1km.m

This is script that averages the bins by depth.

```
% % script that loads in ascii glider dbd data
% % splits into bins of equal size, averages
% % ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% % DATAFILE STRUCTURE
% % 1.  Julday
% % 2.  Lat
% % 3.  Lon
% % 4.  Depth
% % 5.  Altitude
% % 6.  Bottom_depth
% % 7.  Pressure
% % 8.  Temperature
% % 9.  Conductivity
% % 10. Oxygen
% % 11. Backscatter
% % 12. Chlorophyll
% % 13. Cdom
% % 14. Salinity
% % 15. Sigma-t
% % ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

datevec(now)
load glider_transect_line

dbdfile=[
     'raw_IB_m_1km_0604'; 'raw_IB_m_1km_0605'; 'raw_IB_m_1km_0606';…
     'raw_IB_m_1km_0607'; 'raw_IB_m_1km_0608'; 'raw_IB_m_1km_0609';…
    'raw_IB_m_1km_0610'; 'raw_IB_m_1km_0611'; 'raw_IB_m_1km_0612';…
     'raw_IB_m_1km_0701'; 'raw_IB_m_1km_0702'; 'raw_IB_m_1km_0703';…
    'raw_IB_m_1km_0704'; 'raw_IB_m_1km_0705'; 'raw_IB_m_1km_0706';…
```

```
        'raw_IB_m_1km_0707'; 'raw_IB_m_1km_0708'; 'raw_IB_m_1km_0709';…
        'raw_IB_m_1km_0710'; 'raw_IB_m_1km_0711'];


mo=['0604';'0605';'0606';'0607';'0608';'0609';'0610';...
        '0611';'0612';'0701';'0702';'0703';’0704’;…
        ‘0705’;’0706’;’0707’;’0708’;’0709’;’0710’;’0711’];

for jj=1:size(dbdfile,1)-1
   eval(['load ', dbdfile(jj,:)])
   % lonmin=-124.1000;   % nh1
   % lonmax=-125.1167;   % nh45
   % inc=-0.0125;        % approx 1 km lon at 45N
   din=2;                % 2meter depth bins
   counter=[];

   for ii=1:81
      gtemp=T{ii};
      for dbin=1:din:200
         mark=find(gtemp(:,4)>=dbin & gtemp(:,4)<dbin+din);
         for ind=1:15
            goo=nanmean(gtemp(mark,ind)); foo=3*nanstd(gtemp(mark,ind));
            std3=find(gtemp(mark,ind)>goo+foo & gtemp(mark,ind)<goo-foo);
            gtemp(mark(std3),ind)=nan;
            eval(['m',mo(jj,:),'(ii,dbin,ind)=nanmean(gtemp(mark,ind));']);
            eval(['counter',mo(jj,:),'(ii,dbin)=length(mark)-length(std3);']);
         end
      end
   end
   eval(['save ',dbdfile(jj,end-12:end),'_scimat m',mo(jj,:),' counter',mo(jj,:)])
end

datevec(now)
```

OBJECTIVE ANALYSIS

OA_step1_m.m

This is the master file for the objective analysis method. This file will load the data, and call the script that performs the objective analysis.

```
beginning=datevec(now);
yearday=[
        datenum(2006,4,1); datenum(2006,5,1); datenum(2006,6,1); datenum(2006,7,1);...
        datenum(2006,8,1); datenum(2006,9,1); datenum(2006,10,1); datenum(2006,11,1);...
        datenum(2006,12,1); datenum(2007,1,1); datenum(2007,2,1); datenum(2007,3,1);...
        datenum(2007,4,1); datenum(2007,5,1); datenum(2007,6,1); datenum(2007,7,1);...
        datenum(2007,8,1); datenum(2007,9,1); datenum(2007,10,1); datenum(2007,11,1) ];
 dataname=[
         'DBD_0604'; 'DBD_0605'; 'DBD_0606'; 'DBD_0607'; 'DBD_0608'; 'DBD_0609';...
         'DBD_0610'; 'DBD_0611'; 'DBD_0612'; 'DBD_0701'; 'DBD_0702'; 'DBD_0703';...
         'DBD_0704'; 'DBD_0705'; 'DBD_0706'; 'DBD_0707'; 'DBD_0708'; 'DBD_0709';...
         'DBD_0710'; 'DBD_0711'  ];
matname=[
         'OA_m_0604'; 'OA_m_0605'; 'OA_m_0606'; 'OA_m_0607'; 'OA_m_0608';…
         'OA_m_0609'; 'OA_m_0610'; 'OA_m_0611'; 'OA_m_0612'; 'OA_m_0701';…
         'OA_m_0702'; 'OA_m_0703'; 'OA_m_0704'; 'OA_m_0705'; 'OA_m_0706';…
         'OA_m_0707'; 'OA_m_0708'; 'OA_m_0709'; 'OA_m_0710'; 'OA_m_0711' ];
for kk=1:length(yearday)-1
    nx=80; ny=1; xo=80; yo=0; dx=1; dy=1;
    cd ..;    cd IB
    eval(['load ' dataname(kk,:)])
    cd ..;    cd OA
    jd=find(Julday>=yearday(kk) & Julday<yearday(kk+1));
    disp(strcat('STEP 2 BEGINS-',num2str(kk)))
    oa_step2_aug
    eval(['save ' matname(kk,:) ' dummy error']);
    disp(strcat('STEP 2 ENDS-',num2str(kk)))
    end
disp('total runtime...'); datevec(now)-beginning
```

OBJECTIVE ANALYSIS

OA_step2_m.m

This is the script that performs the objective analysis, it defines the objective analysis parameters and then calls a function that performs the objective analysis.

```
temp=Temp(jd); lon=Lon(jd); lat=Lat(jd); depth=Pressure(jd);
lon=(abs(lon)-124.1)./0.0125; lat=((lat)-44.65)./0.009; % NH-01 coords
% lon=(abs(lon)-124.3035)./0.0125; lat=((lat)-44.6330)./0.009; % OrCOOS mooring coords
lon=lon; lat=lat;
acov=2; bcov=acov*2; acov2=7.5; bcov2=acov2*2; e=0.1; u=temp;

disp('OA BEGINS')
count=1;
for zz=0:2:200
   zi=find(depth>=zz & depth<zz+2);
   outlier=find(u(zi)>(nanmean(u(zi))+3*nanstd(u(zi))) & u(zi)<(nanmean(u(zi))-
3*nanstd(u(zi))));
   u(zi(outlier))=nan;
   if size(zi,1)>4
   X=[lon(zi) lat(zi) ones(size(lon(zi)))]; [B,BINT]=regress(u(zi),X);
   Tt=B(1)*lon(zi)+B(2)*lat(zi)+B(3);
   u(zi)=u(zi)-Tt;
   [ui,ei]=oa(nx,ny,xo,yo,dx,dy,lon(zi),lat(zi),u(zi),length(u(zi)),acov,bcov,acov2,bcov2,e);
   dummy(count,:)=ui+B(1)*0+B(2)*0+B(3); error(count,:)=ei; count=count+1;
   end
end
disp('OA ENDS')
```

OBJECTIVE ANALYSIS

oa.m

This is function that performs the objective analysis, it calls a function to calculate the covariance function.

```
function [ui,ei] = oa(nx,ny,xo,yo,dx,dy,x,y,u,lmax,acov,bcov,acov2,bcov2,e)

% % The gridding technique used in this routine
% % is standard statistical objective analysis
% % following Bretherton et al (1976) using the
% % covariance function
% %
% % C(R) = EXP(-R^2/A^2) * (1 - R^2/B^2)
% %
% % the output variables are ui and ei.  These will
% % be 2-D arrays (ny rows by nx columns) that are
% % reshaped into a single column vecotr, where
% % the index is given by
% %
% % N = (I-1)*NY + J
% %
% % and "I" is the columns index and "J" is the row index
% %
% % The input variables are
% %
% % nx,ny   = scalar number of gridpoints in x/y direction
% % xo,yo   = coordinates of lower left hand corner
% % dx,dy   = grid spacing, x/y
% % x,y     = locations of input data to be gridded
% % u       = input data to be gridded
% % lmax    = number of data points
% % acov    = decay scale in covariance function
% % bcov    = zero-crossing in covariance function
% % e       = percent variance of random uncorrelated noise
```

```
%=====================================
% ELIMINATE NANs

mrk=find(~isnan(u.*x.*y));
u=u(mrk); x=x(mrk); y=y(mrk);
lmax=length(u);

nmax=500000;
nnmax=100000;

%=====================================
% DETERMINE IF PARAMETERS WILL COMPILE
if (acov > bcov)
   disp('Acov > Bcov  ...covariance matrix may not invert correctly')
end
if (lmax>nnmax)
   disp('too many input points')
end
if ((nx.*ny)>nmax)
   disp('too many output points')
end

%=====================================
% SET CONSTANTS

thresh=1*10^-5;
mis_val=1*10^22;

%=====================================
% CREATE GRID

% for i=1:nx
%     for j=1:ny
```

```
%         n=(i-1)*ny+j;
%         xi(n)=xo+(i-1)*dx;
%         yi(n)=yo+(j-1)*dy;
%     end
% end
%
% …or define grid yourself.
% --ATP 12.19.2007

xi=[1:nx]; yi=zeros(size(xi));



%=====================================
% CALCULATE FLAT MEAN AND VARIANCE, REMOVE MEAN

u_mn=nanmean(u);
u_vr=nanvar(u);
u=u-u_mn;

%=====================================
% CALCULATE COVARIANCE MATRIX A

for l=1:lmax
    for m=1:lmax
        A(l,m)=covfcn(x(l),x(m),y(l),y(m),acov,bcov,acov2,bcov2);
        if (abs(A(l,m)) < thresh); A(l,m)=0; end
    end
    A(l,l)=1+e;
end

%=====================================
% INVERT COVARIANCE MATRIX

invA=inv(A);
```

```
%=====================================
% CALCULATE GRID TO DATA COVARIANCE MATRIX

for n=1:(nx.*ny)
    for l=1:lmax
        C(n,l)=covfcn(xi(n),x(l),yi(n),y(l),acov,bcov,acov2,bcov2);
    end
end

%=====================================
% CALCULATE GRIDDED VALUE AND
% ERROR COVARIANCE
%
for n=1:(nx.*ny)
    suml=0;
    sum2l=0;
    for l=1:lmax
        summ=0;
        sum2m=0;
        for m=1:lmax
            summ=summ+invA(l,m)*u(m);
            sum2m=sum2m+C(n,m)*invA(l,m);
        end
        suml=suml+C(n,l)*summ;
        sum2l=sum2l+C(n,l)*sum2m;
    end
    ui(n)=suml+u_mn;
    ei(n)=1-sum2l;
end
```

OBJECTIVE ANALYSIS

covfcn.m

This is routine that performs the covariance function.

```
function y = covfcn(x1,x2,y1,y2,ax,bx,ay,by)
dx=abs(x1-x2); dy=abs(y1-y2);
y=exp(-((dx./ax).^2+(dy./ay).^2)).*cos(pi/2.*(sqrt((dx./bx).^2+sqrt(dy./by).^2)))
```

HYBRID METHOD

PH_step1_m_1km.m

This is the script that performs the hybrid method. It uses data already binned in the second step of the isobath binning method to perform an objective analysis instead of block averaging by depth.

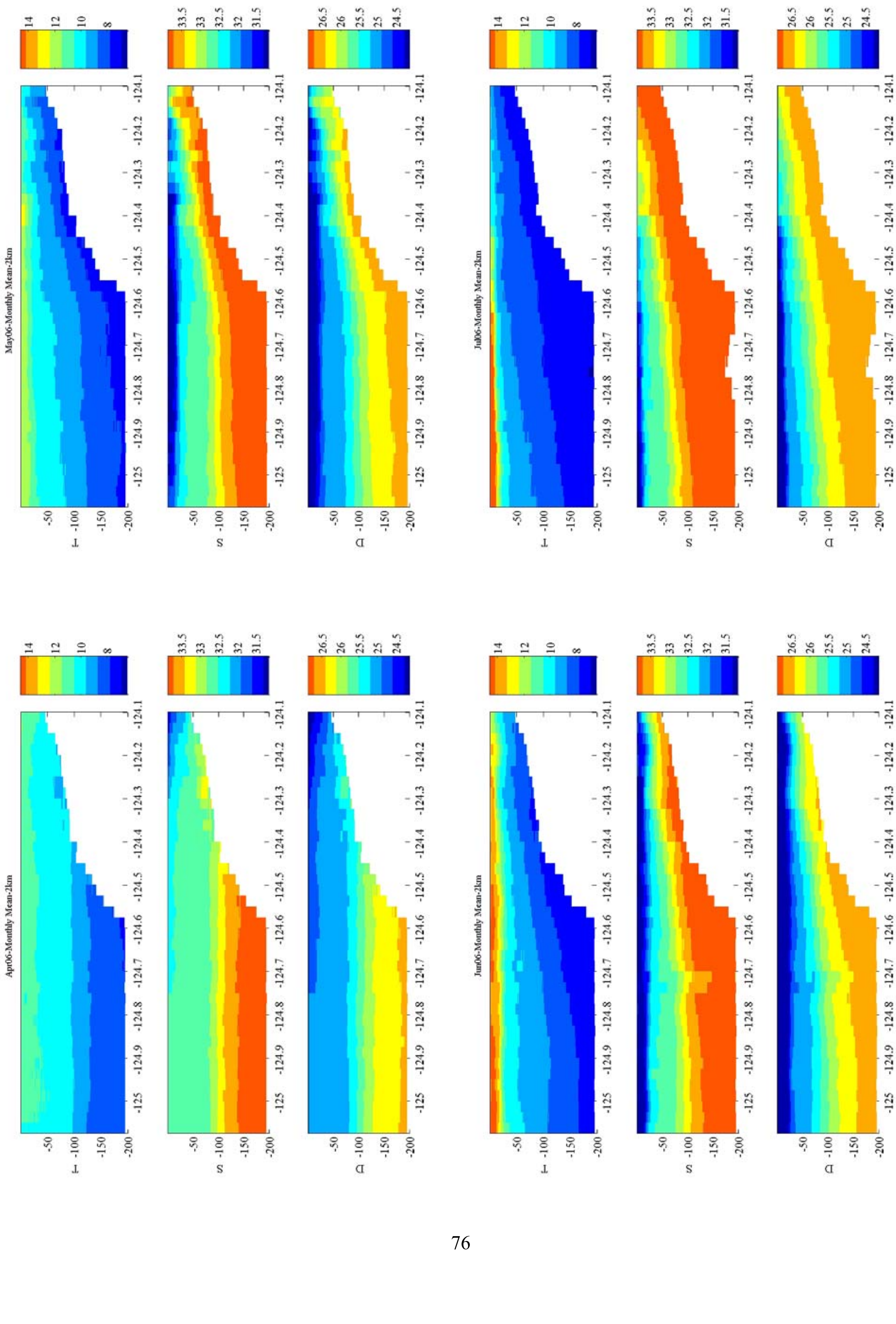
```
% % script that loads in ascii glider dbd data
% % splits into bins of approximate size and then
% % visualizes the results
% % ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% % DATAFILE STRUCTURE
% % 1.  Julday
% % 2.  Lat
% % 3.  Lon
% % 4.  Pressure
% % 5.  Bottom Depth
% % 6.  Temperature
% % 7.  Salinity
% % 8.  Sigma-t
% % 9.  Interpolated Bottom Depth
% % ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  % lonmin=-124.1000;   % nh1
  % lonmax=-125.1167;   % nh45
  % inc=-0.0125;        % approx 1 km lon at 45N

dbdfile=[
      'raw_IB_m_1km_0604'; 'raw_IB_m_1km_0605'; 'raw_IB_m_1km_0606';
      'raw_IB_m_1km_0607'; 'raw_IB_m_1km_0608'; 'raw_IB_m_1km_0609';
      'raw_IB_m_1km_0610'; 'raw_IB_m_1km_0611'; 'raw_IB_m_1km_0612';
      'raw_IB_m_1km_0701'; 'raw_IB_m_1km_0702'; 'raw_IB_m_1km_0703';
      'raw_IB_m_1km_0704'; 'raw_IB_m_1km_0705'; 'raw_IB_m_1km_0706';
      'raw_IB_m_1km_0707'; 'raw_IB_m_1km_0708'; 'raw_IB_m_1km_0709';
      'raw_IB_m_1km_0710'; 'raw_IB_m_1km_0711'];

mo=[ '0604'; '0605'; '0606'; '0607'; '0608'; '0609'; '0610'; '0611'; '0612'; '0701'; '0702';
```

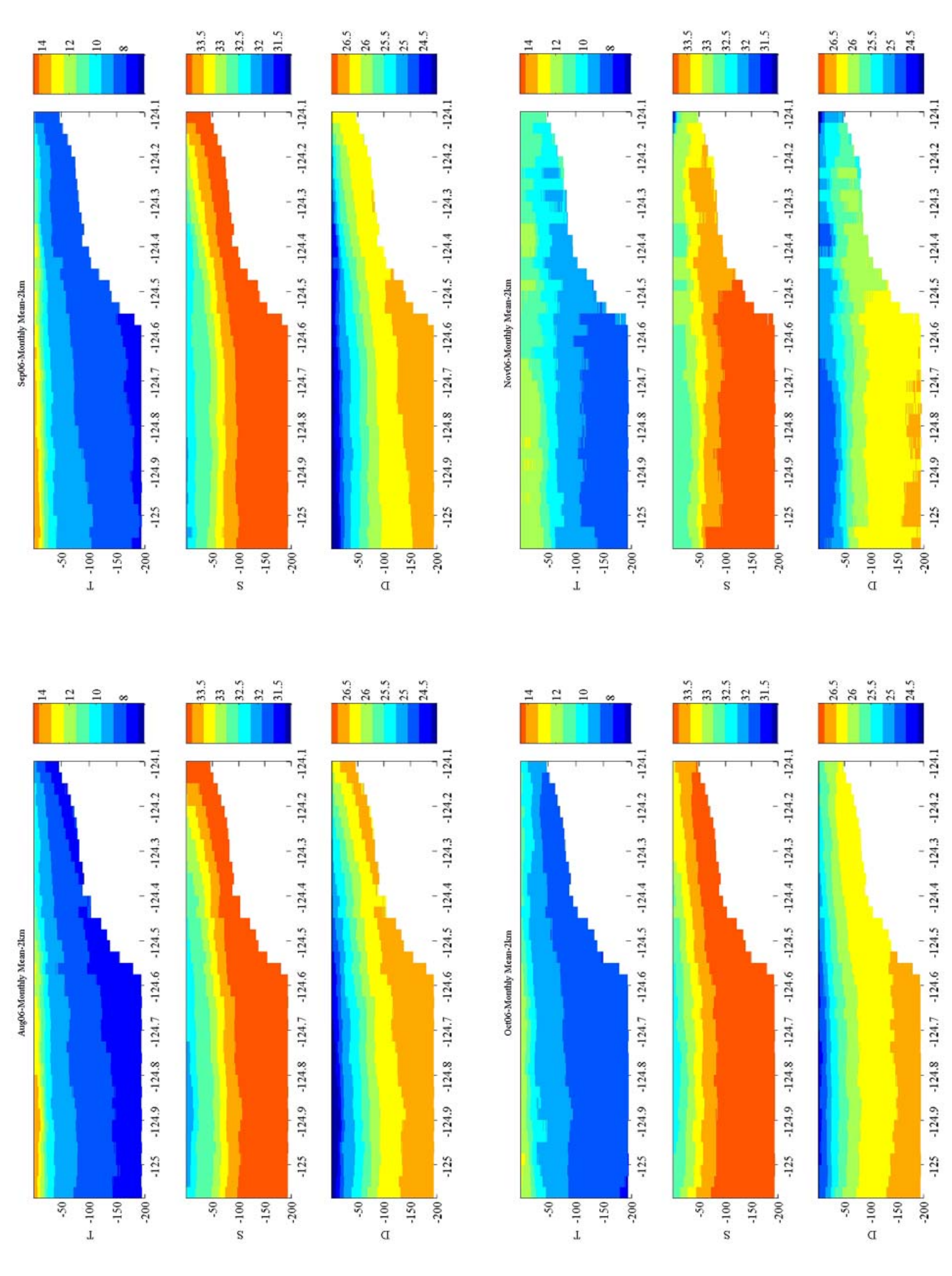
```
    '0703'; '0704'; '0705'; '0706'; '0707'; '0708'; '0709'; '0710'; '0711'];


nx=1; ny=1; xo=80; yo=0; dx=1; dy=1;
acov=2; bcov=acov*2; acov2=7.5; bcov2=acov2*2; e=0.1;

for jj=1:size(dbdfile,1)
    cd ..; cd IB;
    eval(['load ', dbdfile(jj,:)])
    cd ..; cd OA;
    din=2;                          % 2-meter depth bins
    gtemp=T{1};
    for dbin=1:din:200
        mark=find(gtemp(:,4)>=dbin & gtemp(:,4)<dbin+din);
        for ind=8
            poo=nanmean(gtemp(mark,ind)); foo=3*nanstd(gtemp(mark,ind));
            std3=find(gtemp(mark,ind)>poo+foo & gtemp(mark,ind)<poo-foo);
            gtemp(mark(std3),ind)=nan;
            lon=gtemp(mark,3); lat=gtemp(mark,2);
            lon=(abs(lon)-124.1)./0.0125; lat=((lat)-44.65)./0.009; % OrCOOS mooring coords
            u=gtemp(mark,ind);
            if size(u,1)>4
                 X=[lon lat ones(size(lon))]; [B,BINT]=regress(u,X);
                 Tt=B(1)*lon+B(2)*lat+B(3);
                 u=u-Tt;
                cd ..; cd OA;
                    [ui,ei]=oa(nx,ny,xo,yo,dx,dy,lon,lat,u,length(u),acov,bcov,acov2,bcov2,e);
                cd ..; cd PH;
                ui=ui+B(1)*0+B(2)*0+B(3);
                ui_p(dbin,jj)=ui;
                ei_p(dbin,jj)=ei;
            end;  end; end; end
save ph_m_1km_aug06_gerr ui ei ui_p ei_p
disp(jj); datevec(now)
```

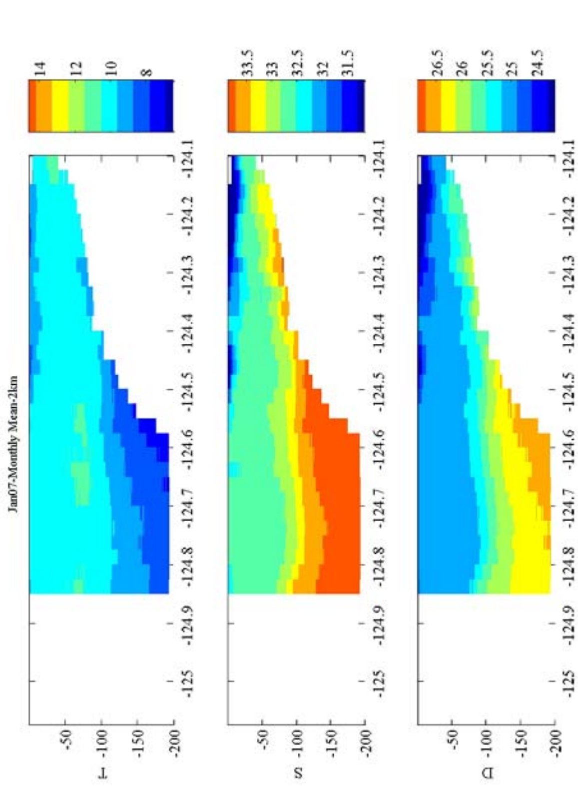
APPENDIX B – FIGURES

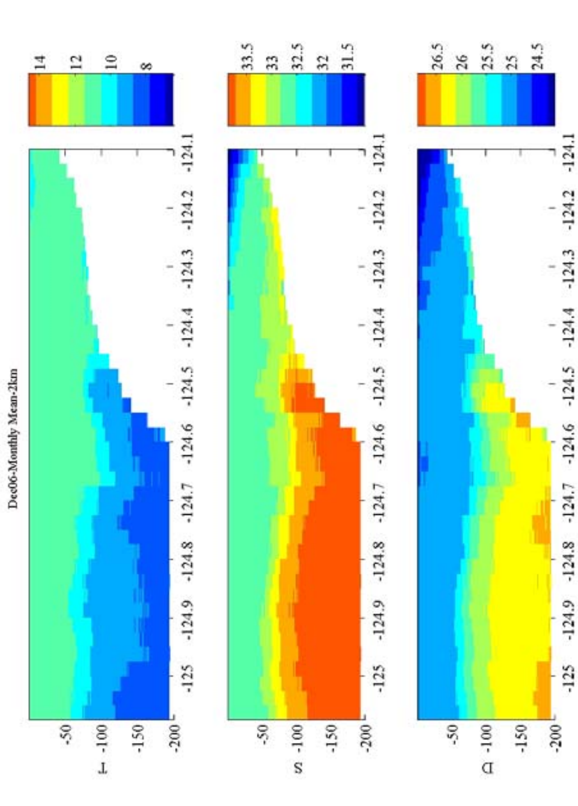
ISOBATH BINNING
2 km bin resolution
1 month timescale

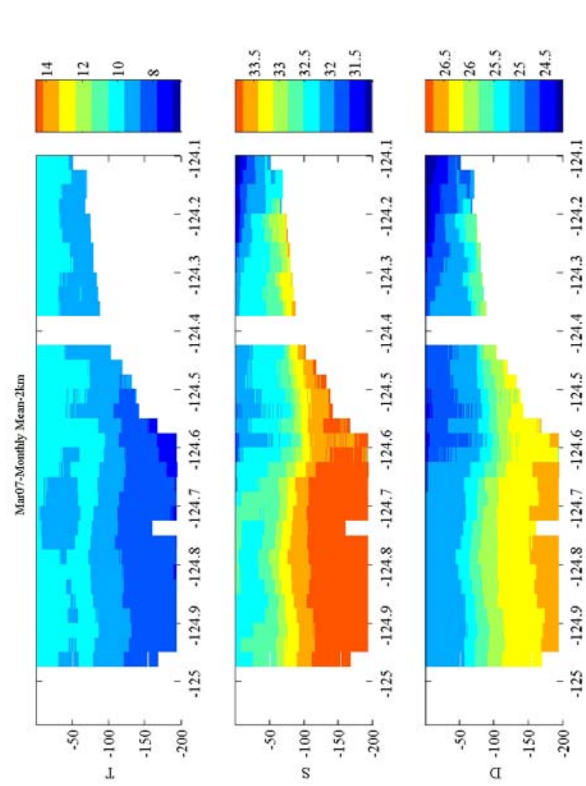
Apr. 2007 – Nov. 2007
Not Shown

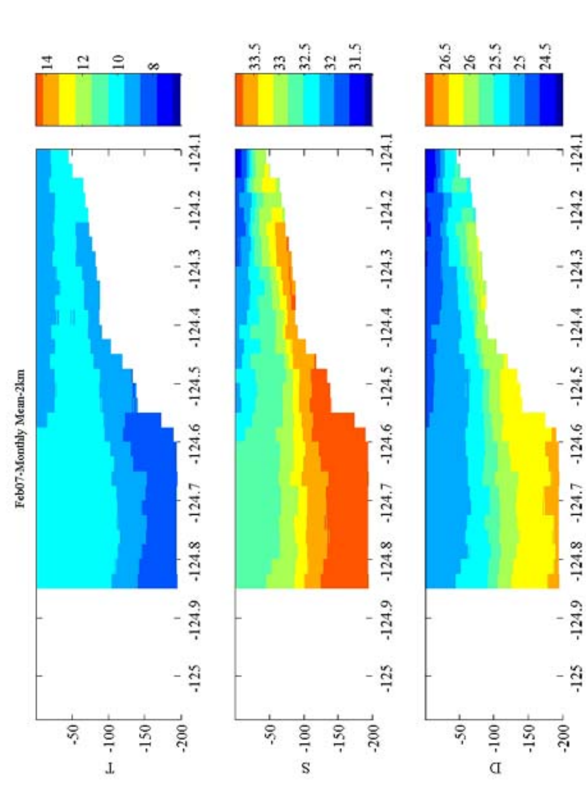

Apr06-Monthly Mean-2km
May06-Monthly Mean-2km
Jun06-Monthly Mean-2km
Jul06-Monthly Mean-2km
T
S
D


Aug06-Monthly Mean-2km
Sep06-Monthly Mean-2km
Oct06-Monthly Mean-2km
Nov06-Monthly Mean-2km


Jan07-Monthly Mean-2km
T
S
D
-50
-100
-150
-200
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
-124.3
-124.2
-124.1
14
12
10
8
33.5
33
32.5
32
31.5
26.5
26
25.5
25
24.5

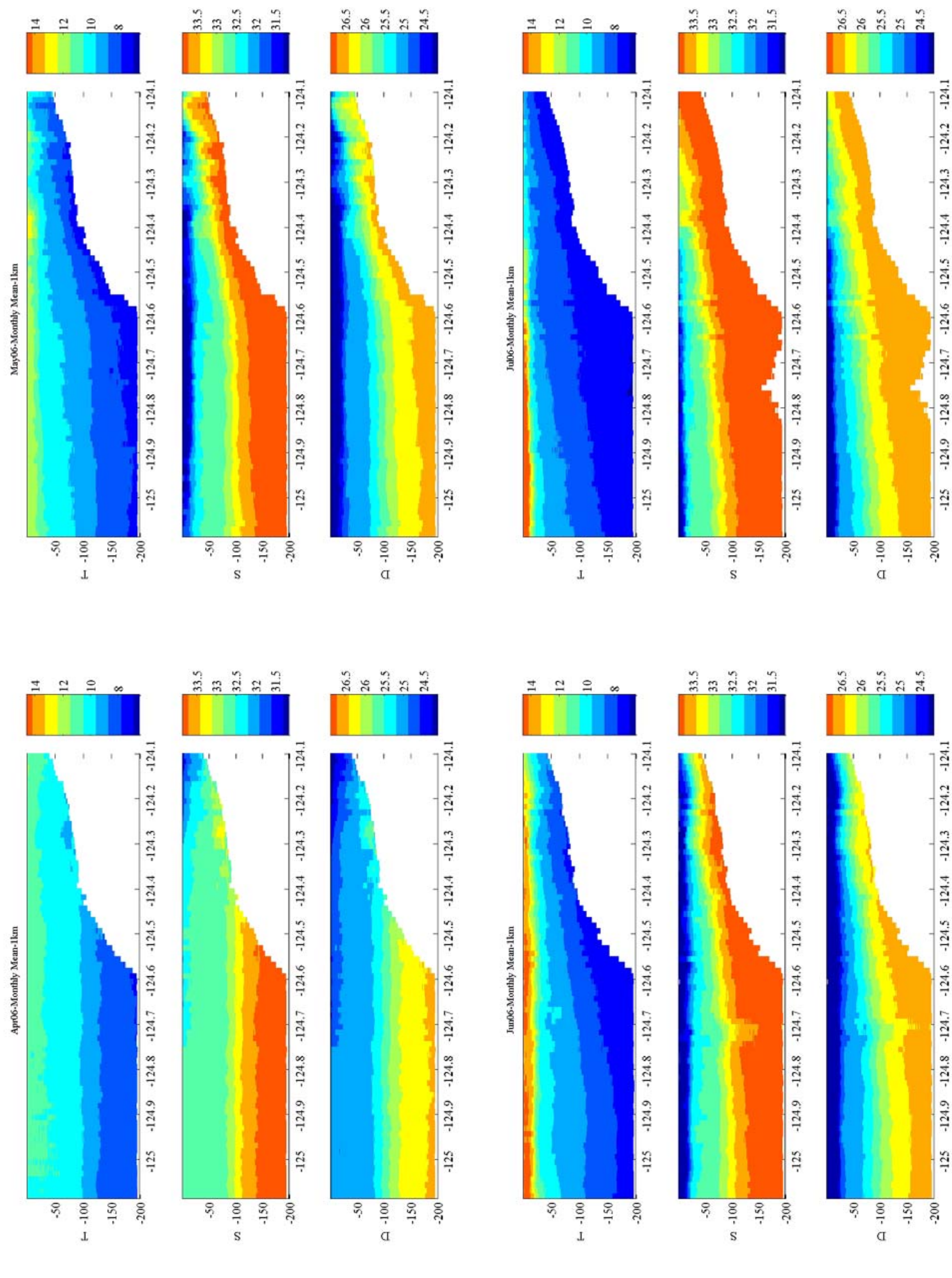

Dec06-Monthly Mean-2km
T
S
D
-50
-100
-150
-200
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
-124.3
-124.2
-124.1
14
12
10
8
33.5
33
32.5
32
31.5
26.5
26
25.5
25
24.5

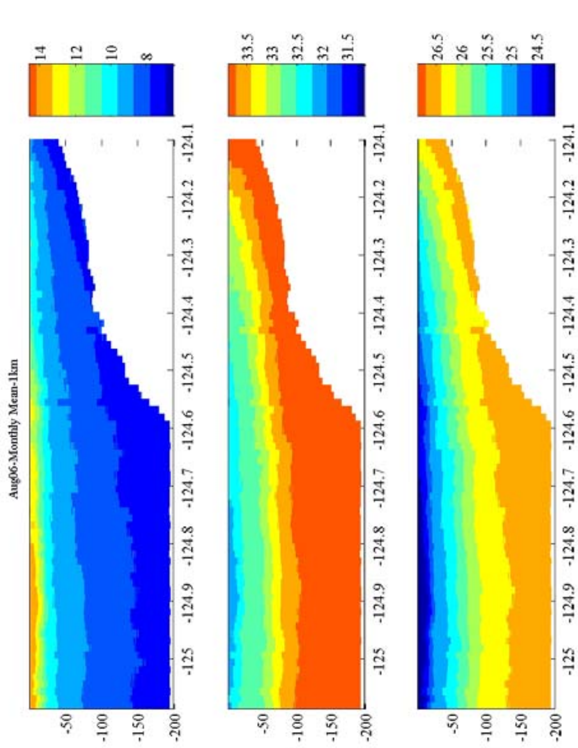

Mar07-Monthly Mean-2km
T
S
D
-50
-100
-150
-200
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
-124.3
-124.2
-124.1
14
12
10
8
33.5
33
32.5
32
31.5
26.5
26
25.5
25
24.5

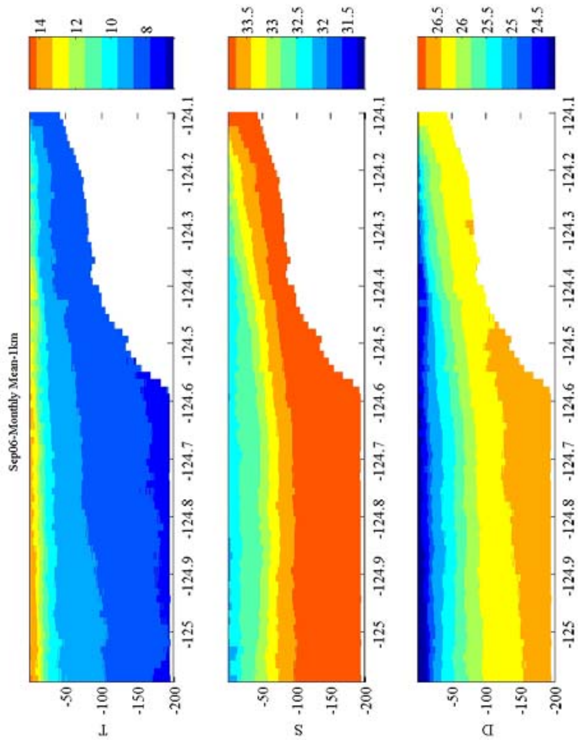

Feb07-Monthly Mean-2km
T
S
D
-50
-100
-150
-200
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
-124.3
-124.2
-124.1
14
12
10
8
33.5
33
32.5
32
31.5
26.5
26
25.5
25
24.5

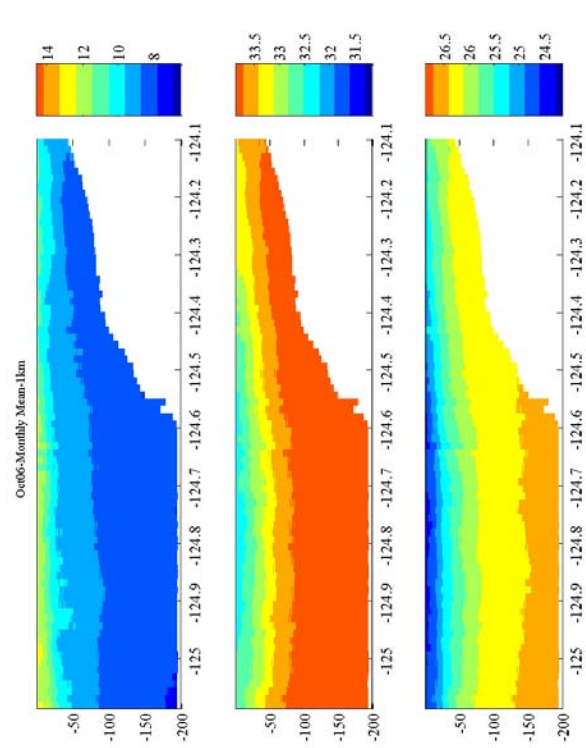
ISOBATH BINNING
1 km bin resolution
1 month timescale

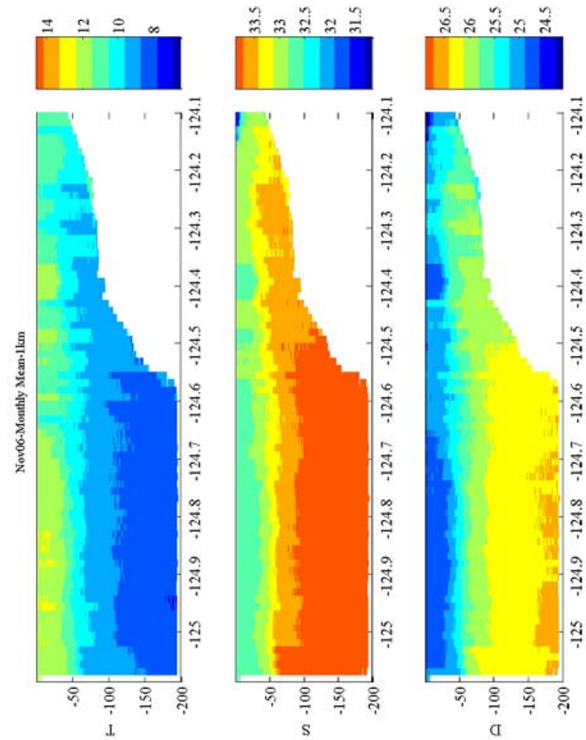
Apr. 2007 – Nov. 2007
Not Shown


Apr06-Monthly Mean-1km
May06-Monthly Mean-1km
Jun06-Monthly Mean-1km
Jul06-Monthly Mean-1km


Aug06-Monthly Mean-1km
T
S
D


Sep06-Monthly Mean-1km
T
S
D


Oct06-Monthly Mean-1km
T
S
D


Nov06-Monthly Mean-1km
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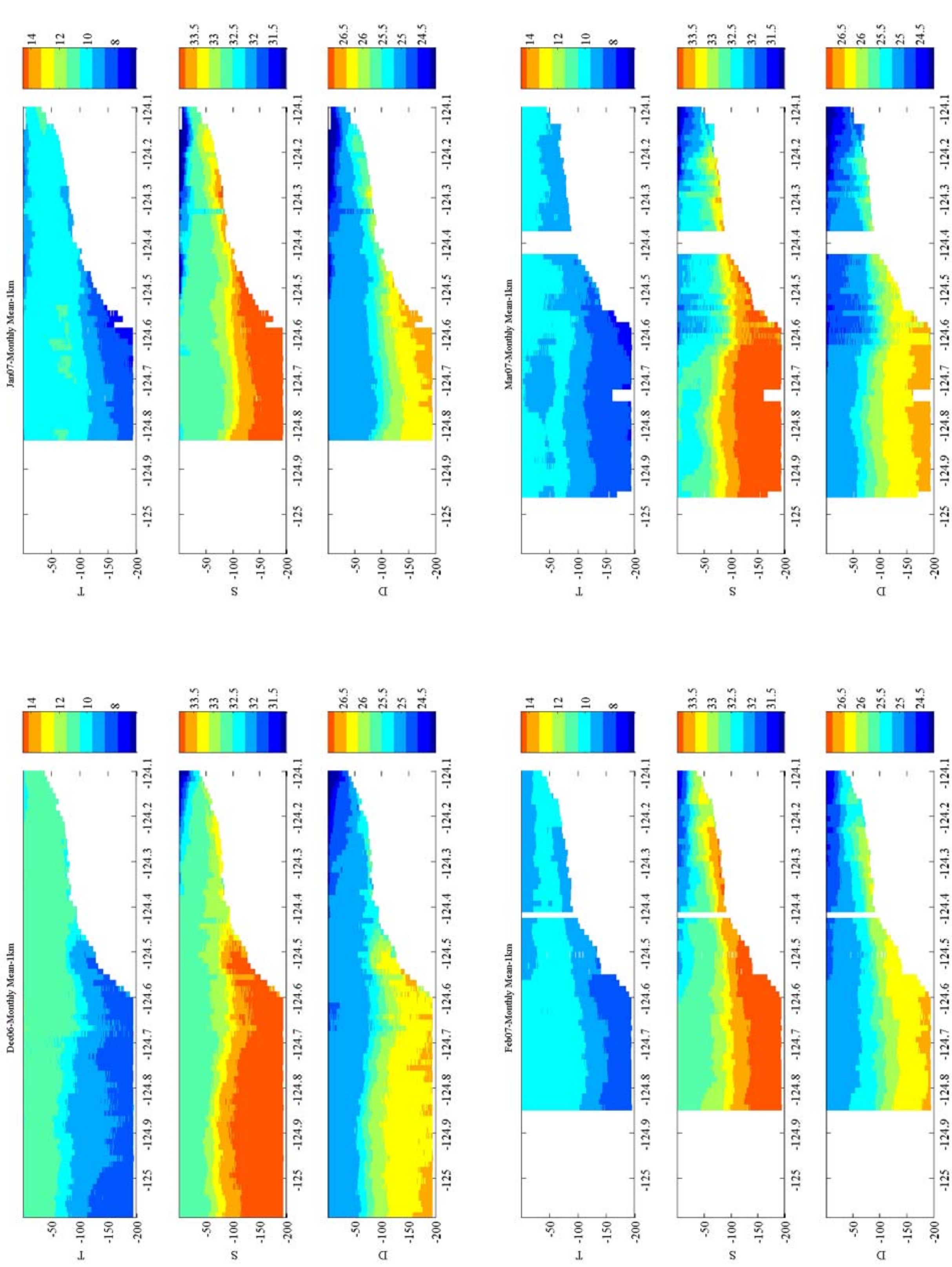
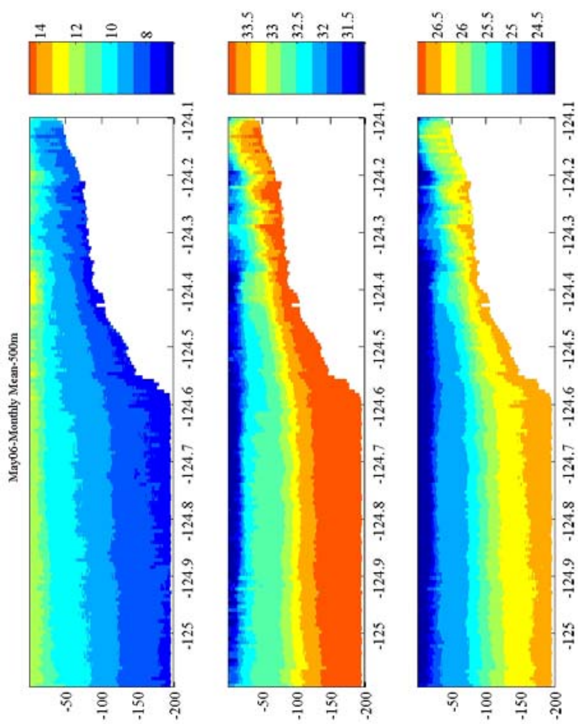
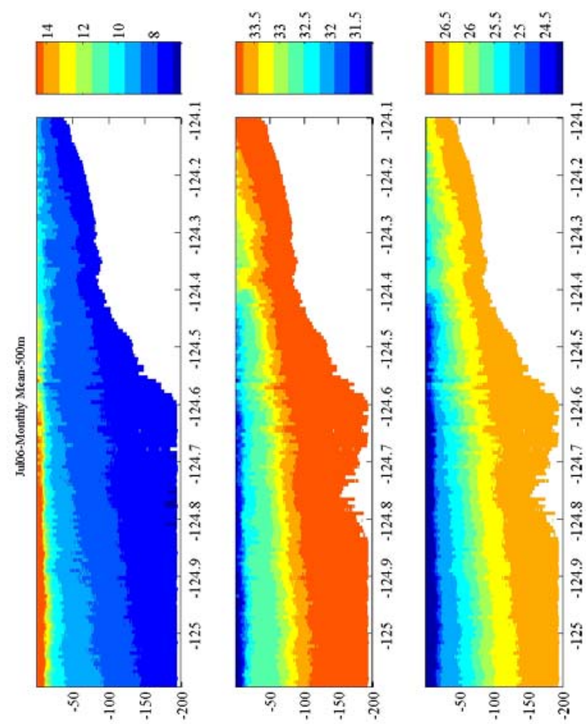


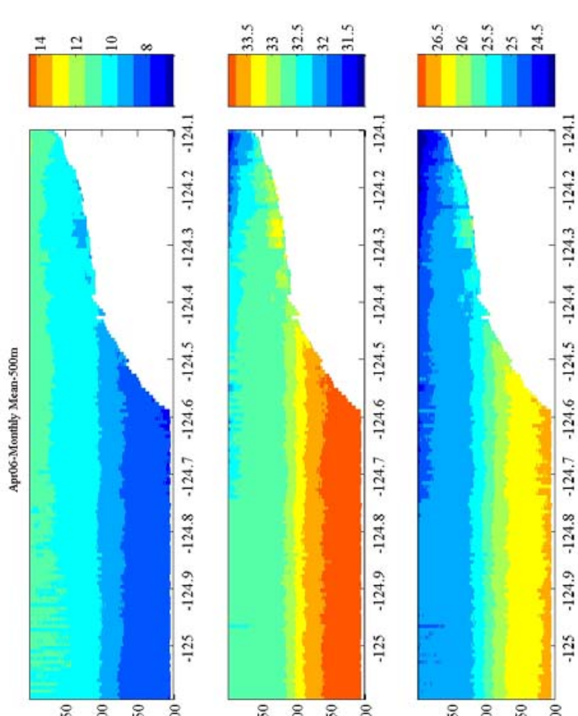
Dec06-Monthly Mean-1km
Jan07-Monthly Mean-1km
Feb07-Monthly Mean-1km
Mar07-Monthly Mean-1km
T
S
D

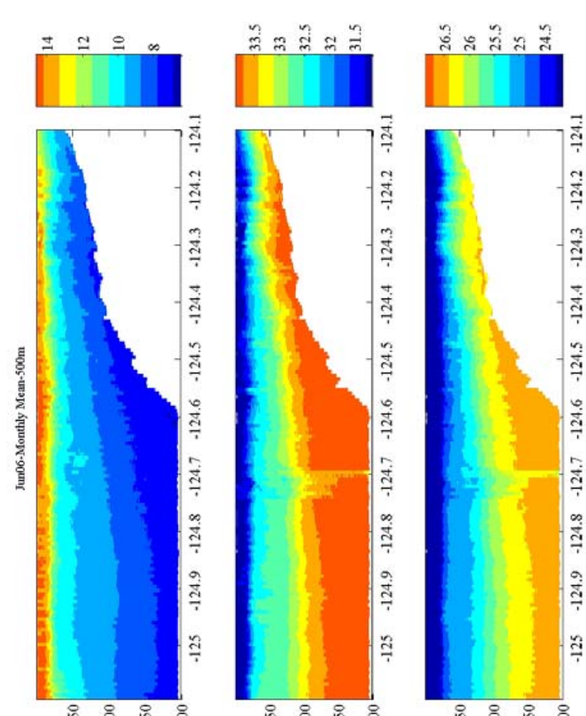
ISOBATH BINNING
500 m bin resolution
1 month timescale

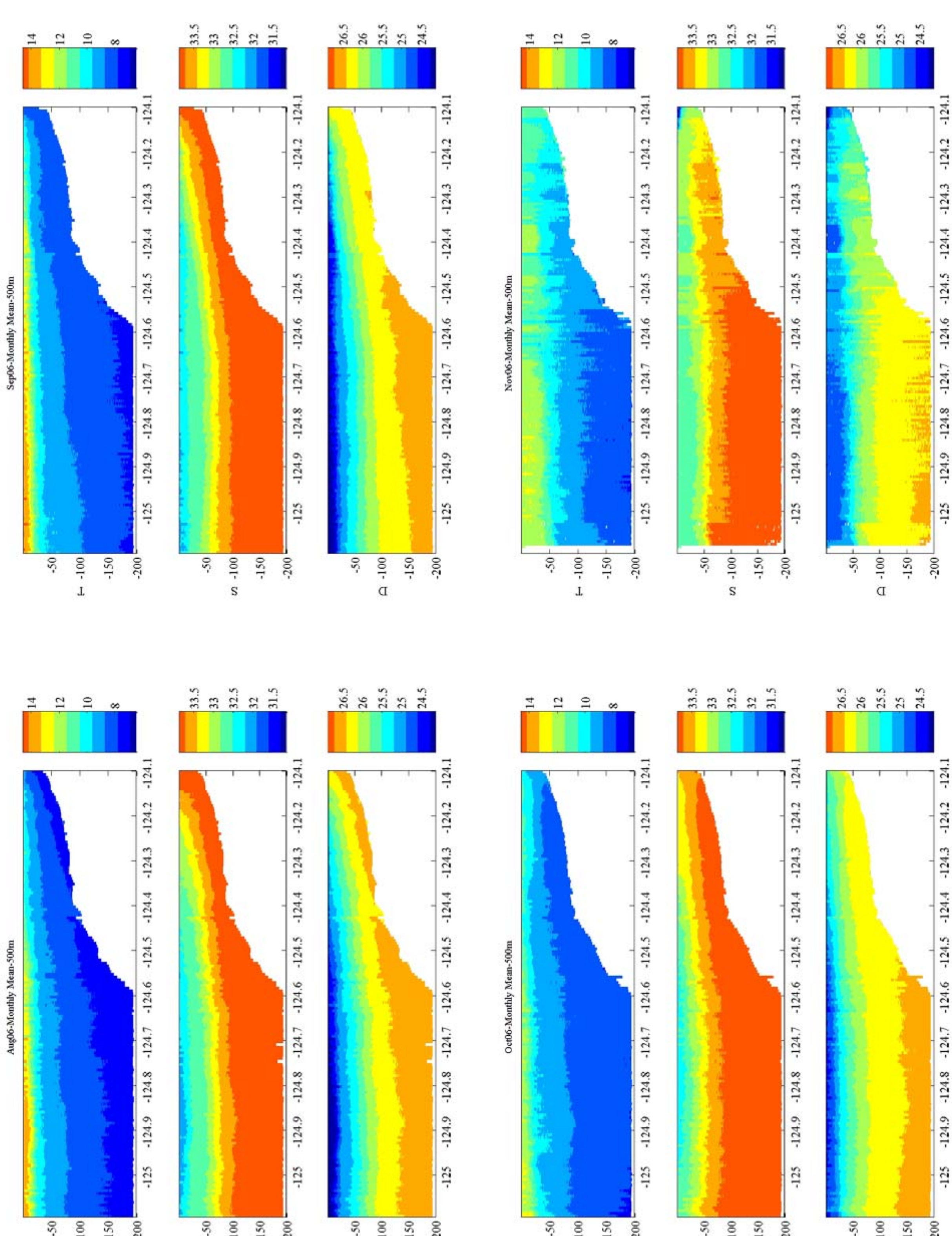
Apr. 2007 – Nov. 2007
Not Shown


May06-Monthly Mean-500m


Jul06-Monthly Mean-500m


Apr06-Monthly Mean-500m


Jun06-Monthly Mean-500m



Aug06-Monthly Mean-500m
Sep06-Monthly Mean-500m
Oct06-Monthly Mean-500m
Nov06-Monthly Mean-500m
T
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-50
-100
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-125
-124.9
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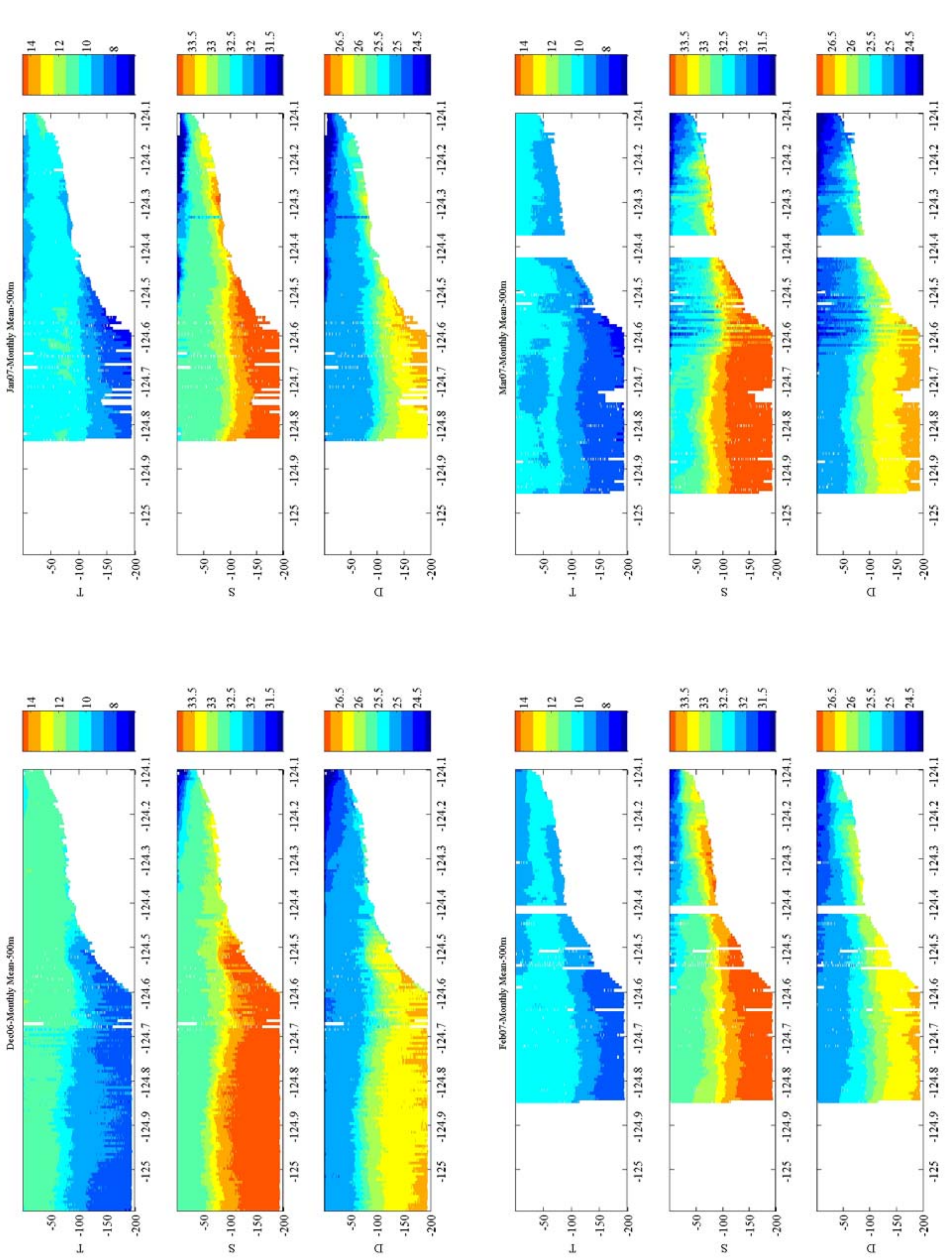
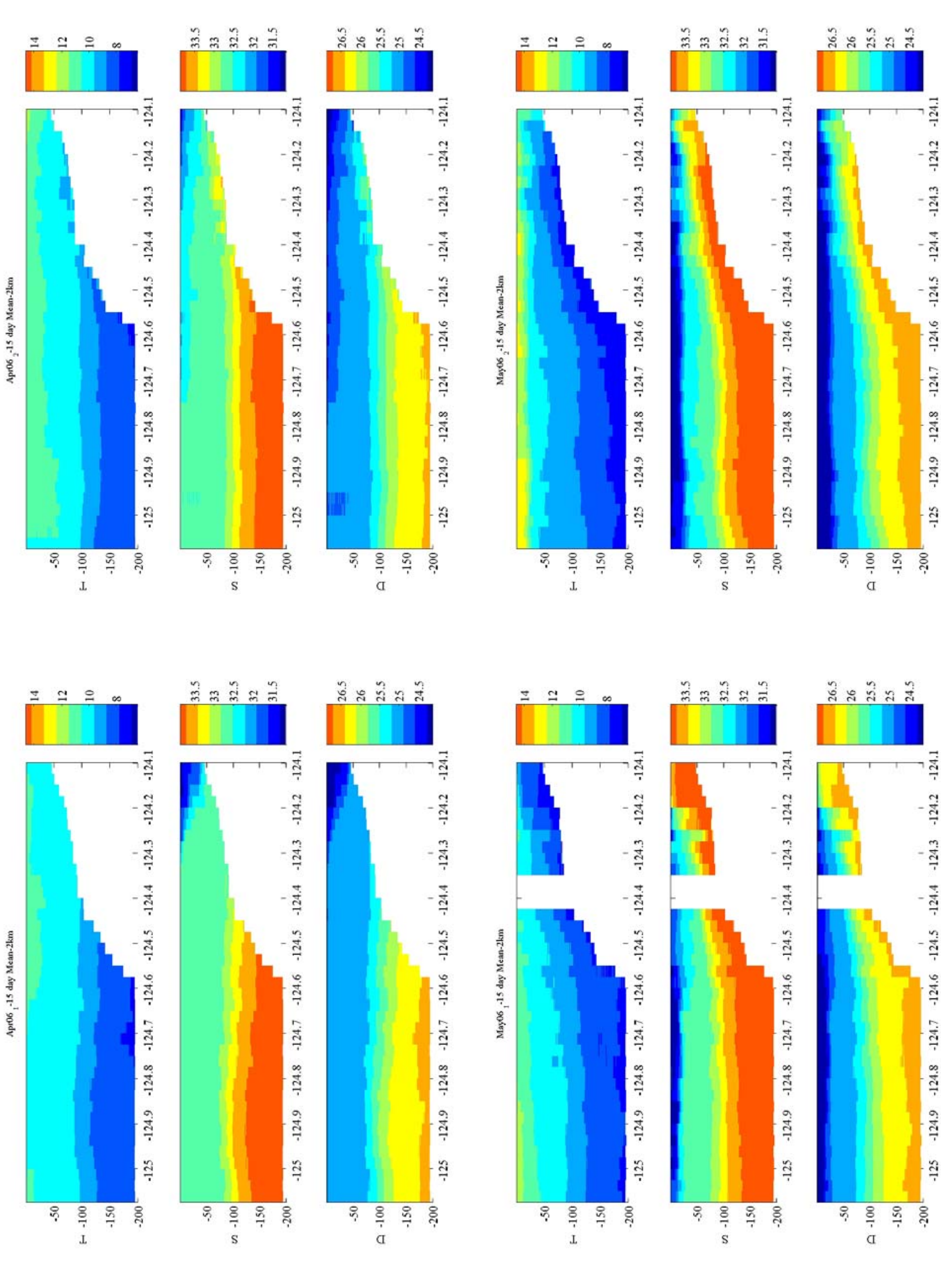

Dec06-Monthly Mean-500m
Jan07-Monthly Mean-500m
Feb07-Monthly Mean-500m
Mar07-Monthly Mean-500m

ISOBATH BINNING
2 km bin resolution
1 fortnight timescale

Jan. 2007 – Nov. 2007
Not Shown



Apr06_1 -15 day Mean-2km
Apr06_2 -15 day Mean-2km
May06_1 -15 day Mean-2km
May06_2 -15 day Mean-2km
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-50
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-124.9
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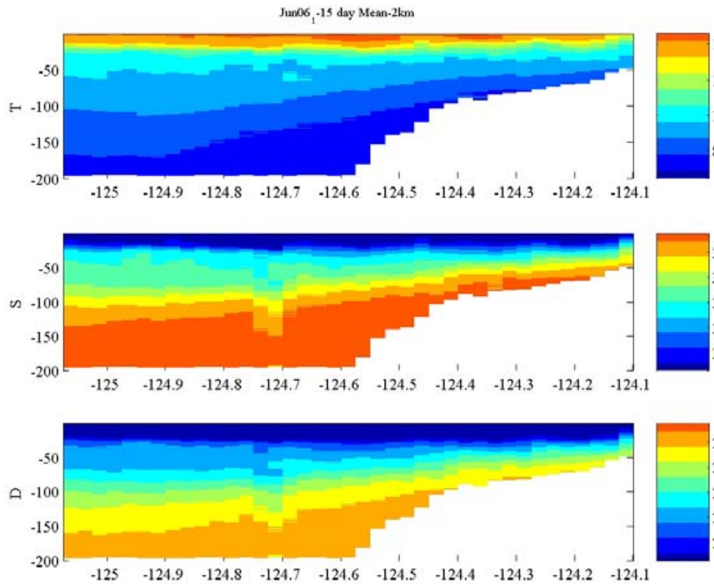
Jun06_1 -15 day Mean-2km
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-200
-125 -124.9 -124.8 -124.7 -124.6 -124.5 -124.4 -124.3 -124.2 -124.1
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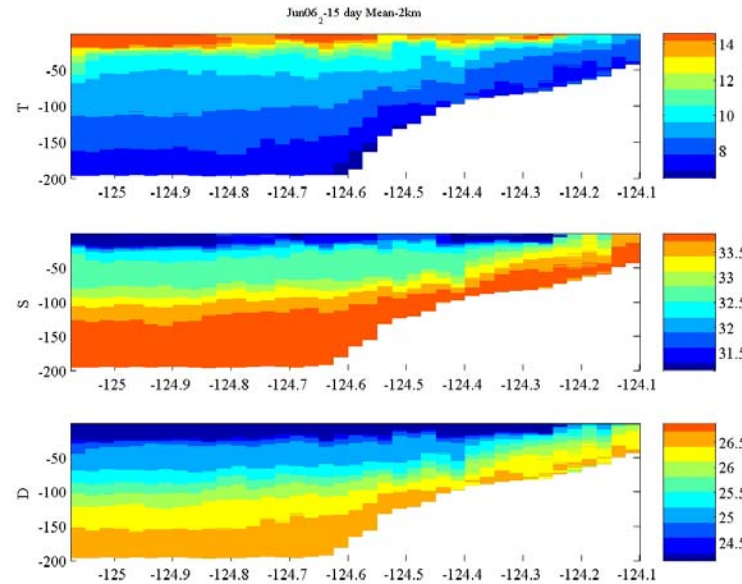
26.5 26 25.5 25 24.5


Jun06_2 -15 day Mean-2km
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-200
-125 -124.9 -124.8 -124.7 -124.6 -124.5 -124.4 -124.3 -124.2 -124.1
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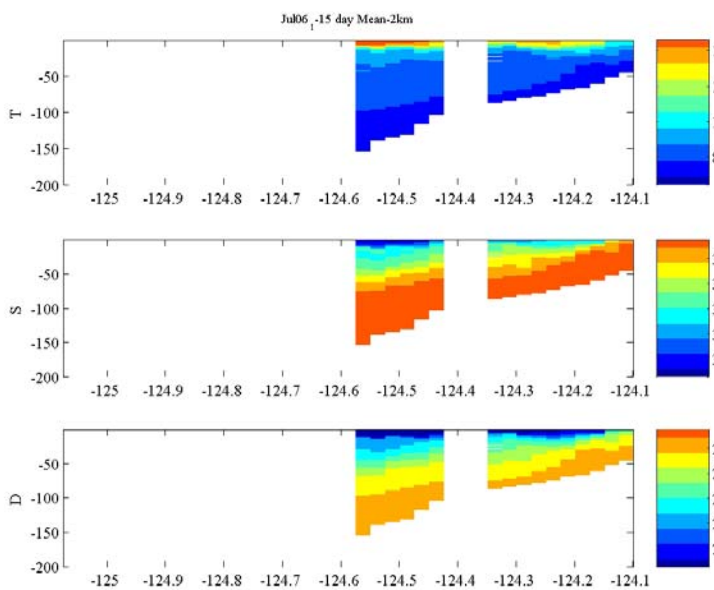
33.5 33 32.5 32 31.5
26.5 26 25.5 25 24.5


Jul06_1 -15 day Mean-2km
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-125 -124.9 -124.8 -124.7 -124.6 -124.5 -124.4 -124.3 -124.2 -124.1
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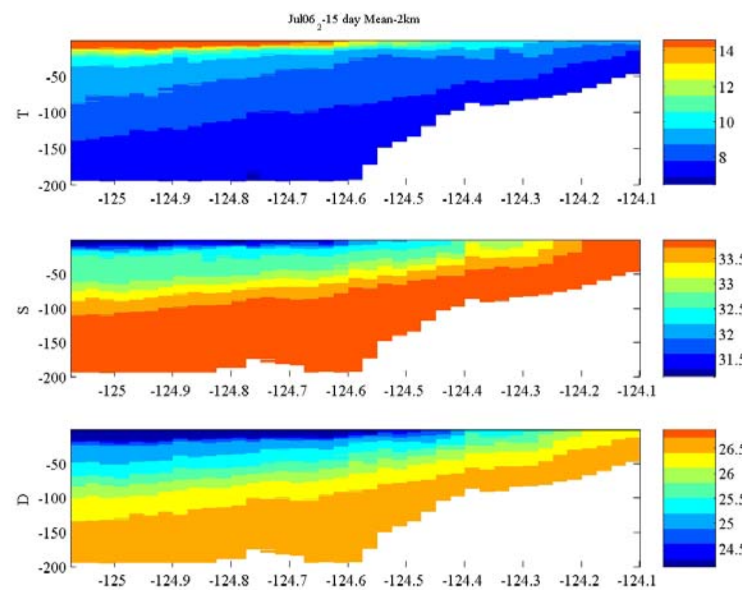
33.5 33 32.5 32 31.5
26.5 26 25.5 25 24.5


Jul06_2 -15 day Mean-2km
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-125 -124.9 -124.8 -124.7 -124.6 -124.5 -124.4 -124.3 -124.2 -124.1
14 12 10 8
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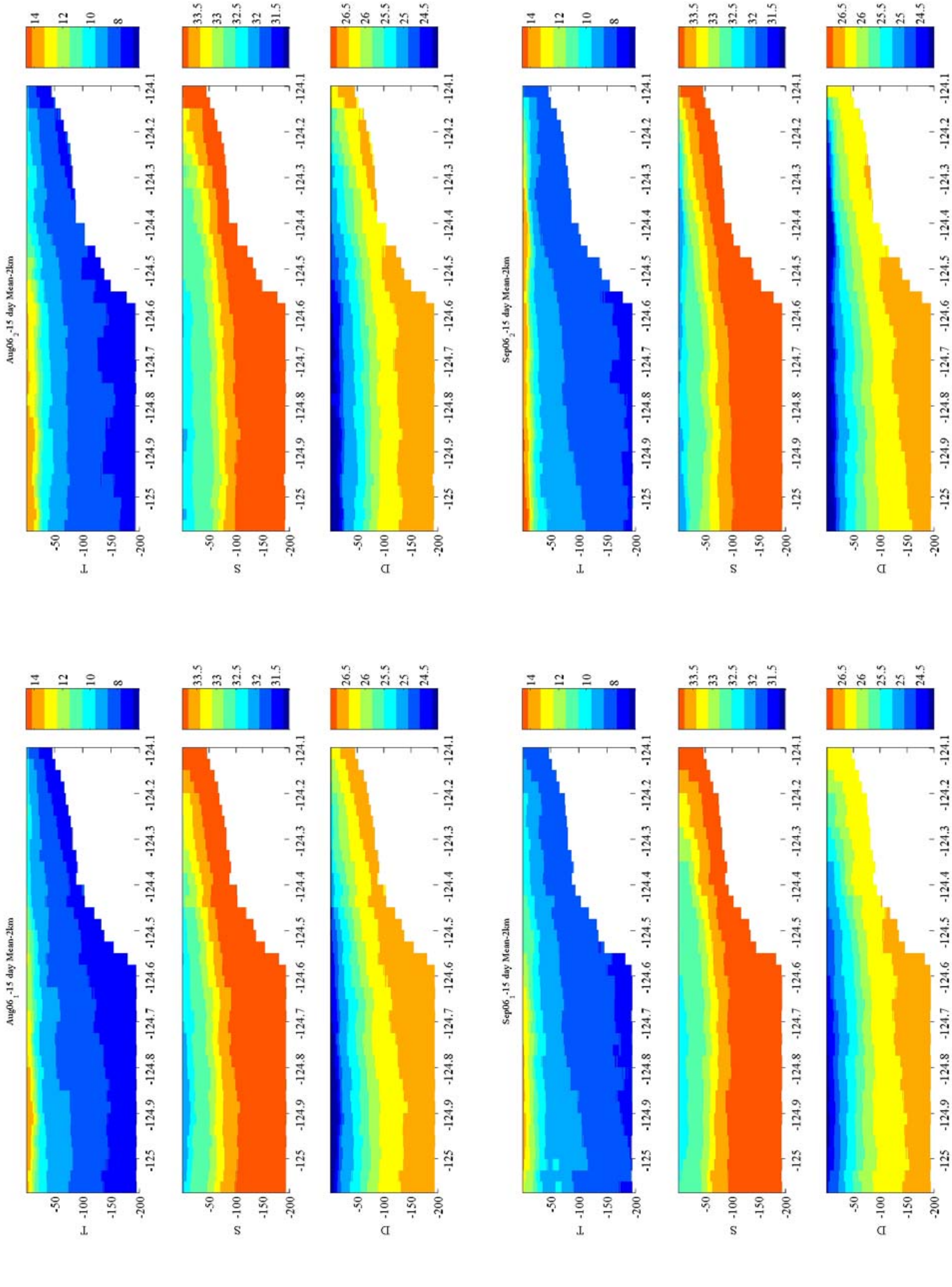
26.5 26 25.5 25 24.5


Aug06_1 -15 day Mean-2km
Aug06_2 -15 day Mean-2km
Sep06_1 -15 day Mean-2km
Sep06_2 -15 day Mean-2km
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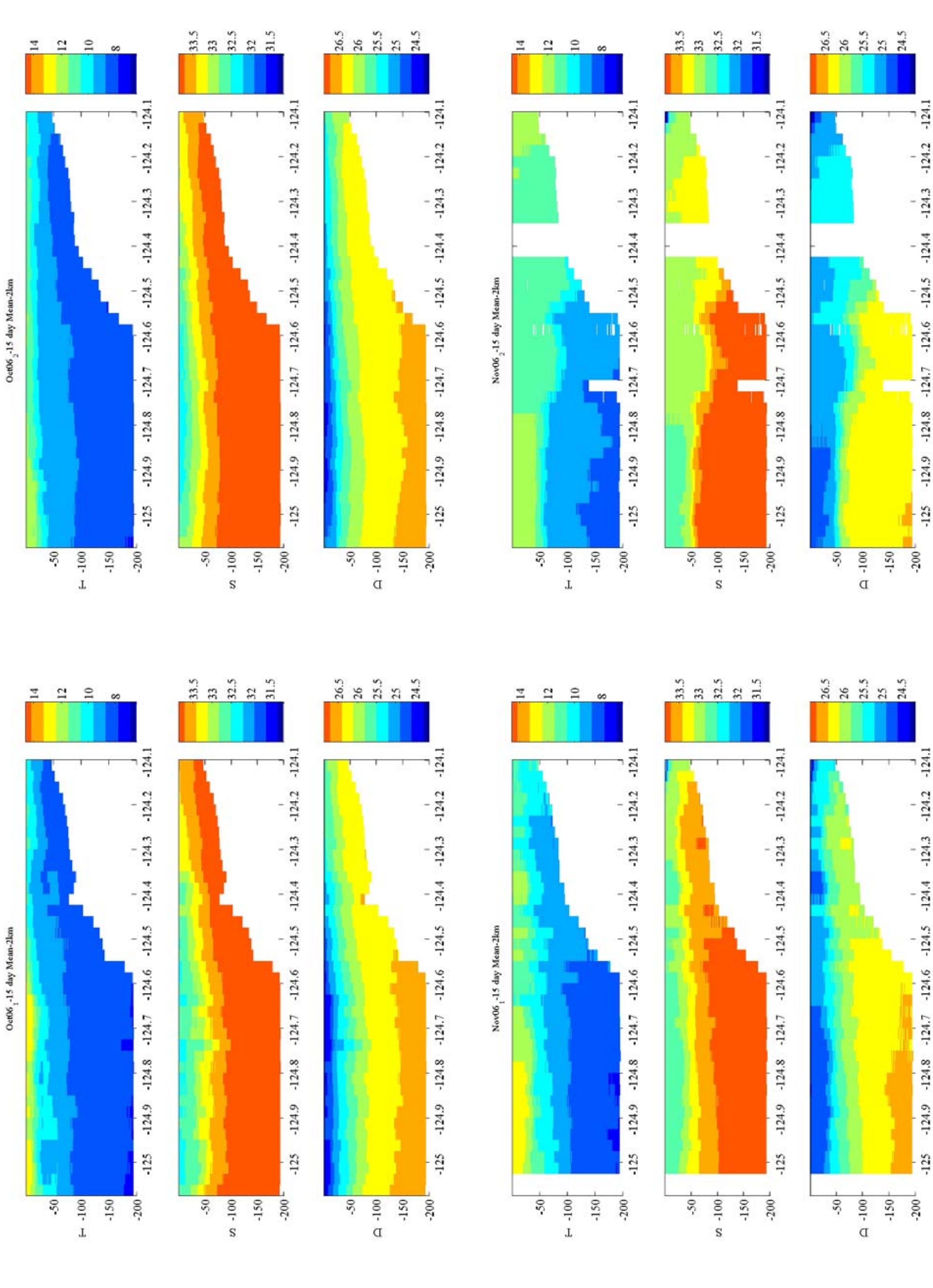
Oct06_1 -15 day Mean-2km
Oct06_2 -15 day Mean-2km
Nov06_1 -15 day Mean-2km
Nov06_2 -15 day Mean-2km
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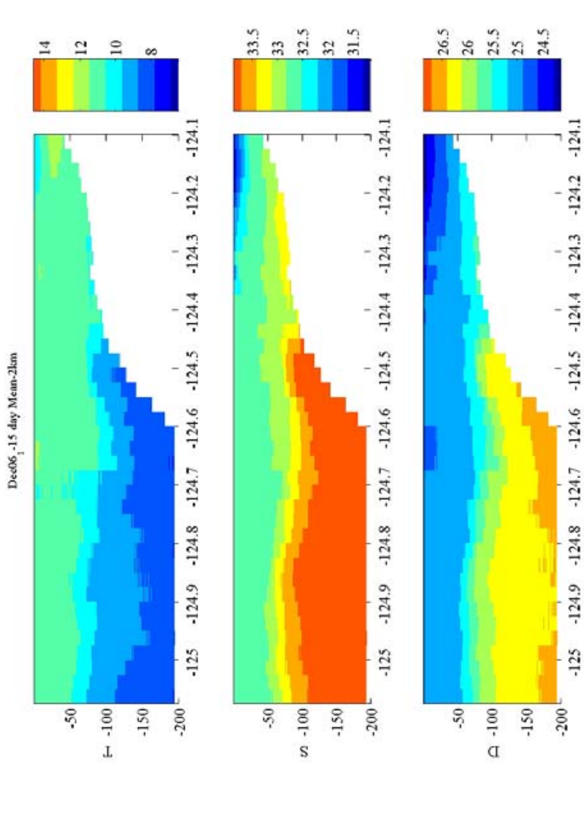
Dec06_1 -15 day Mean-2km
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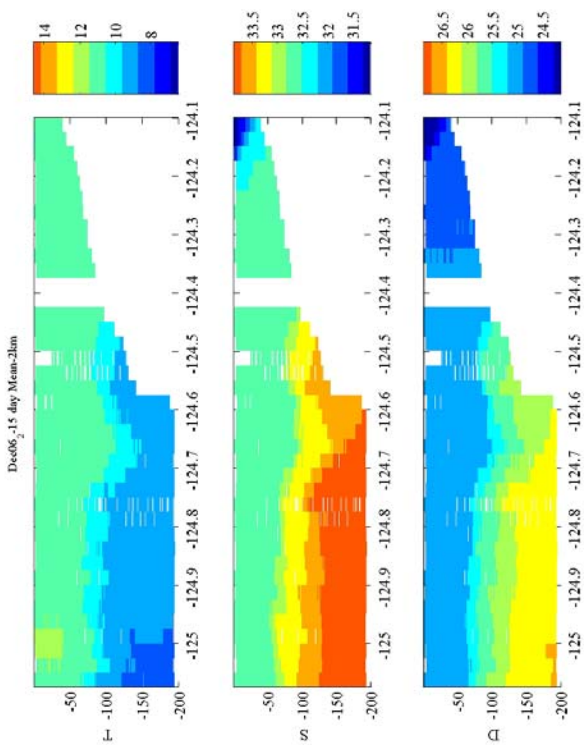
Dec06_2 -15 day Mean-2km
T
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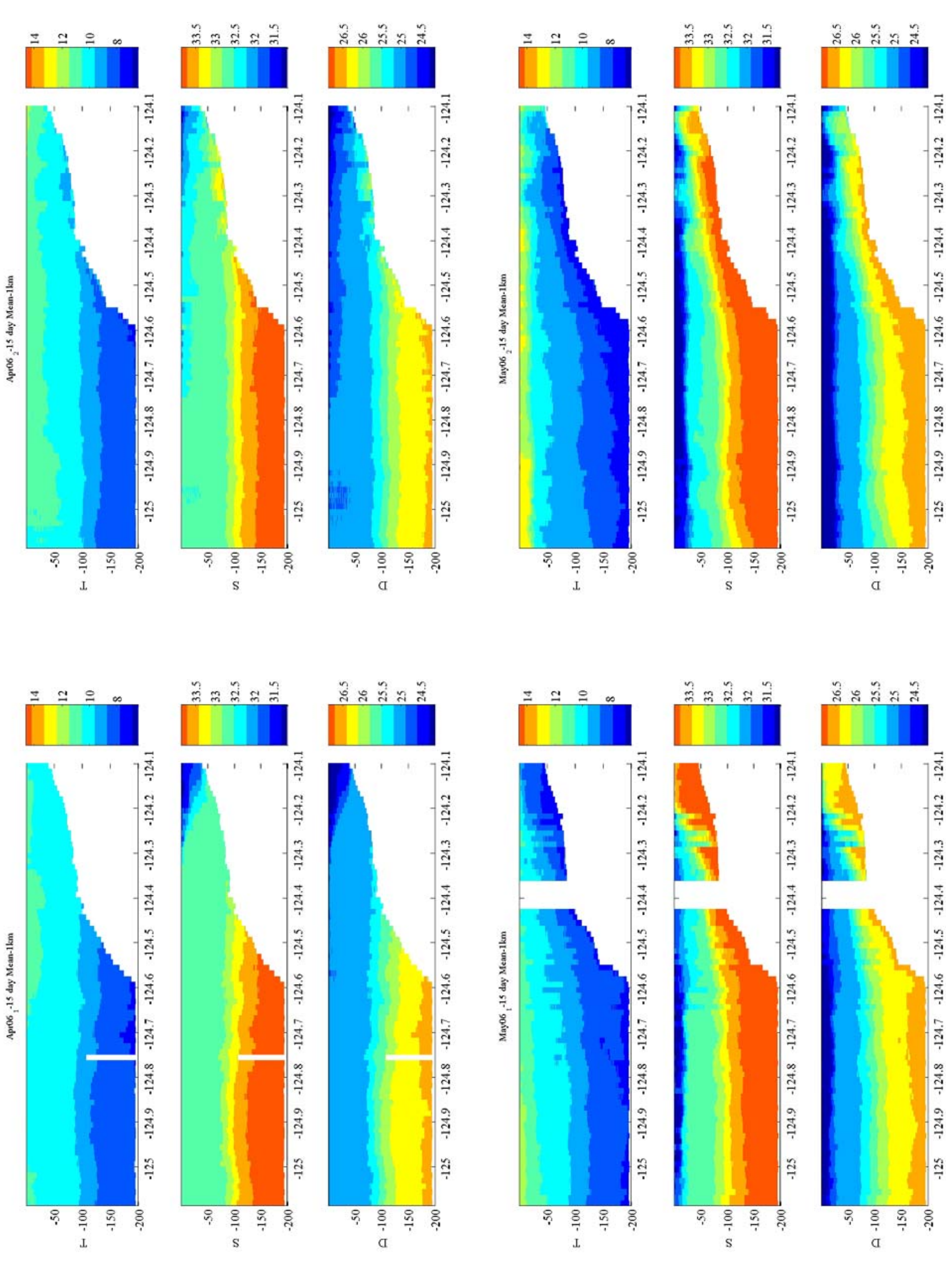
D

ISOBATH BINNING
1 km bin resolution
1 fortnight timescale

Jan. 2007 – Nov. 2007
Not Shown



Apr06_1 -15 day Mean-1km
Apr06_2 -15 day Mean-1km
May06_1 -15 day Mean-1km
May06_2 -15 day Mean-1km
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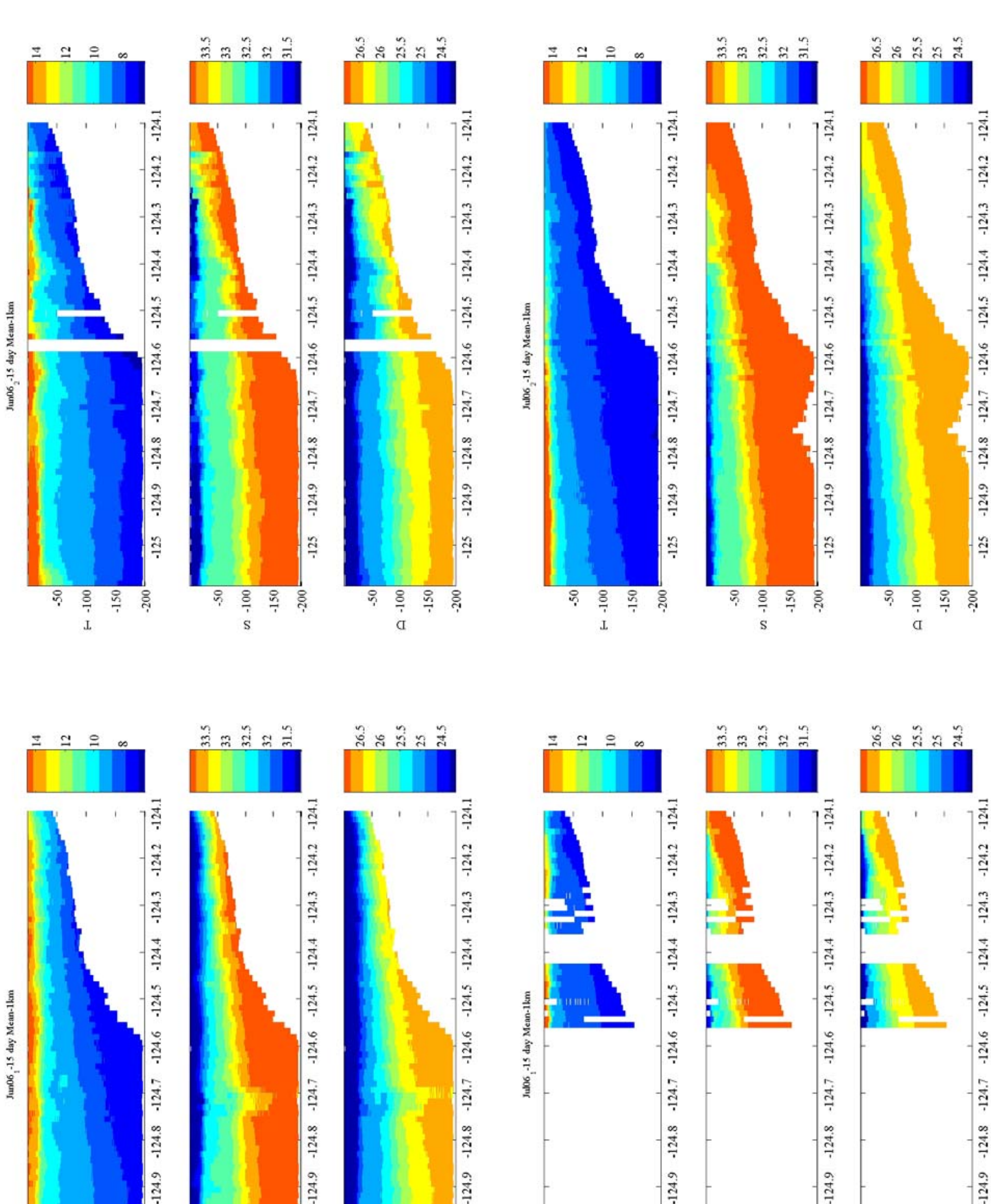
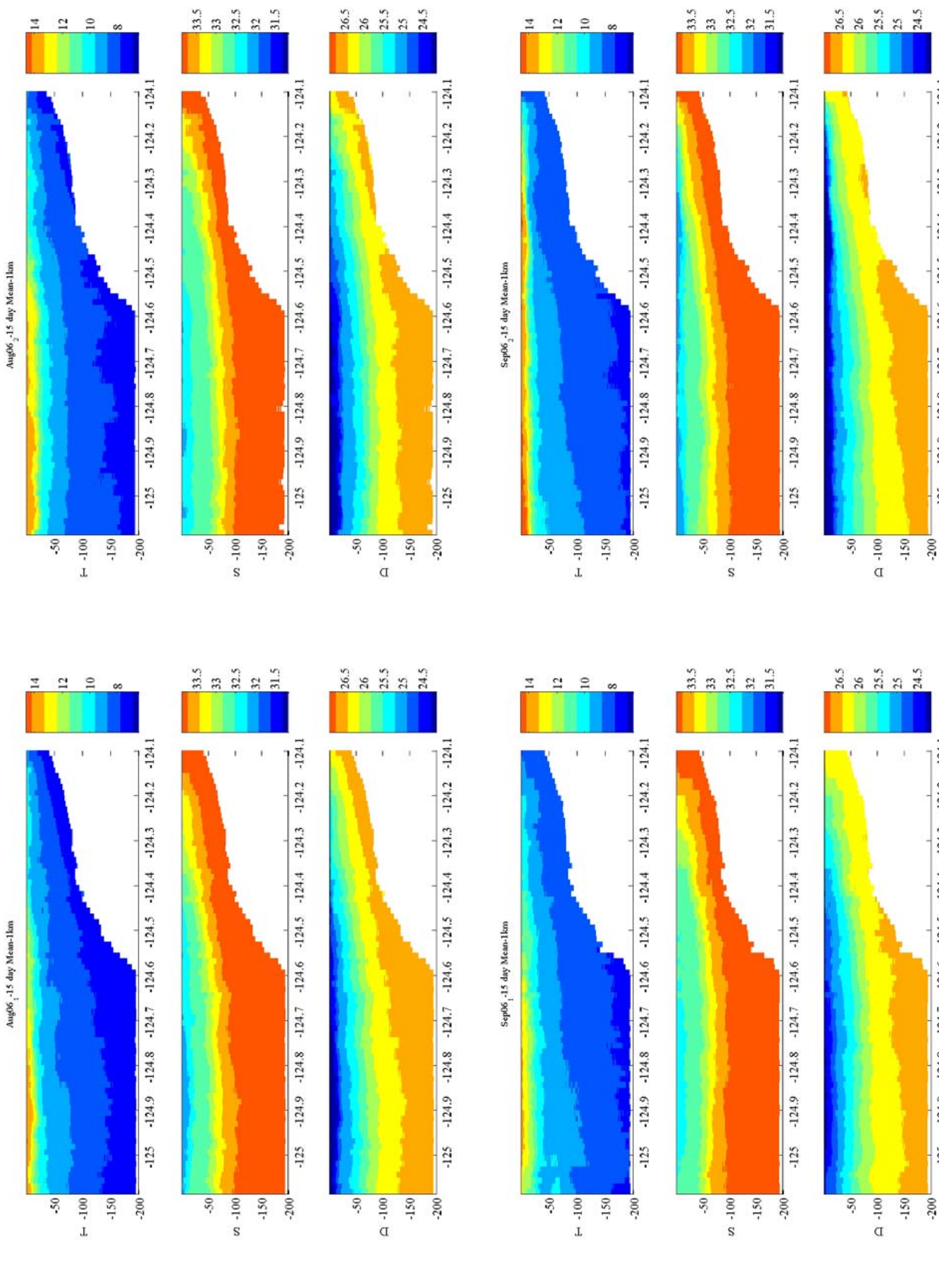
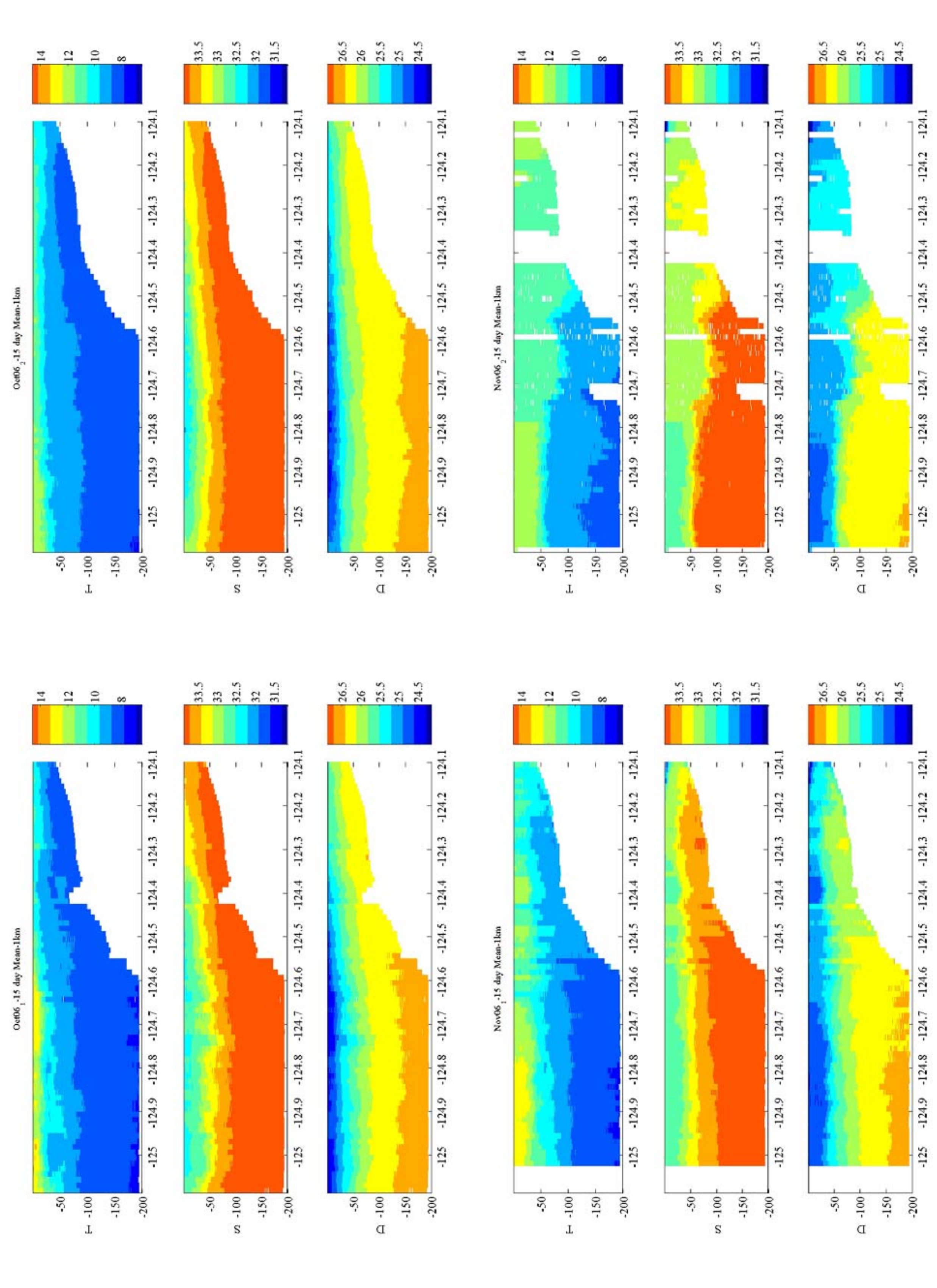

Jun06_1 -15 day Mean-1km
Jun06_2 -15 day Mean-1km
Jul06_1 -15 day Mean-1km
Jul06_2 -15 day Mean-1km


Aug06 1 -15 day Mean-1km
Aug06 2 -15 day Mean-1km
Sep06 1 -15 day Mean-1km
Sep06 2 -15 day Mean-1km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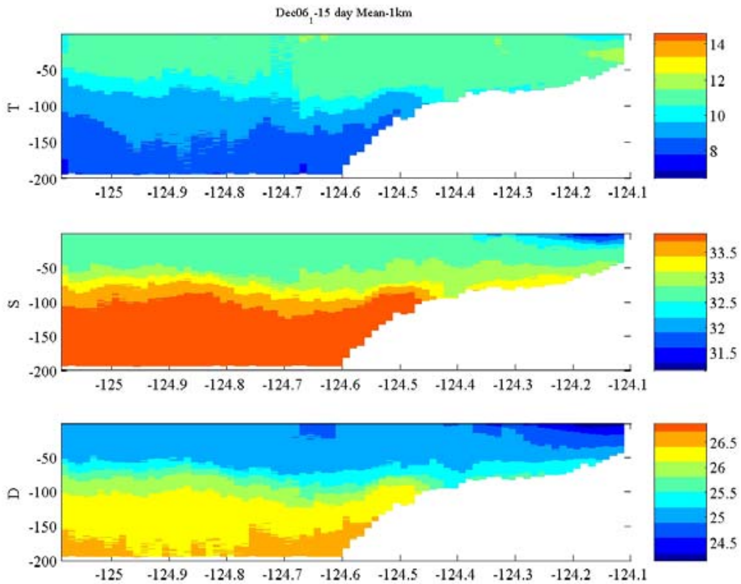
Oct06_2 -15 day Mean-1km
Nov06_1 -15 day Mean-1km
Nov06_2 -15 day Mean-1km


Dec06$_1$-15 day Mean-1km
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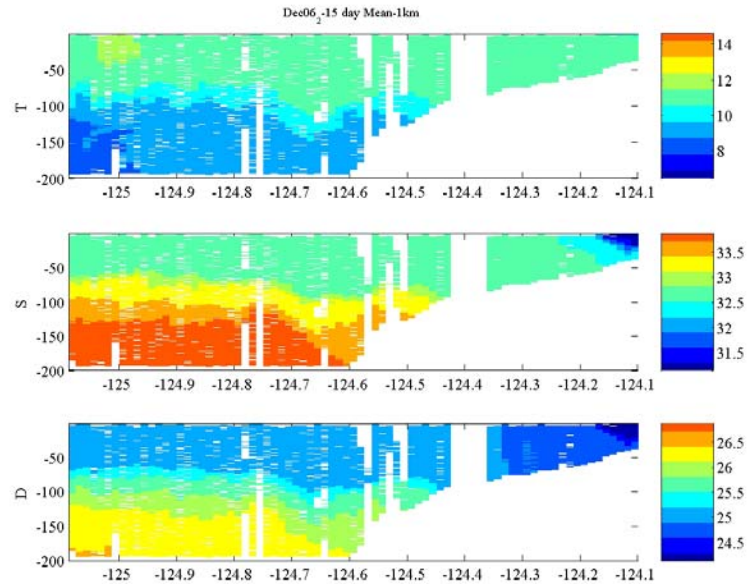
Dec06$_2$-15 day Mean-1km
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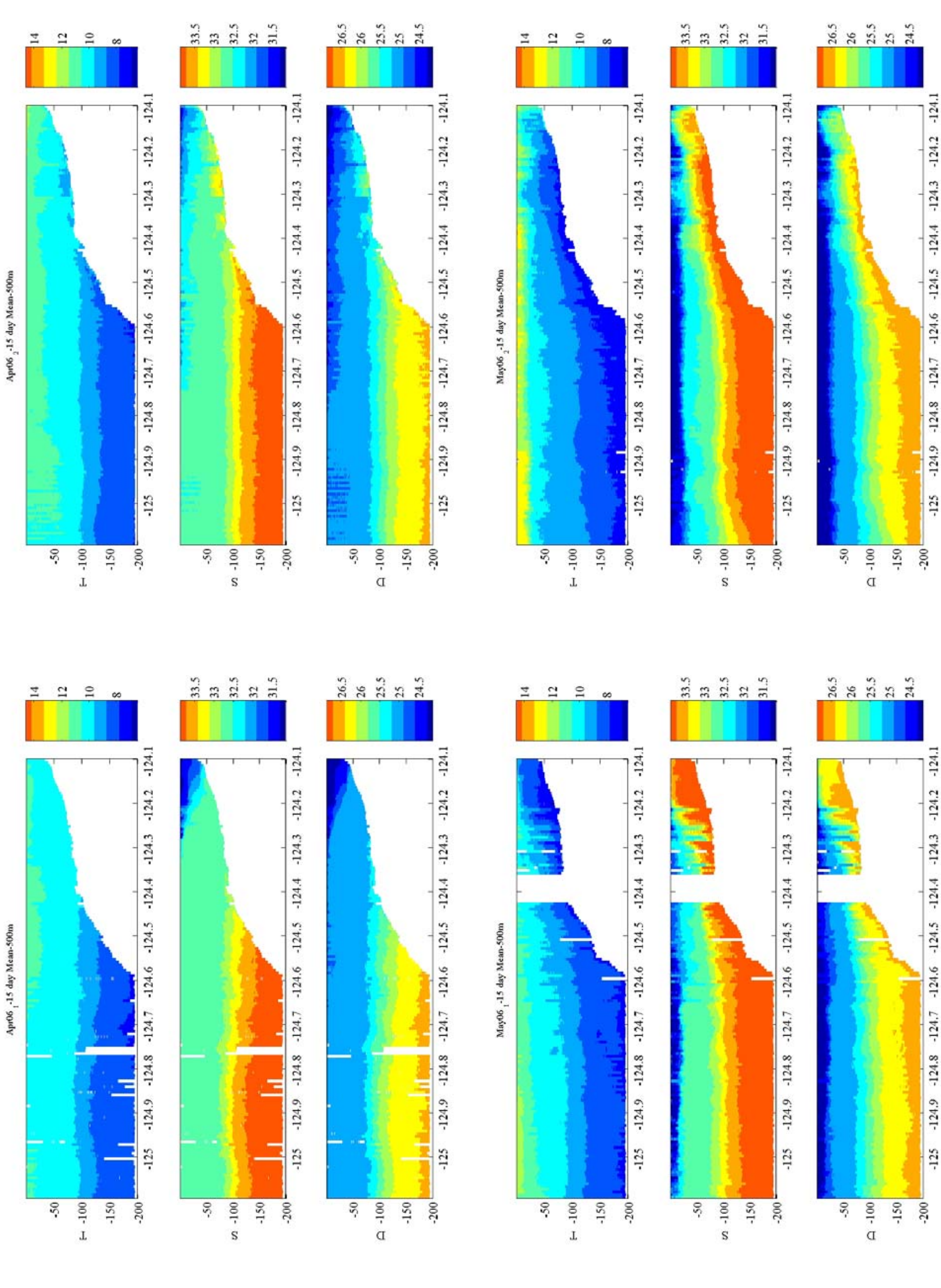
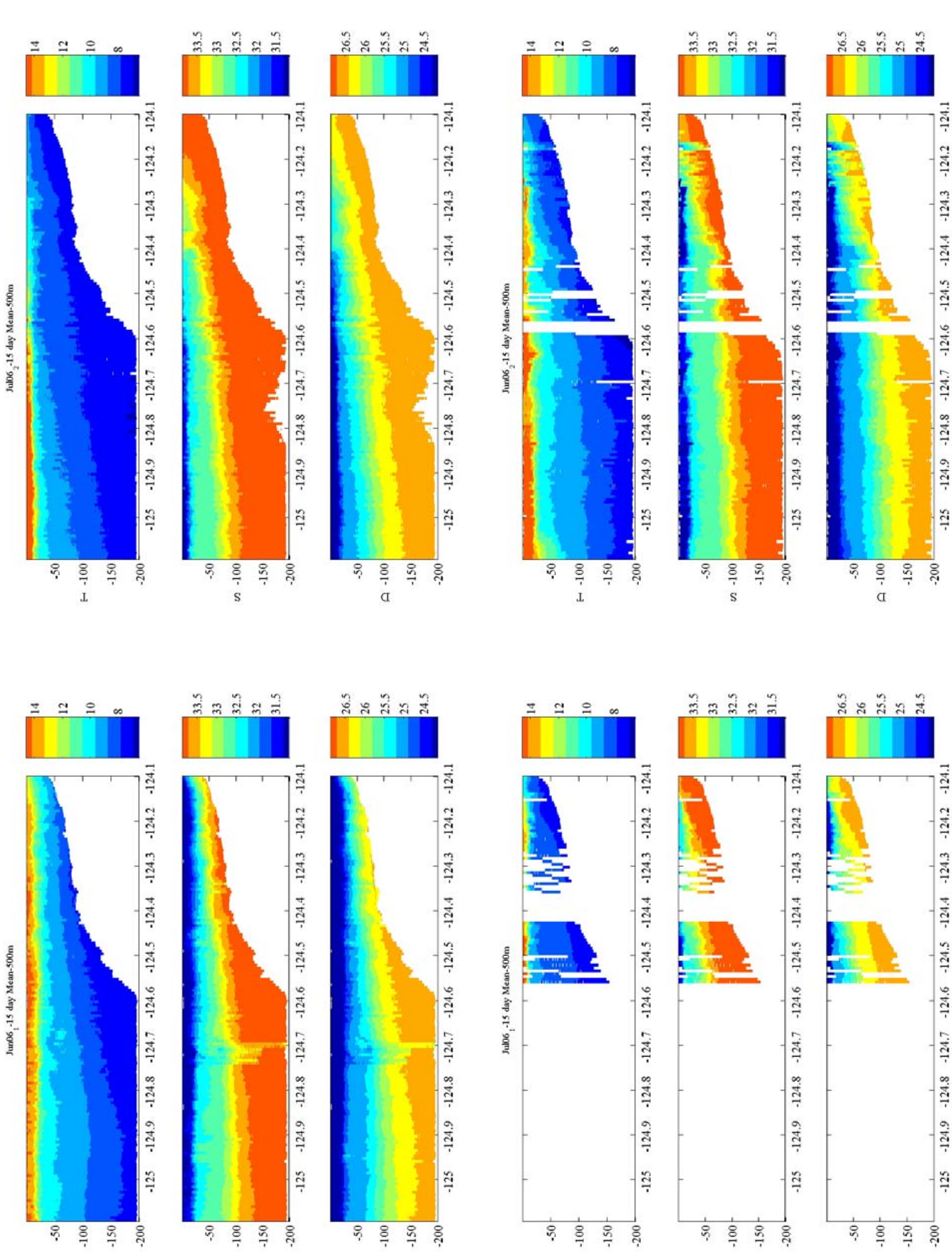
ISOBATH BINNING
500 m bin resolution
1 fortnight timescale

Jan. 2007 – Nov. 2007
Not Shown


Apr06_1 -15 day Mean-500m
Apr06_2 -15 day Mean-500m
May06_1 -15 day Mean-500m
May06_2 -15 day Mean-500m
T
S
D


Jun06_1 -15 day Mean-500m
Jun06_2 -15 day Mean-500m
Jul06_1 -15 day Mean-500m
Jul06_2 -15 day Mean-500m
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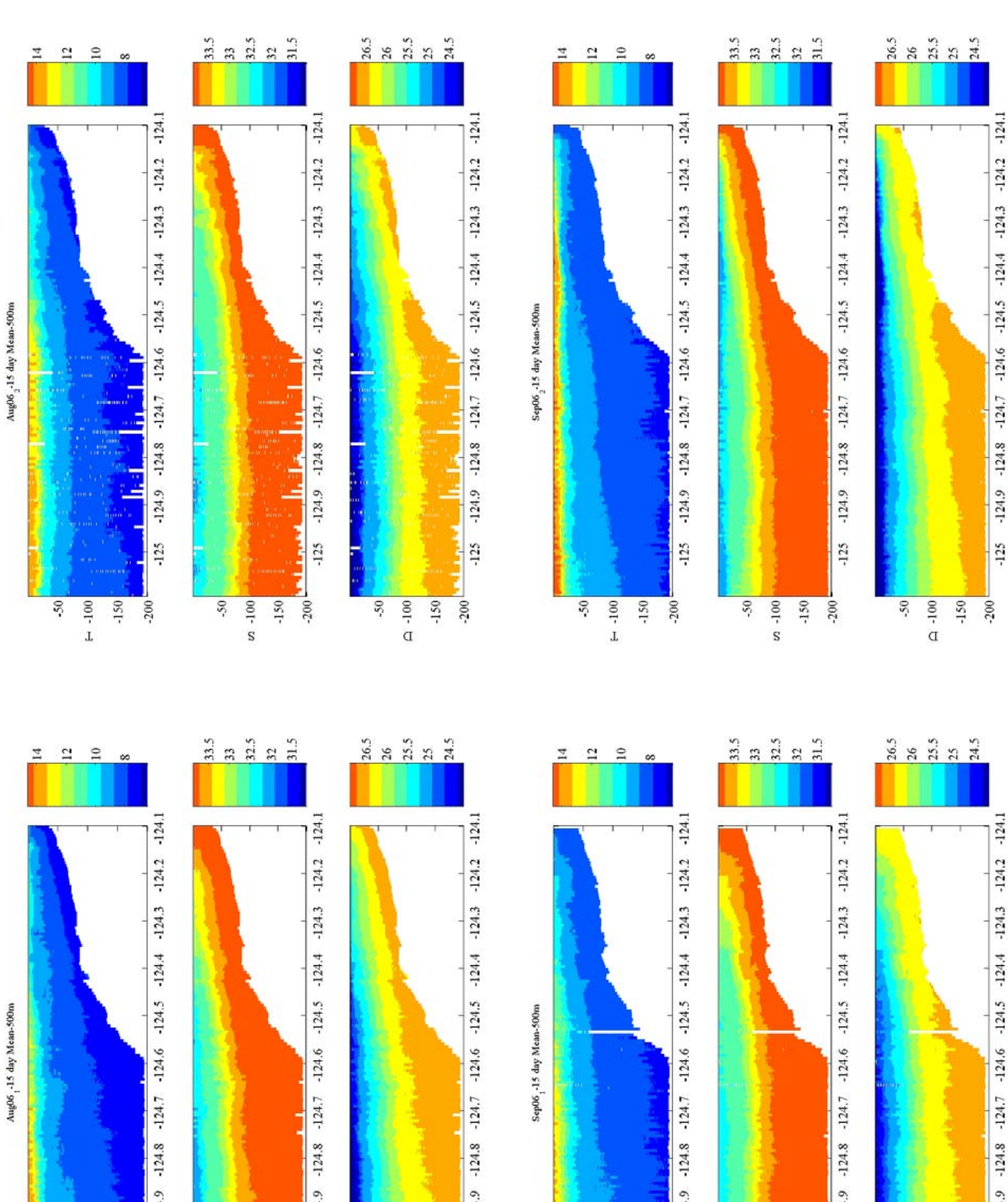
S
D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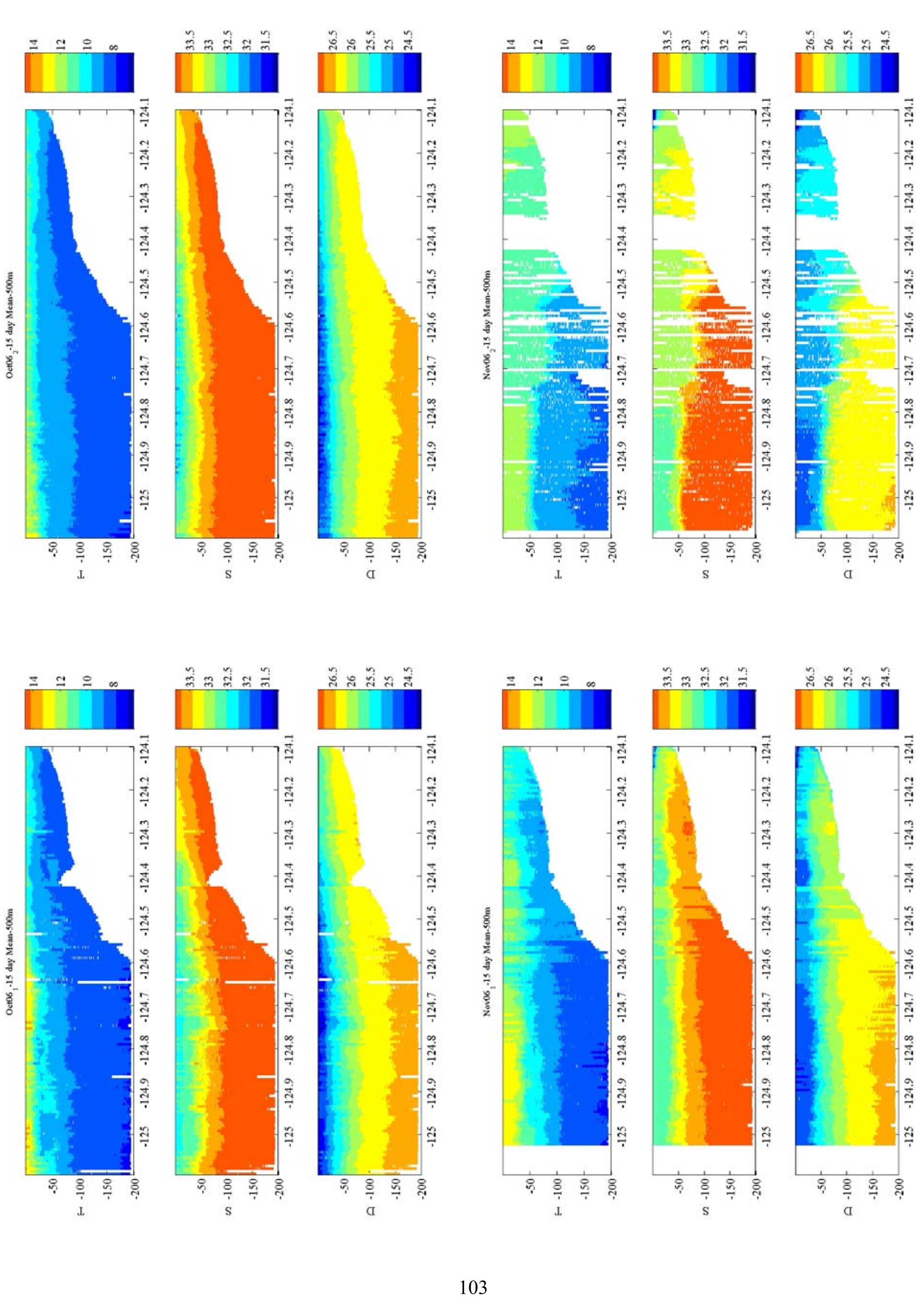
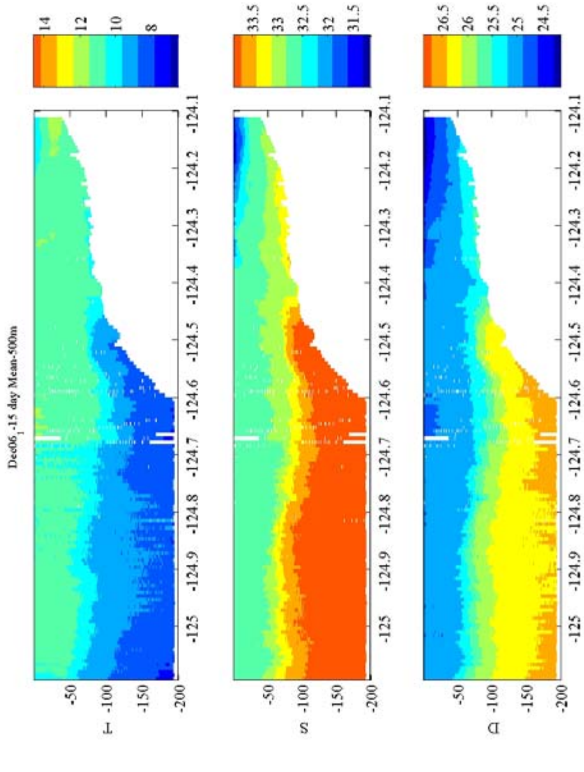
Aug06_2 -15 day Mean-500m
Sep06_1 -15 day Mean-500m
Sep06_2 -15 day Mean-500m


Oct06_1 -15 day Mean-500m
Oct06_2 -15 day Mean-500m
Nov06_1 -15 day Mean-500m
Nov06_2 -15 day Mean-500m


Dec06_1 -15 day Mean-500m
T
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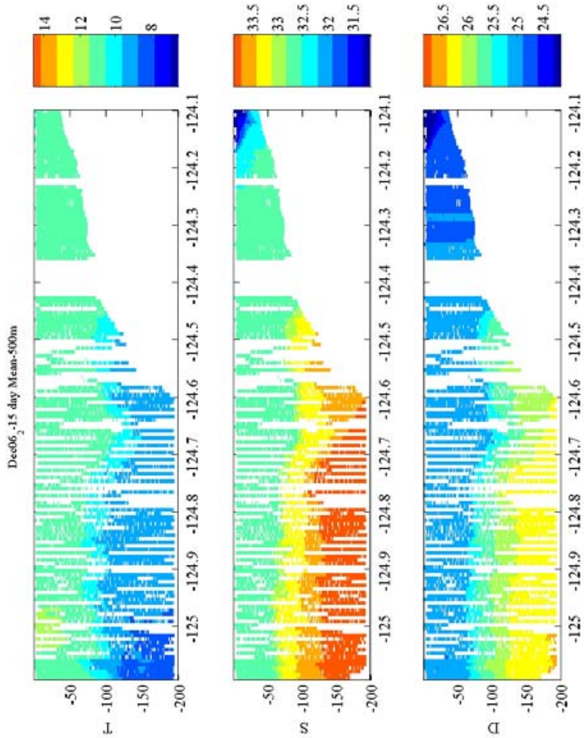
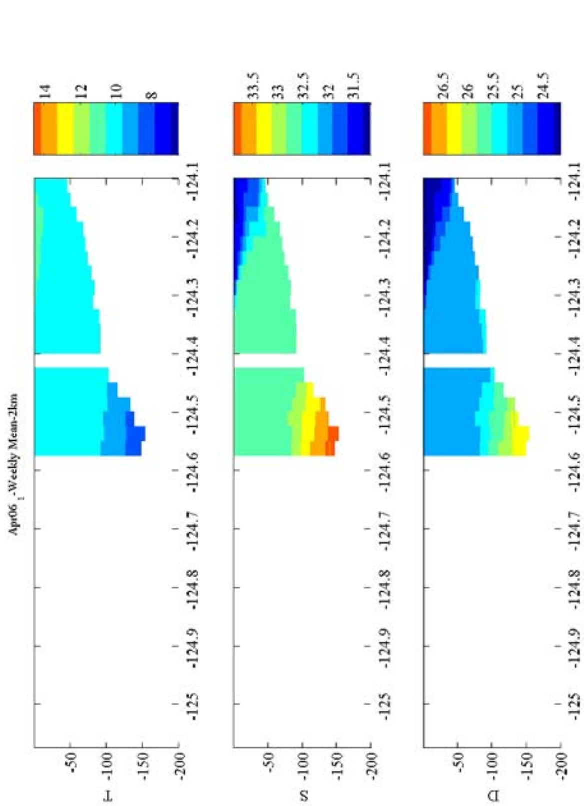
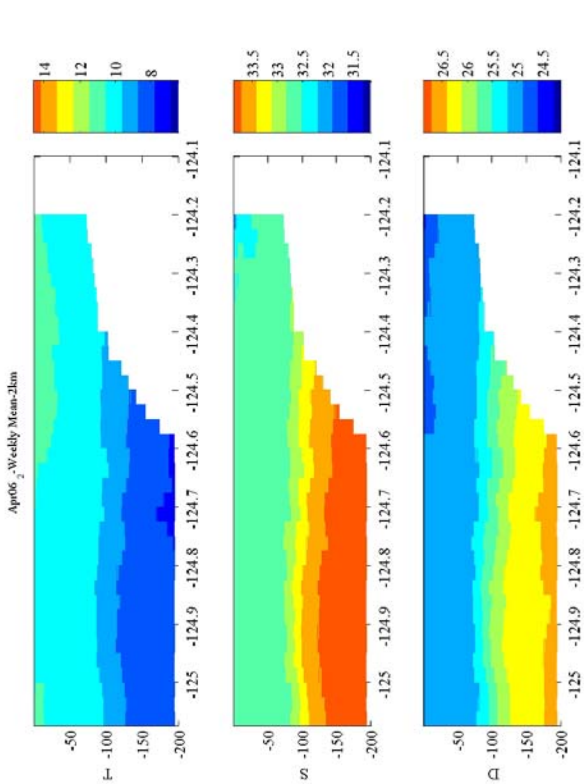
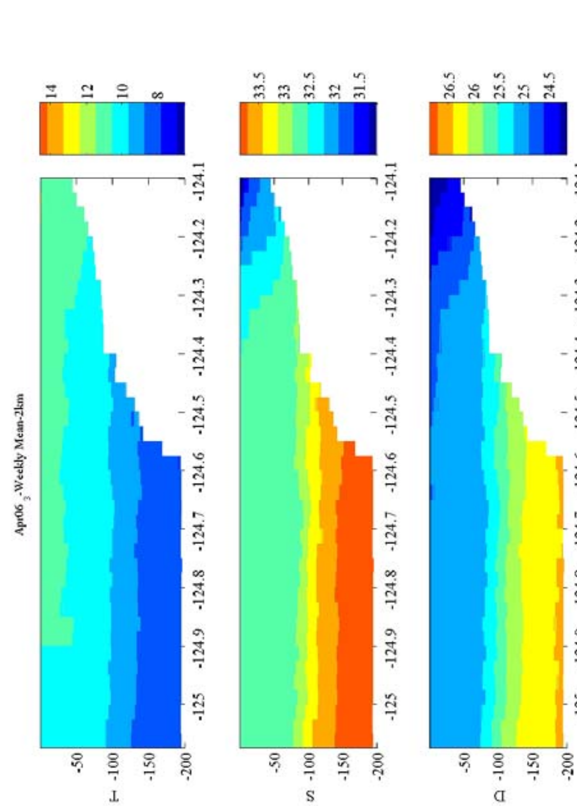

Dec06_2 -15 day Mean-500m
T
S
D

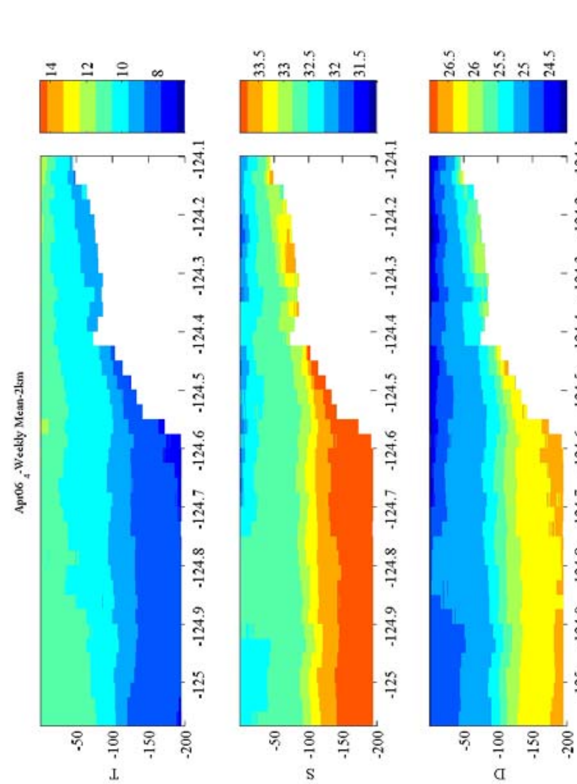
ISOBATH BINNING
2 km bin resolution
1 week timescale

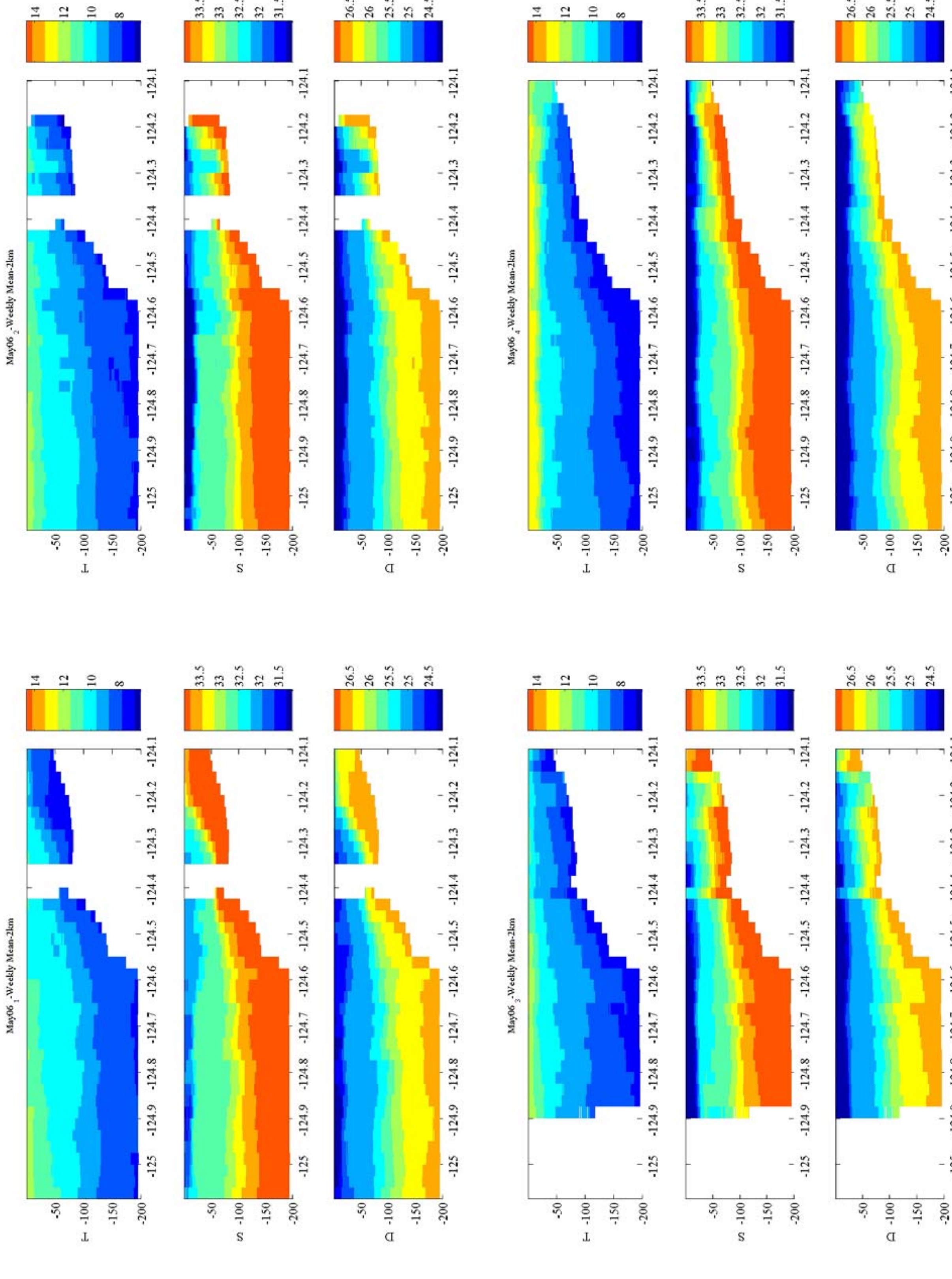
Apr. 2007 – Nov. 2007
Not Shown


Apr06_1-Weekly Mean-2km


Apr06_2-Weekly Mean-2km


Apr06_3-Weekly Mean-2km


Apr06_4-Weekly Mean-2km


May06_1 -Weekly Mean-2km
May06_2 -Weekly Mean-2km
May06_3 -Weekly Mean-2km
May06_4 -Weekly Mean-2km
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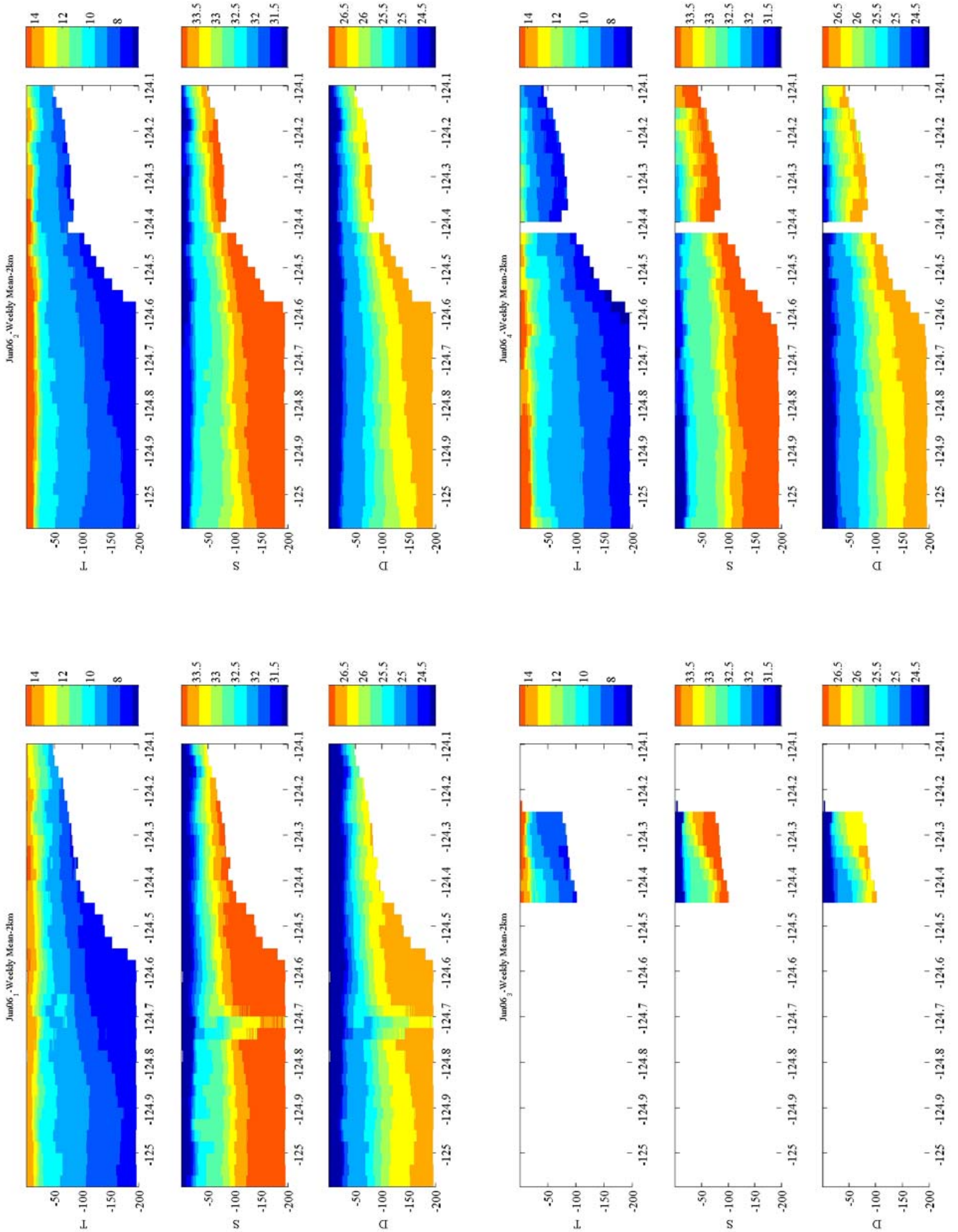
-50 -100 -150 -200
-125 -124.9 -124.8 -124.7 -124.6 -124.5 -124.4 -124.3 -124.2 -124.1
14 12 10 8
33.5 33 32.5 32 31.5
26.5 26 25.5 25 24.5


Jun06_1 -Weekly Mean-2km
Jun06_2 -Weekly Mean-2km
Jun06_3 -Weekly Mean-2km
Jun06_4 -Weekly Mean-2km
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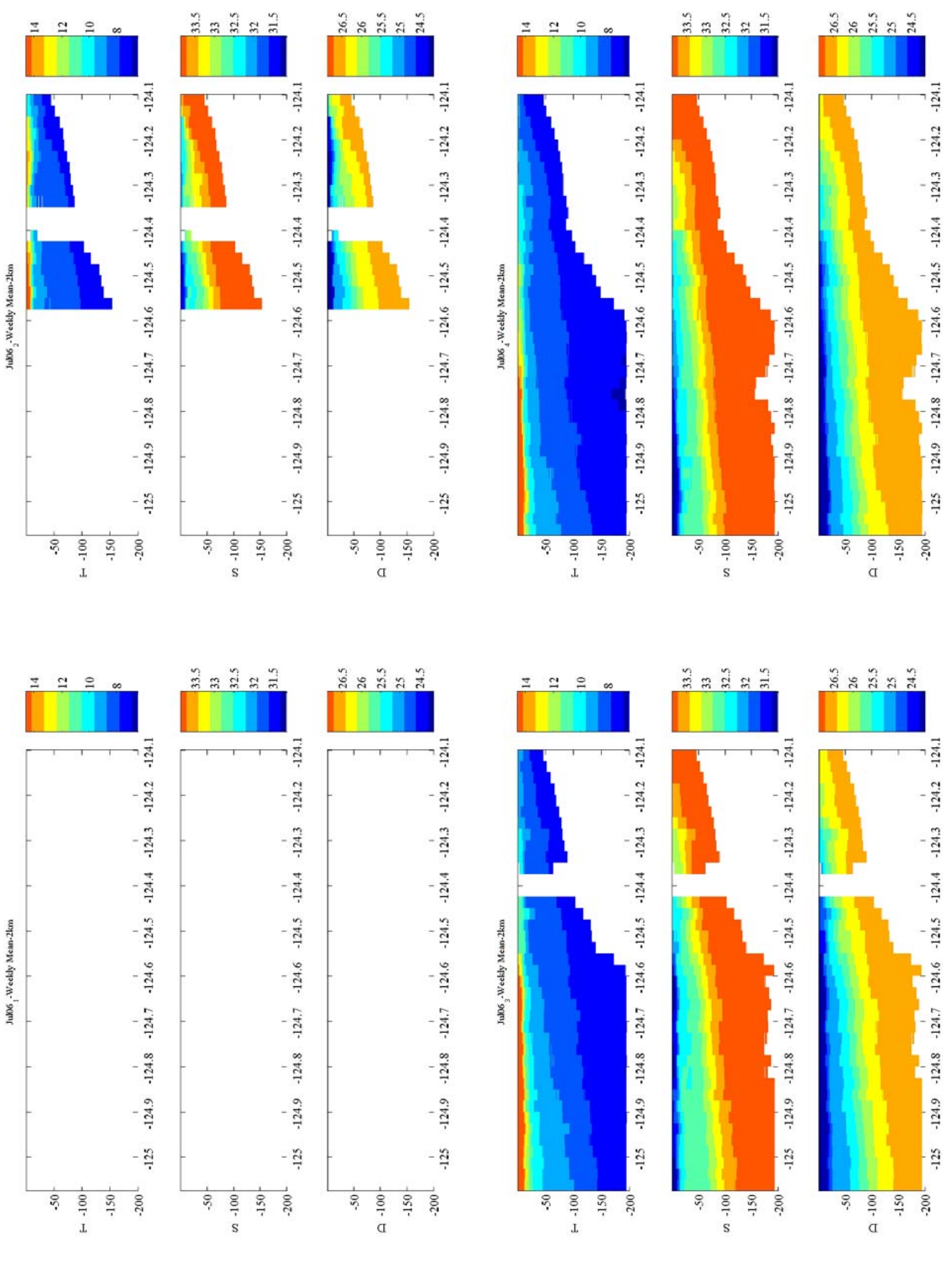
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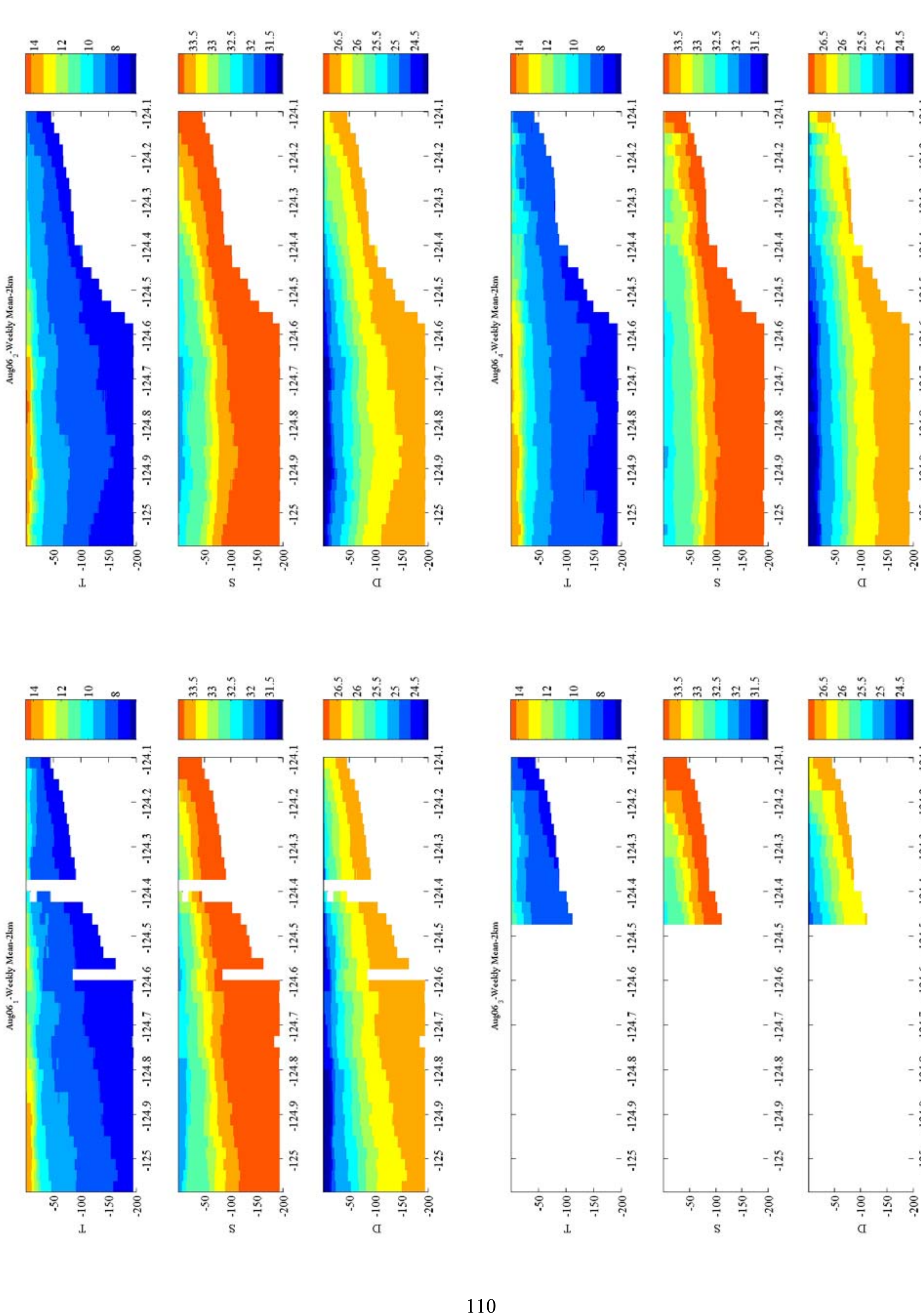
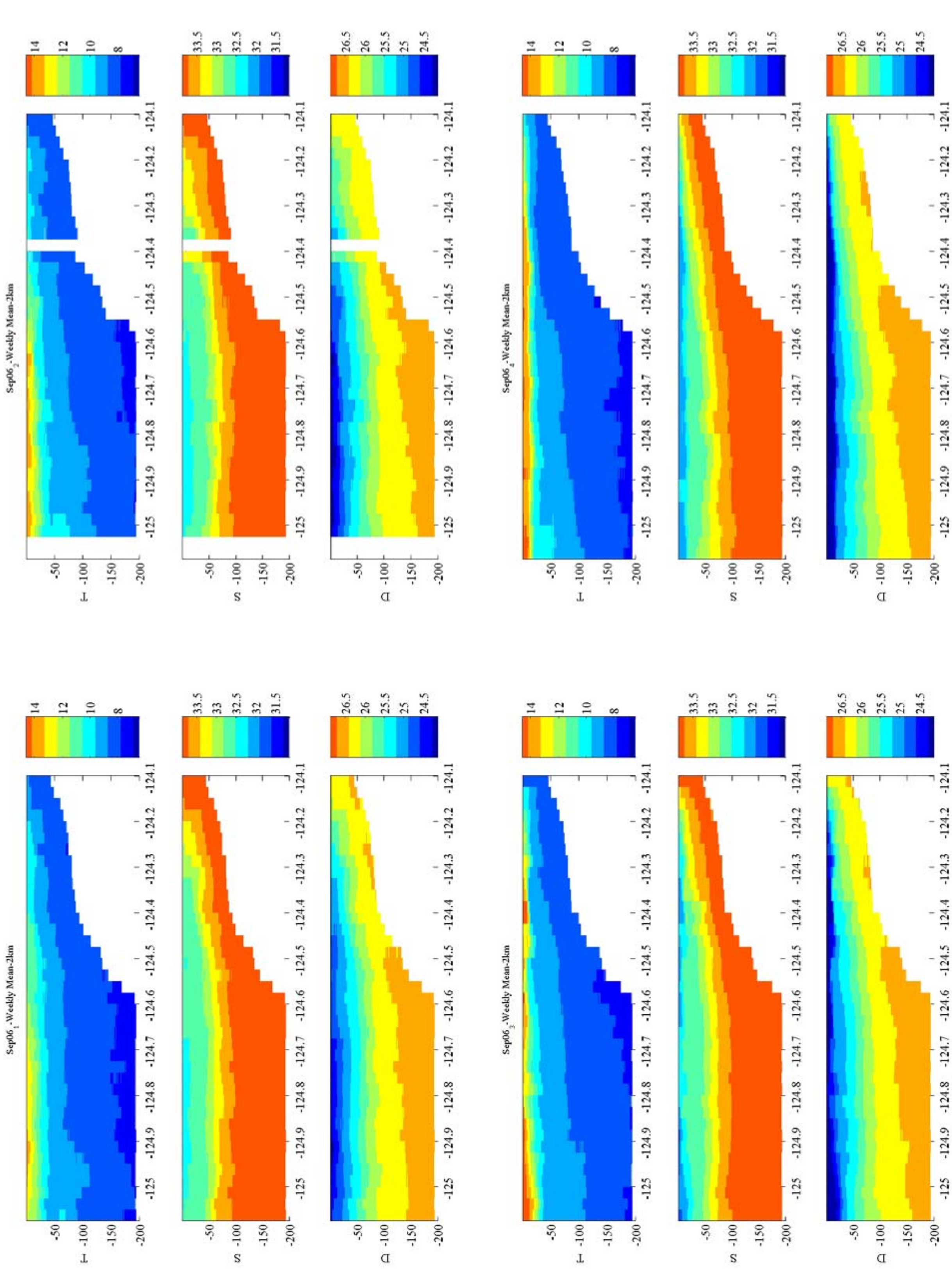
Jul06_2 -Weekly Mean-2km
Jul06_3 -Weekly Mean-2km
Jul06_4 -Weekly Mean-2km


Aug06_1 -Weekly Mean-2km
Aug06_2 -Weekly Mean-2km
Aug06_3 -Weekly Mean-2km
Aug06_4 -Weekly Mean-2km



Sep06_1 -Weekly Mean-2km
Sep06_2 -Weekly Mean-2km
Sep06_3 -Weekly Mean-2km
Sep06_4 -Weekly Mean-2km
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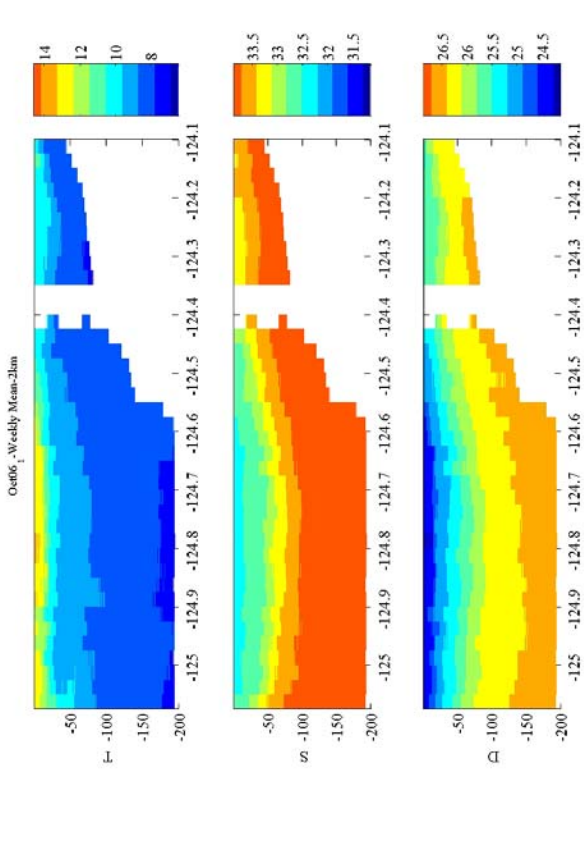
Oct06_1-Weekly Mean-2km
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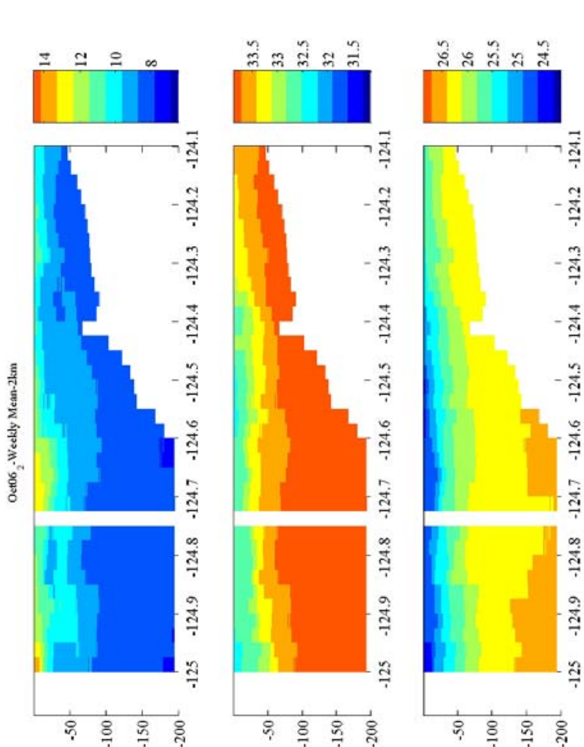
Oct06_2-Weekly Mean-2km
T
S
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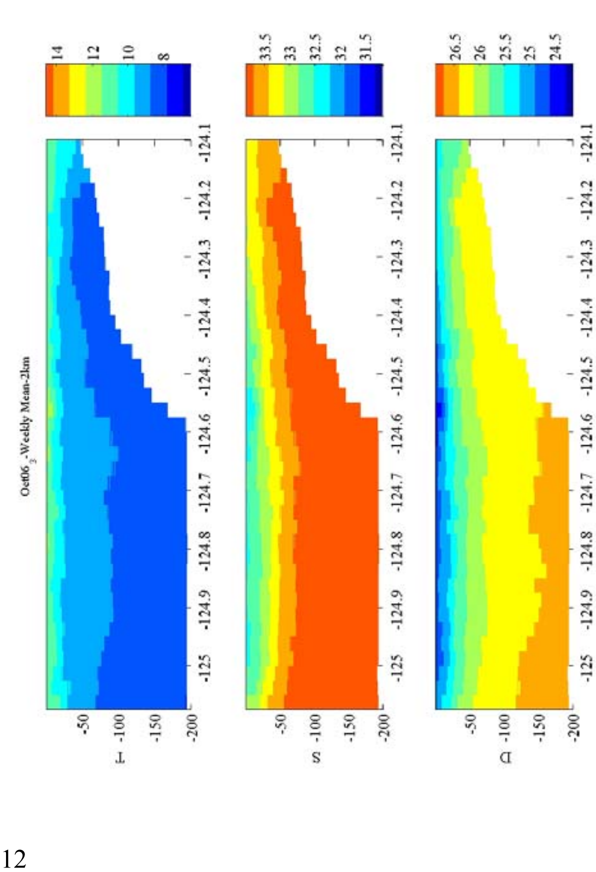
Oct06_3-Weekly Mean-2km
T
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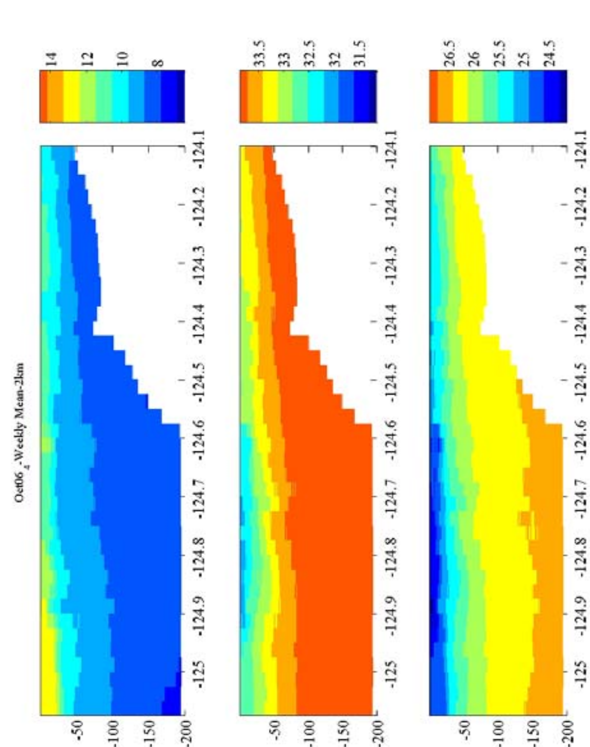
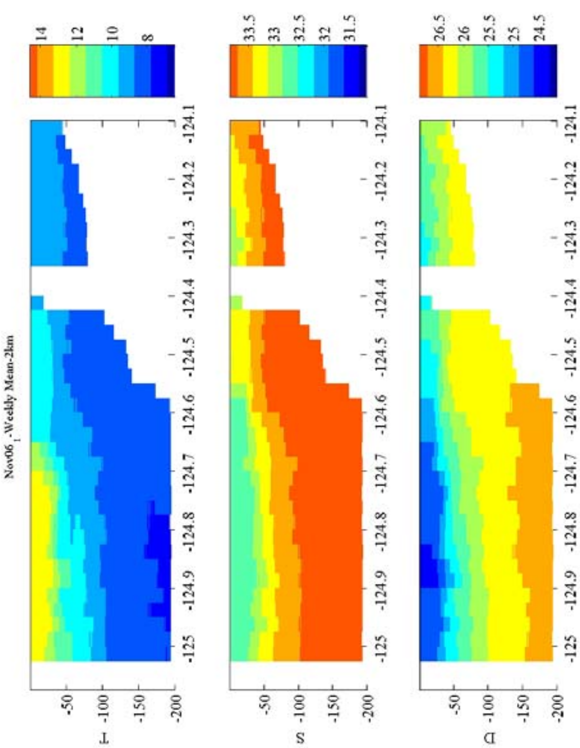

Oct06_4-Weekly Mean-2km
T
S
D


Nov06_1 -Weekly Mean-2km
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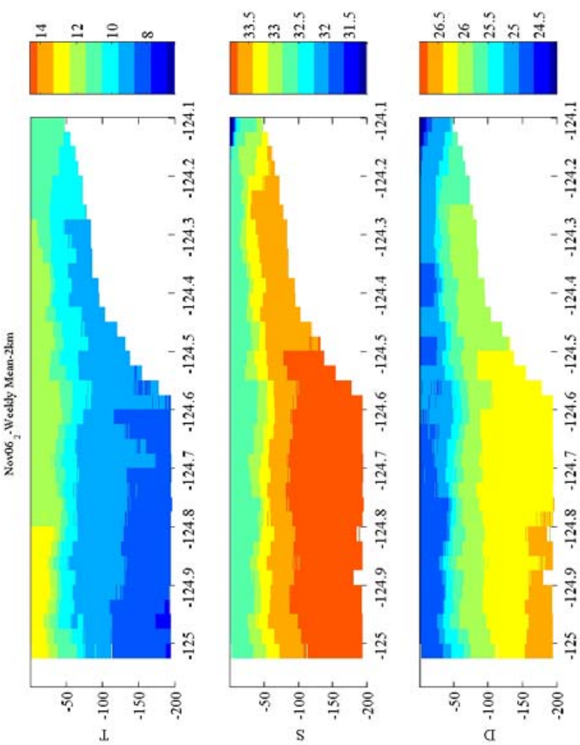
Nov06_2 -Weekly Mean-2km
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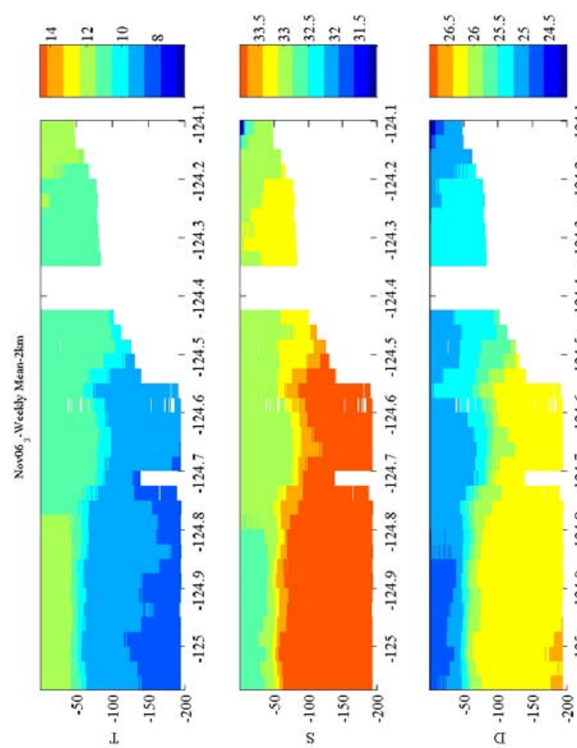
Nov06_3 -Weekly Mean-2km
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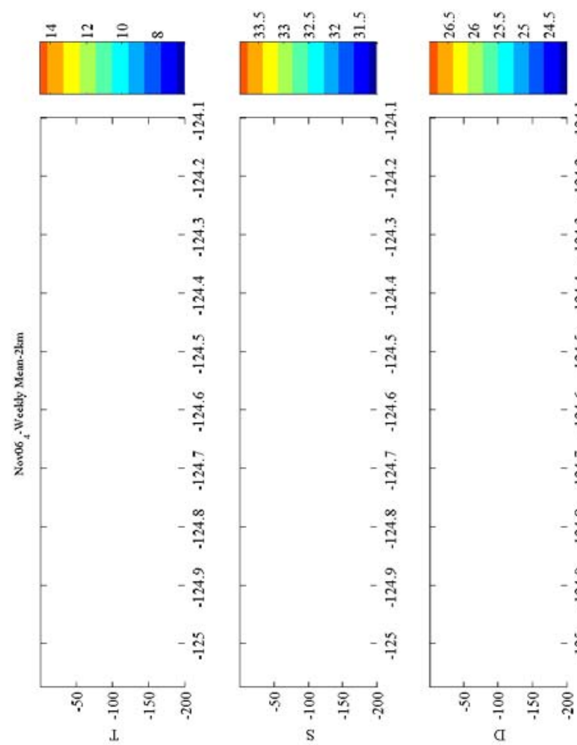
Nov06_4 -Weekly Mean-2km
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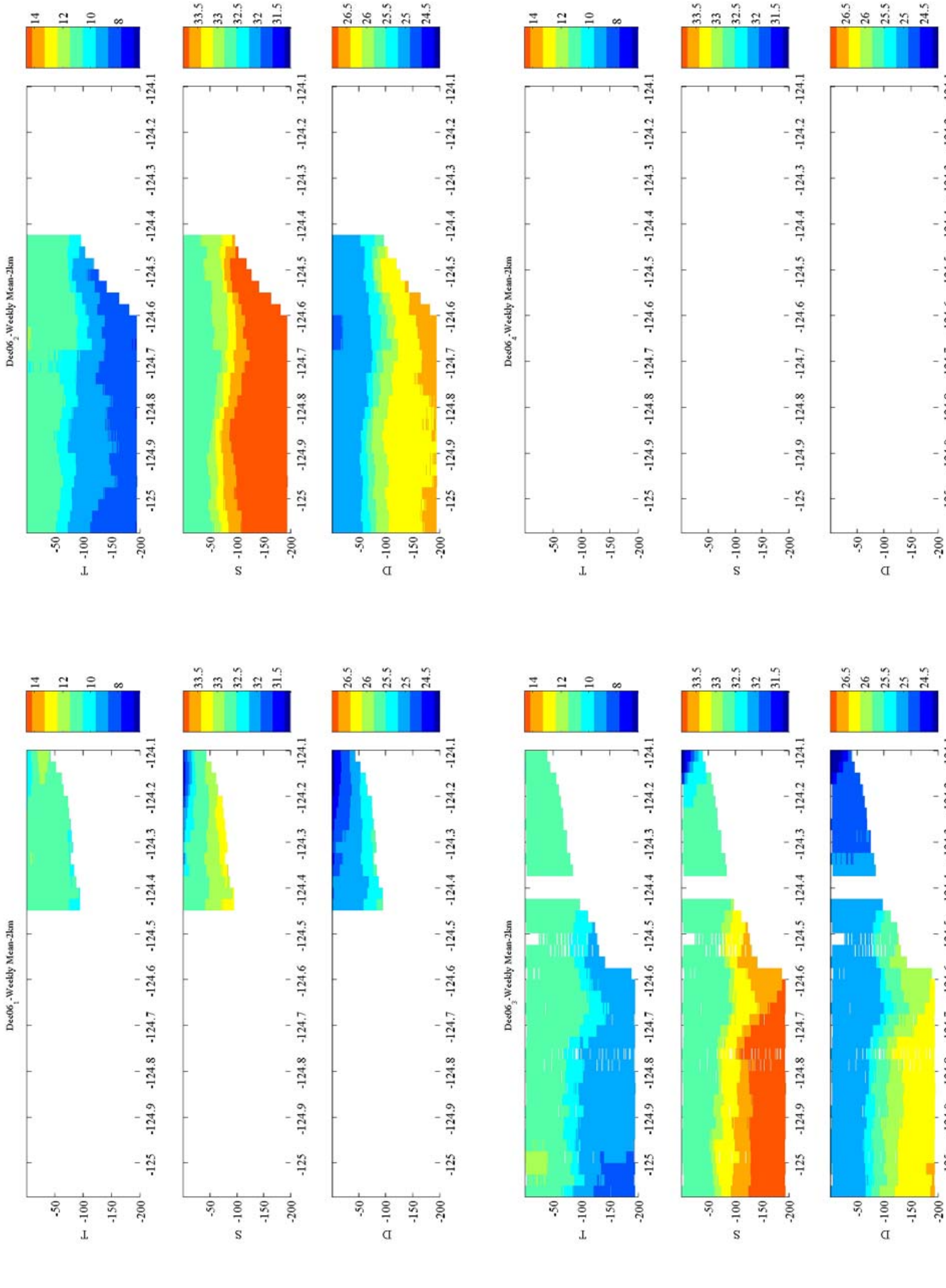
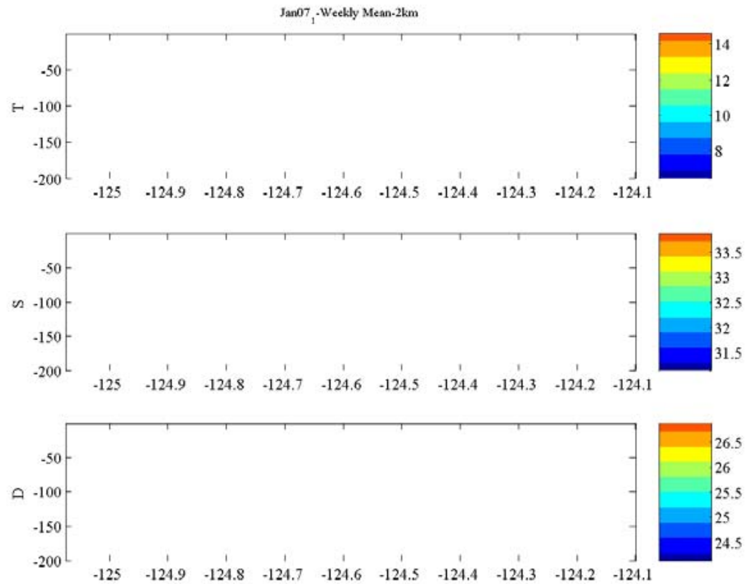
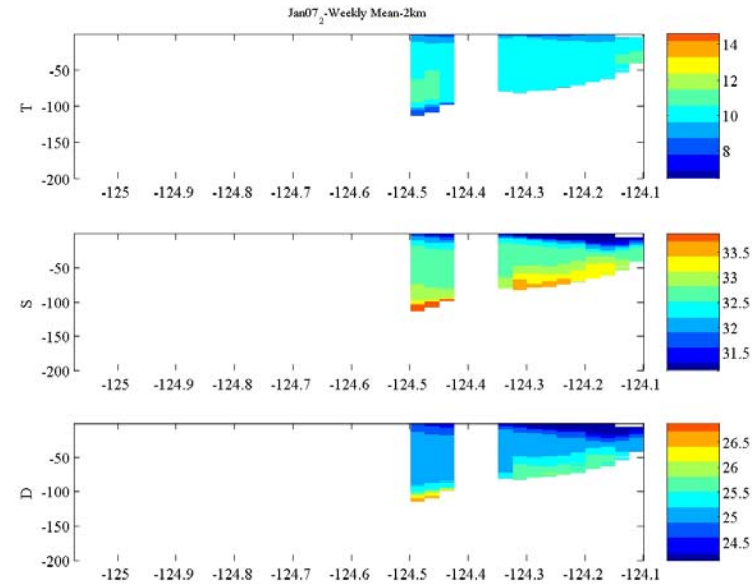
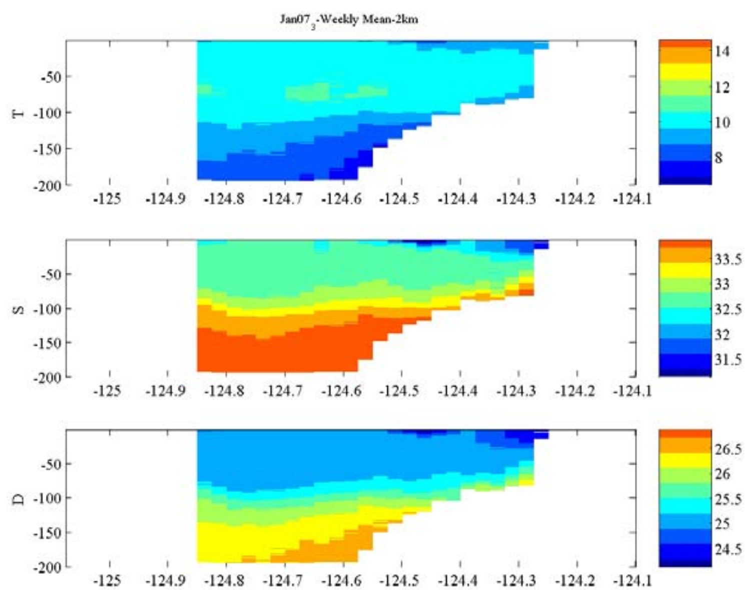
D

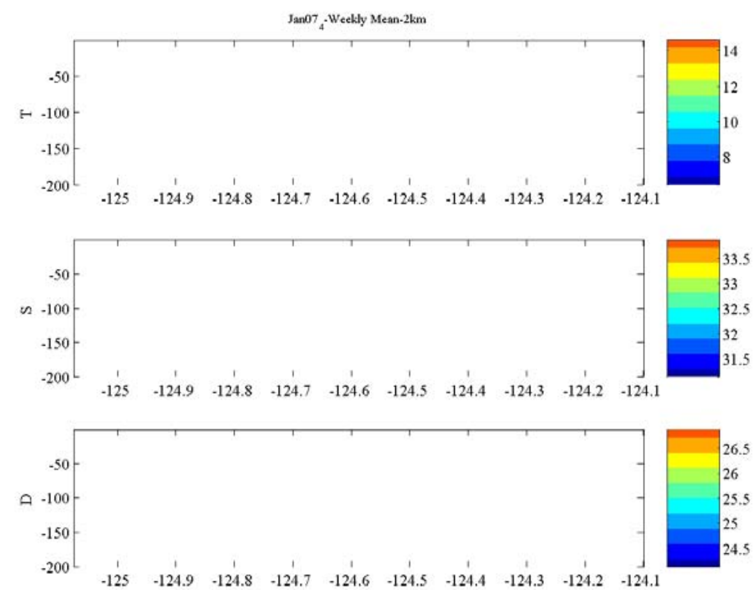


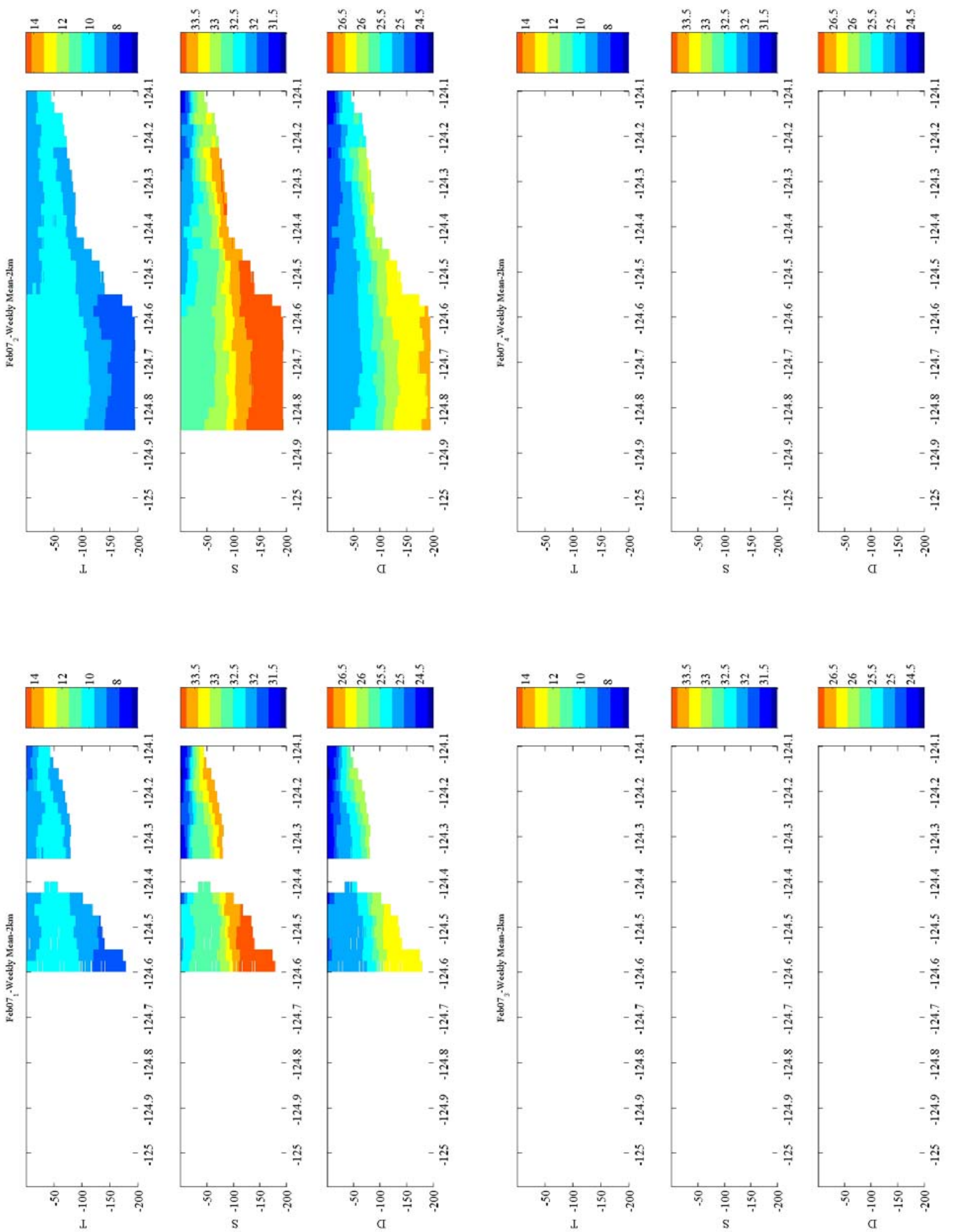
Dec06_1-Weekly Mean-2km
Dec06_2-Weekly Mean-2km
Dec06_3-Weekly Mean-2km
Dec06_4-Weekly Mean-2km


Jan07 1-Weekly Mean-2km
T
S
D

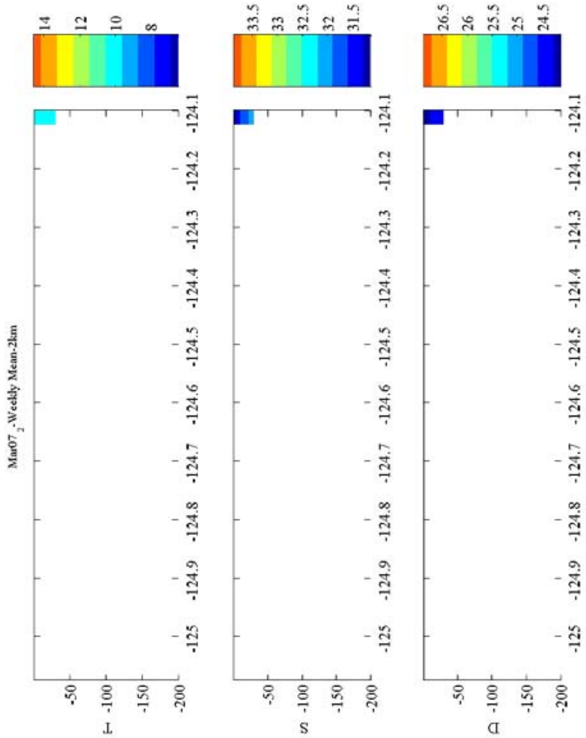

Jan07 2-Weekly Mean-2km
T
S
D

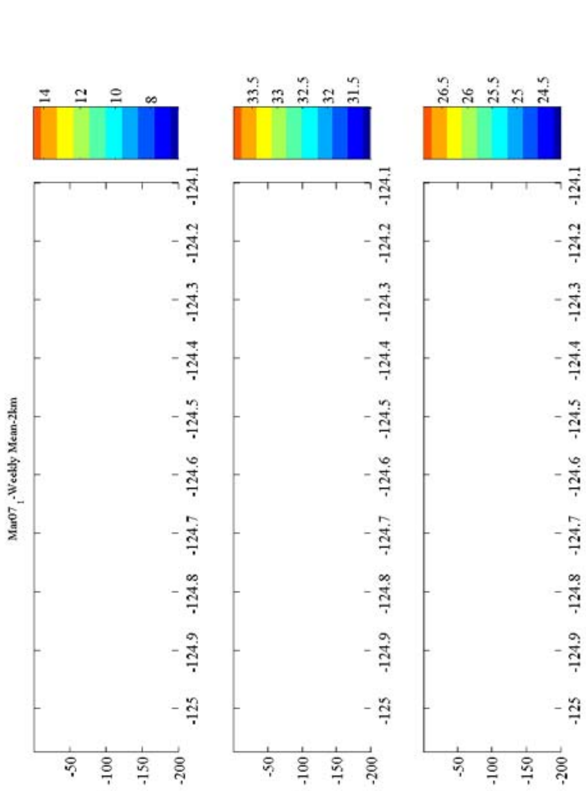

Jan07 3-Weekly Mean-2km
T
S
D

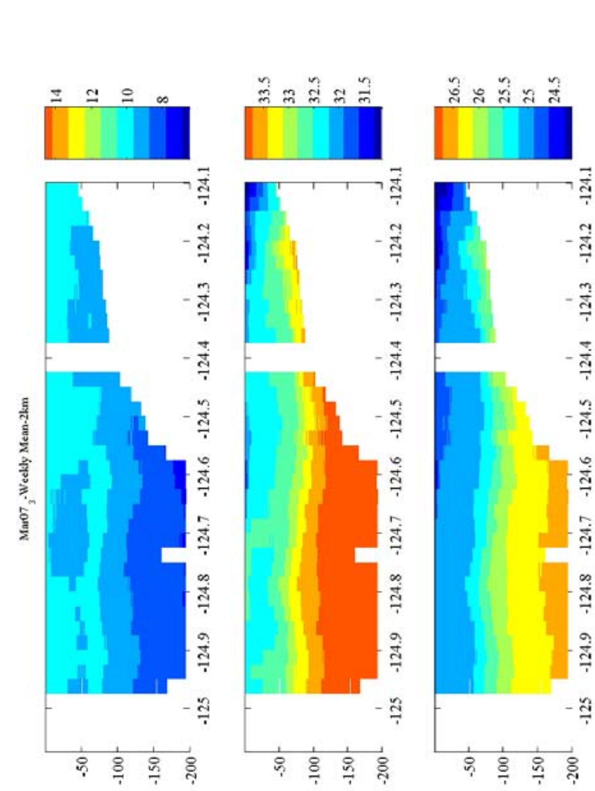

Jan07 4-Weekly Mean-2km
T
S
D



Feb07_1-Weekly Mean-2km
Feb07_2-Weekly Mean-2km
Feb07_3-Weekly Mean-2km
Feb07_4-Weekly Mean-2km

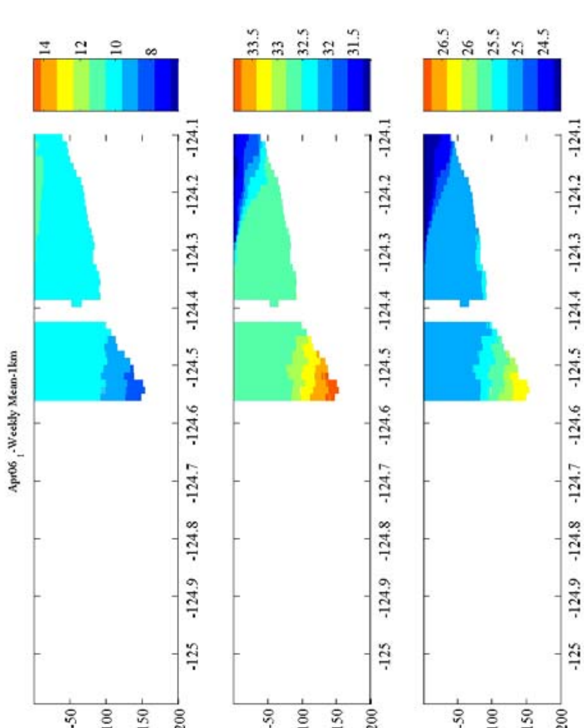

Mar07_2 -Weekly Mean-2km
T
S
D

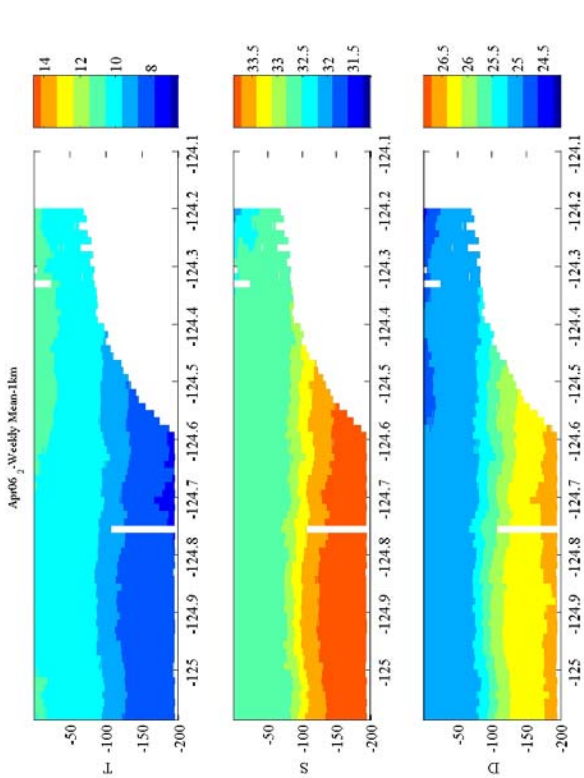

Mar07_1 -Weekly Mean-2km
T
S
D

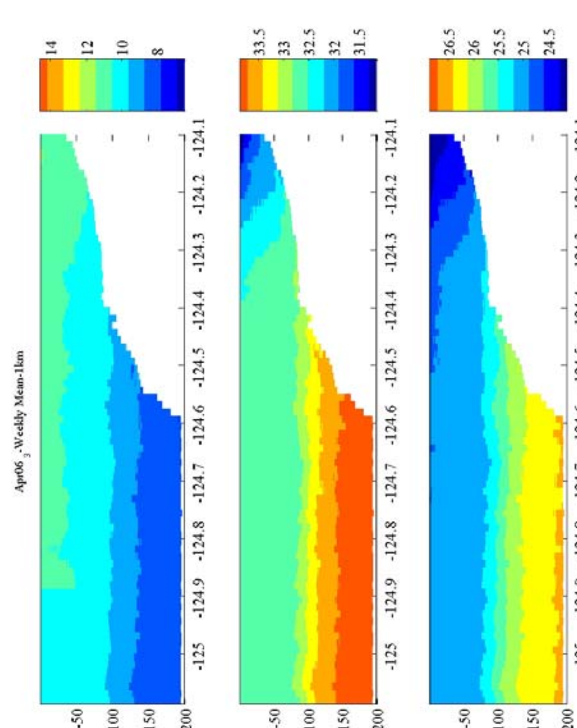

Mar07_3 -Weekly Mean-2km
T
S
D

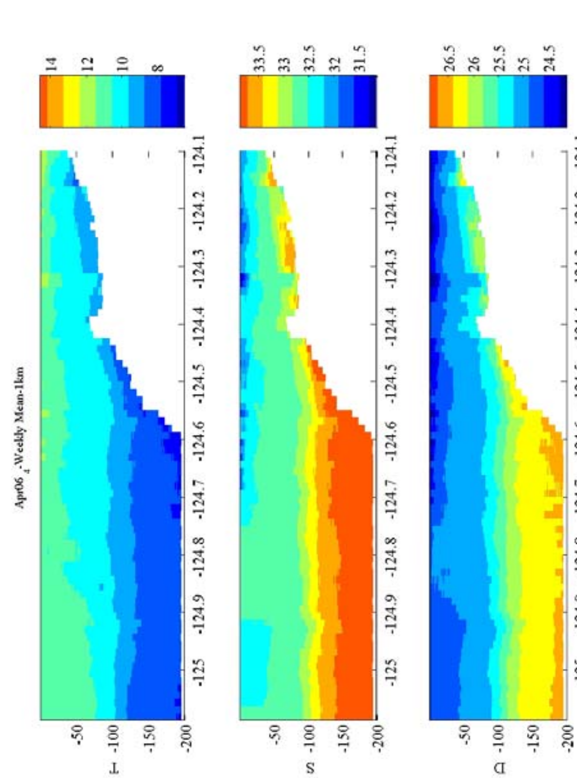
ISOBATH BINNING
1 km bin resolution
1 week timescale

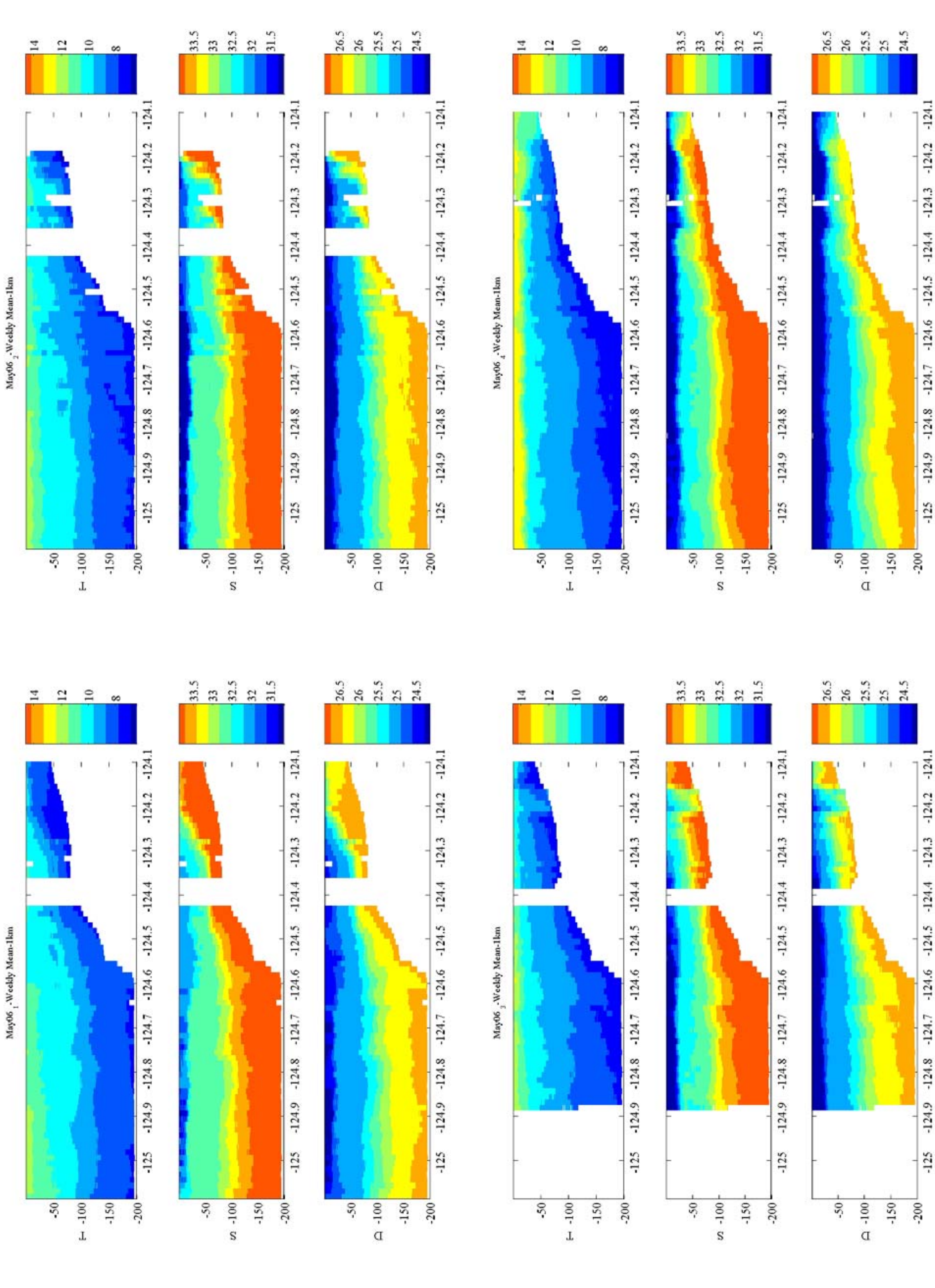
Apr. 2007 – Nov. 2007
Not Shown










May06_1 -Weekly Mean-1km
May06_2 -Weekly Mean-1km
May06_3 -Weekly Mean-1km
May06_4 -Weekly Mean-1km
T
S
D
-50
-100
-150
-200
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
-124.3
-124.2
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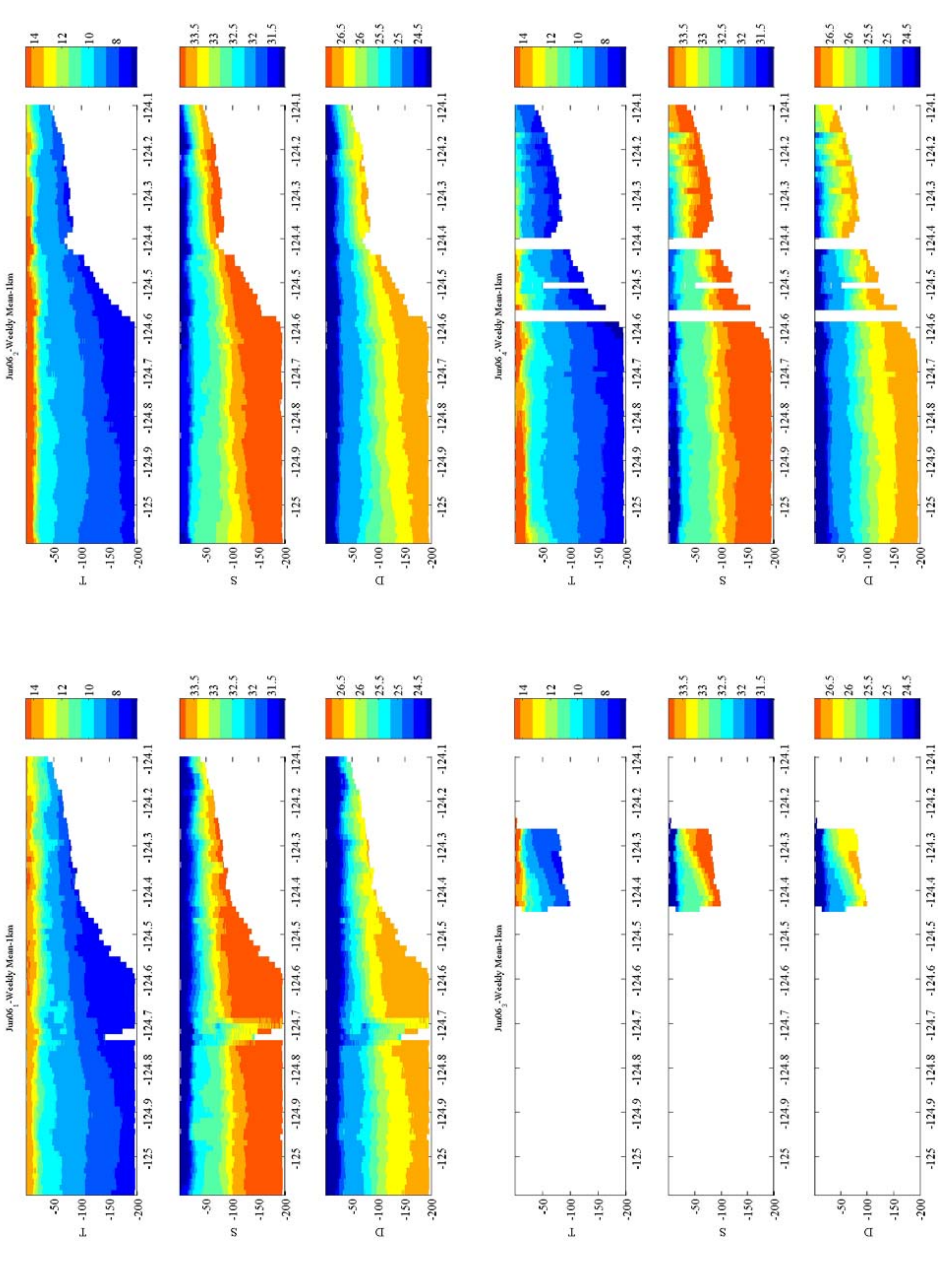
Jun06_1 -Weekly Mean-1km
Jun06_2 -Weekly Mean-1km
Jun06_3 -Weekly Mean-1km
Jun06_4 -Weekly Mean-1km
T
S
D
-50
-100
-150
-200
-125
-124.9
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-124.6
-124.5
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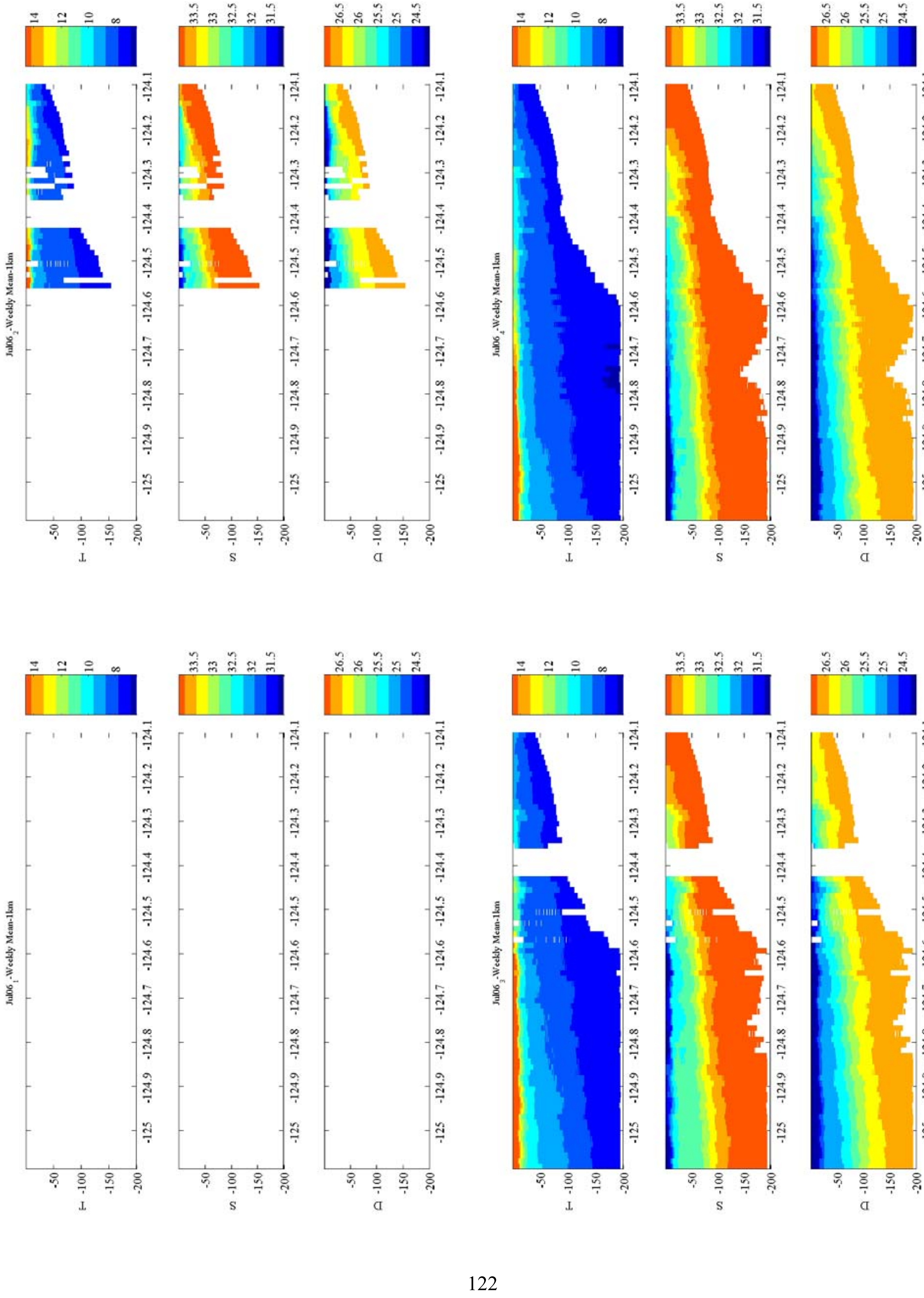

Jul06_1-Weekly Mean-1km
Jul06_2-Weekly Mean-1km
Jul06_3-Weekly Mean-1km
Jul06_4-Weekly Mean-1km
T
S
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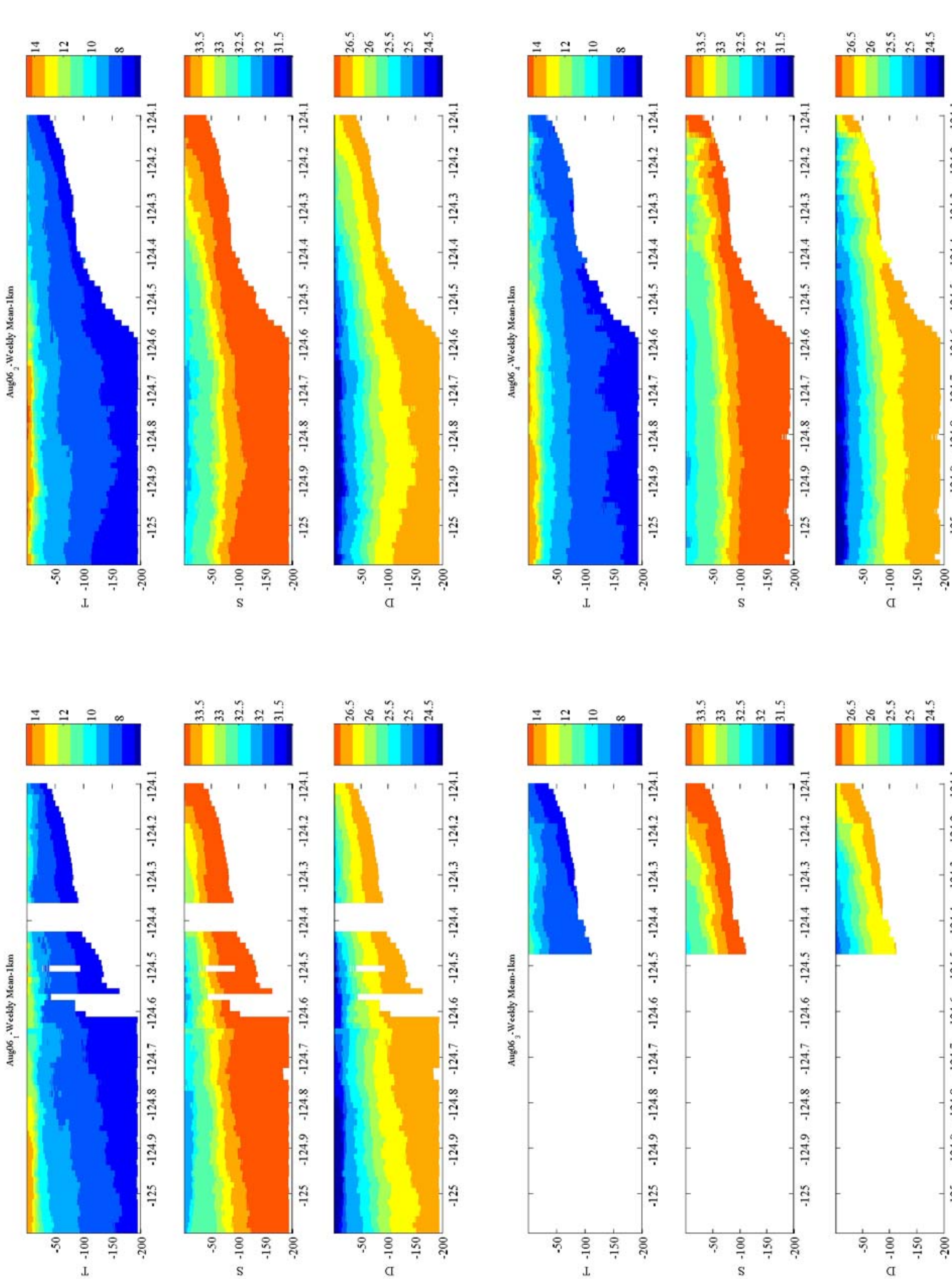
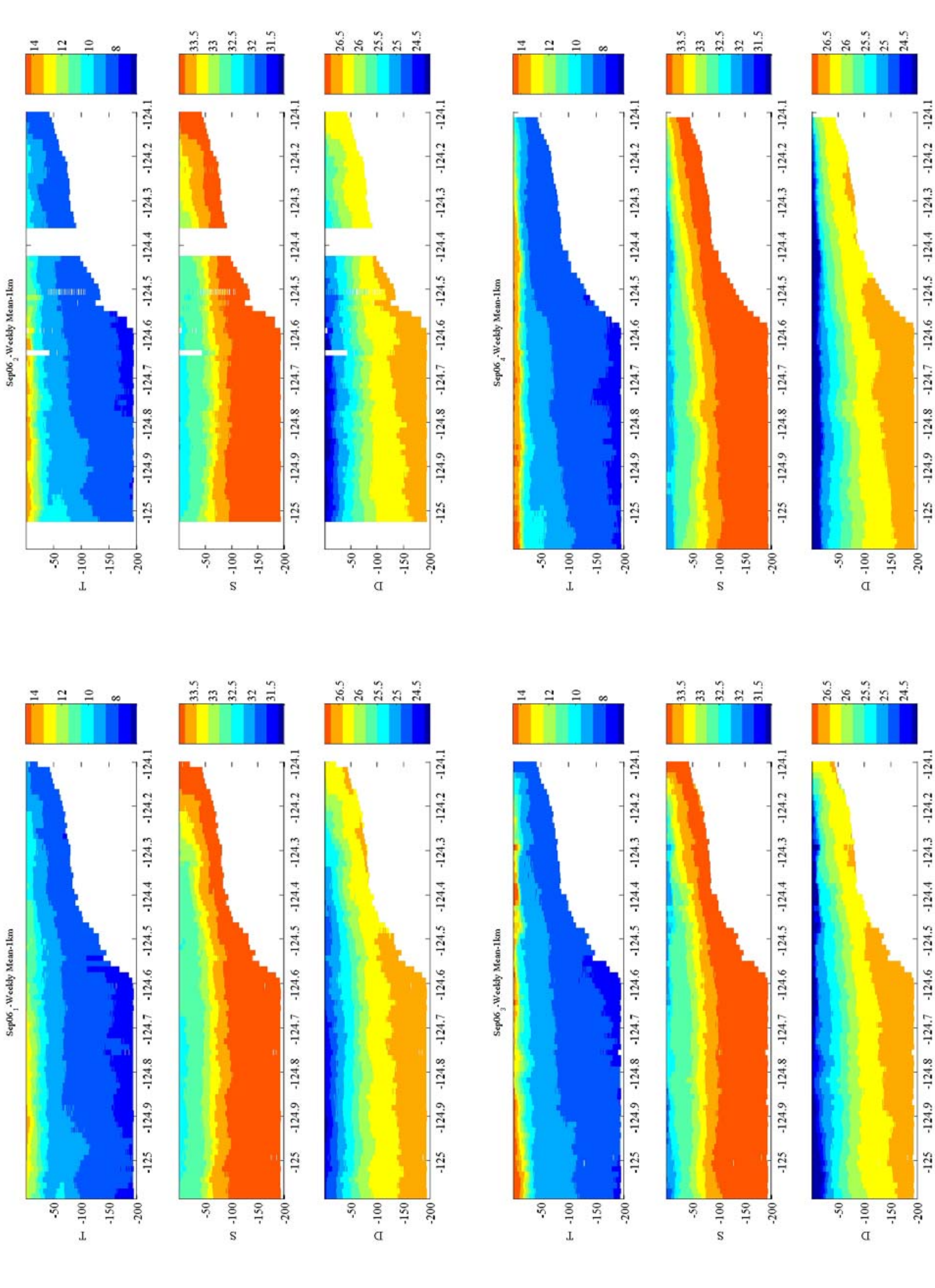
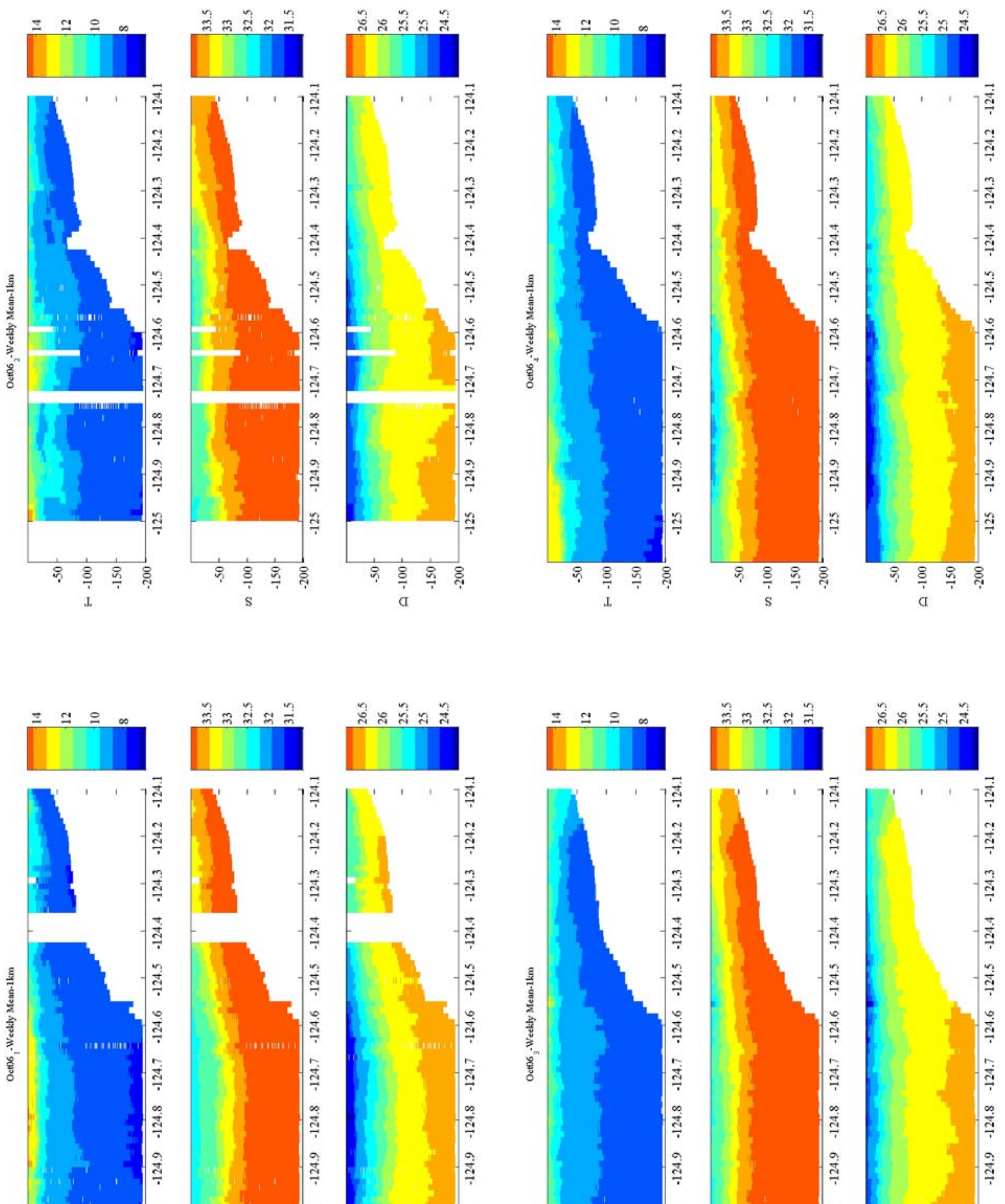
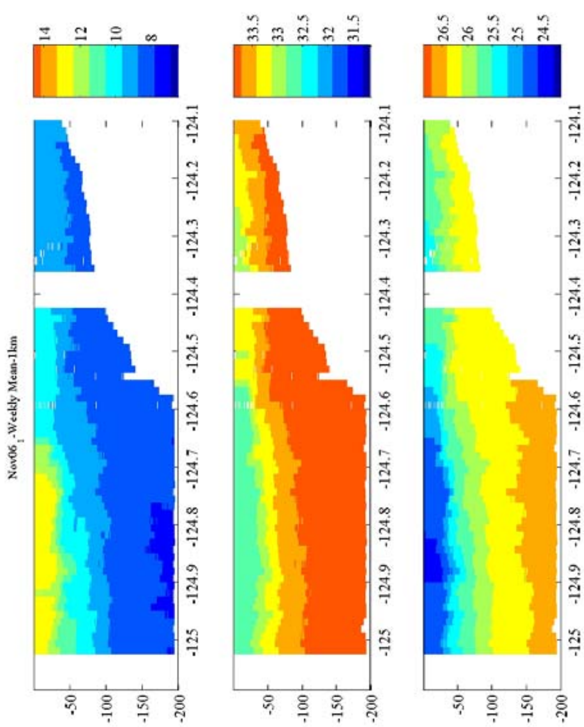

Aug06_1 -Weekly Mean-1km
Aug06_2 -Weekly Mean-1km
Aug06_3 -Weekly Mean-1km
Aug06_4 -Weekly Mean-1km


Sep06_1 -Weekly Mean-1km
Sep06_2 -Weekly Mean-1km
Sep06_3 -Weekly Mean-1km
Sep06_4 -Weekly Mean-1km
T
S
D



Oct06_1 -Weekly Mean-1km
Oct06_2 -Weekly Mean-1km
Oct06_3 -Weekly Mean-1km
Oct06_4 -Weekly Mean-1km



Nov06_1-Weekly Mean-1km
T
S
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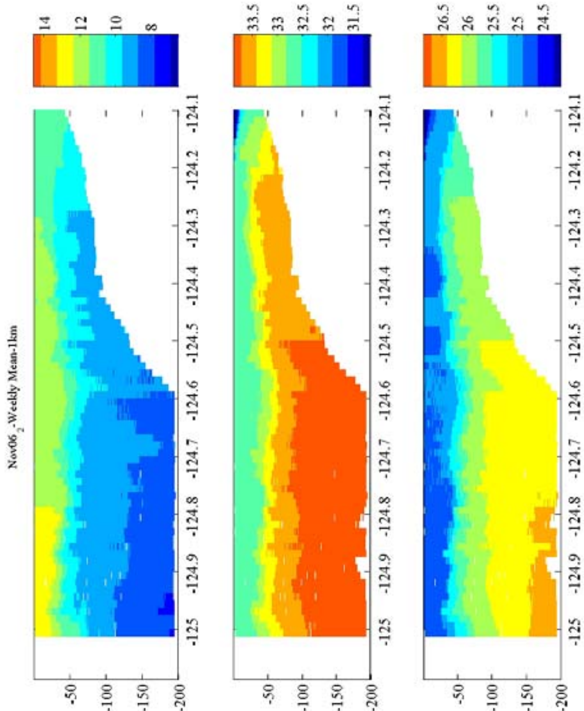
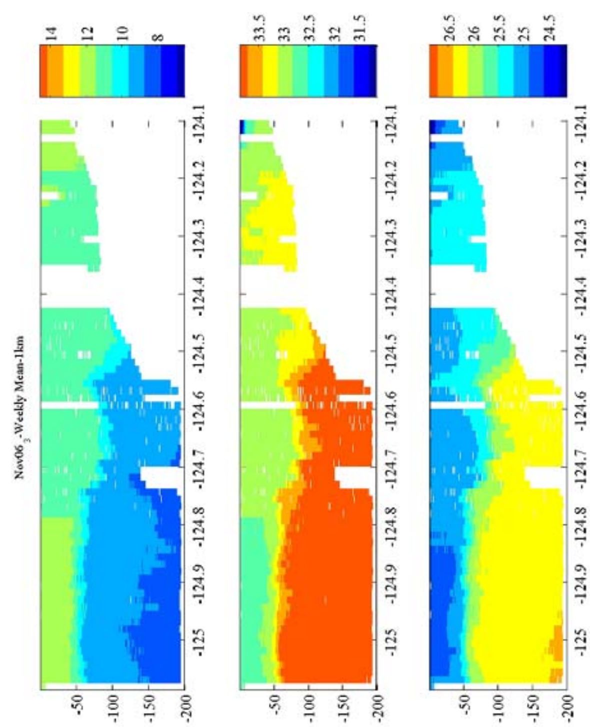


Nov06_2-Weekly Mean-1km
T
S
D



Nov06_3-Weekly Mean-1km
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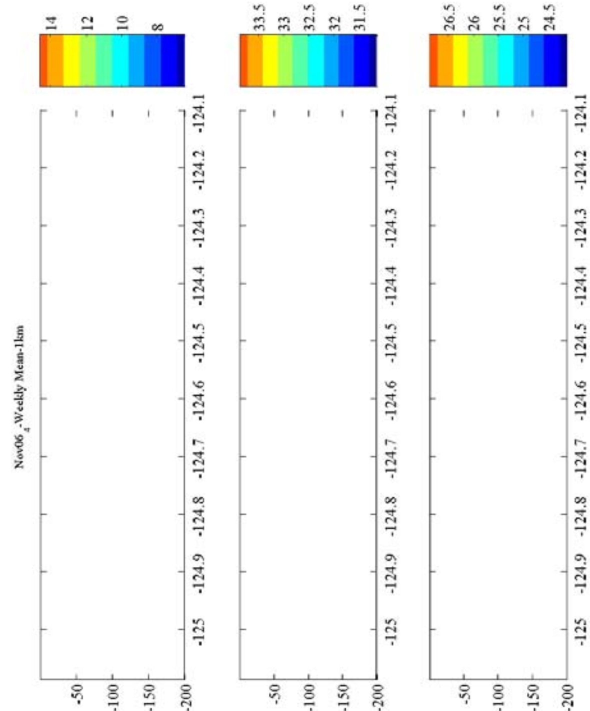
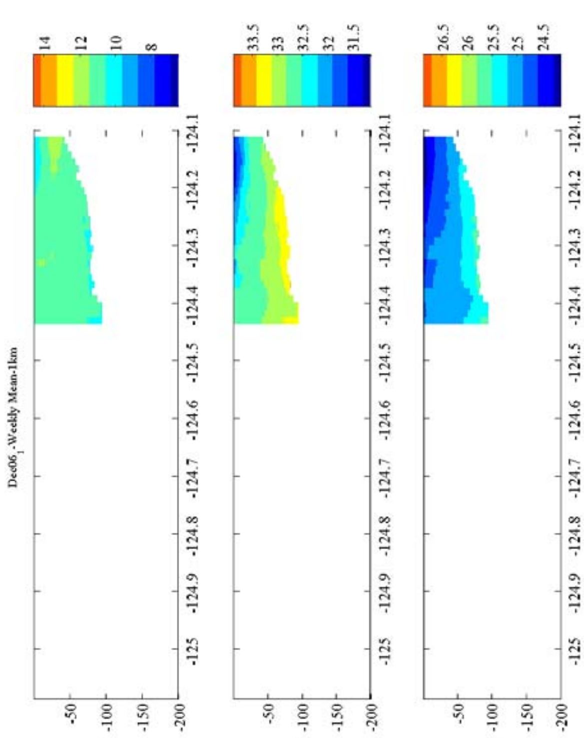
S
D



Nov06_4-Weekly Mean-1km
T
S
D



Dec06_1-Weekly Mean-1km
T
S
D
-50
-100
-150
-200
-125
-124.9
-124.8
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-124.6
-124.5
-124.4
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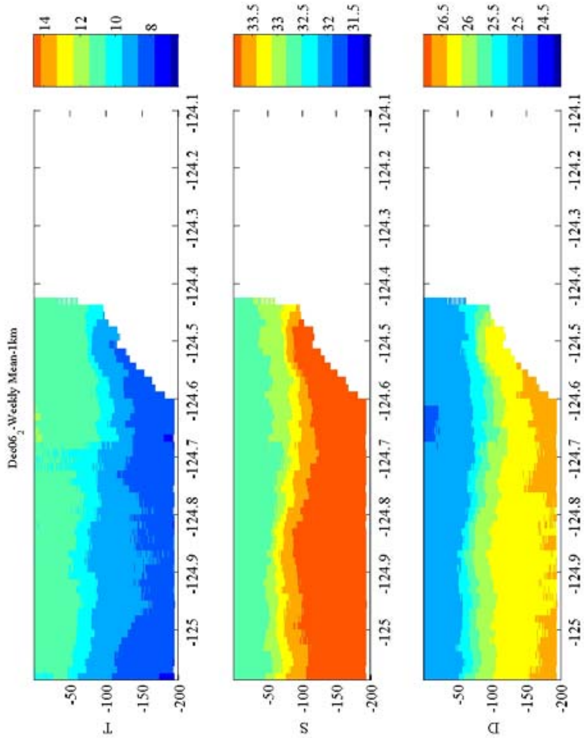

Dec06_2-Weekly Mean-1km
T
S
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-100
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-200
-125
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-124.6
-124.5
-124.4
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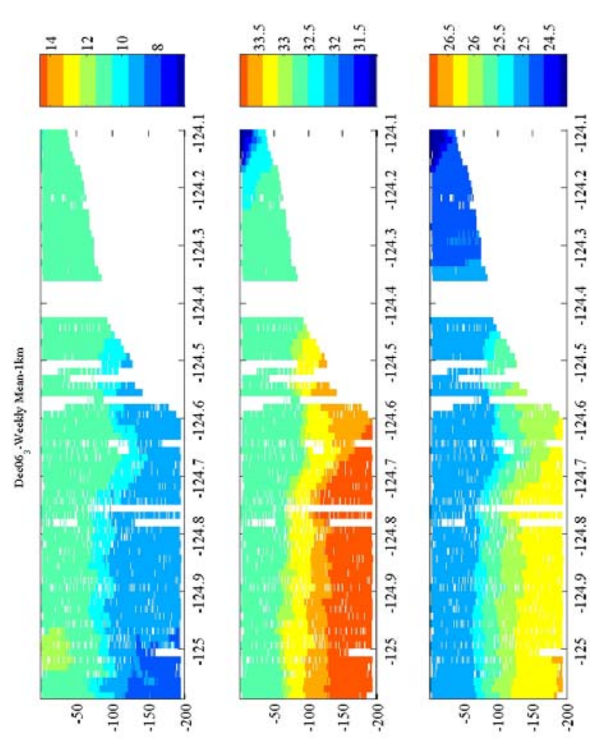

Dec06_3-Weekly Mean-1km
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-100
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-200
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-124.4
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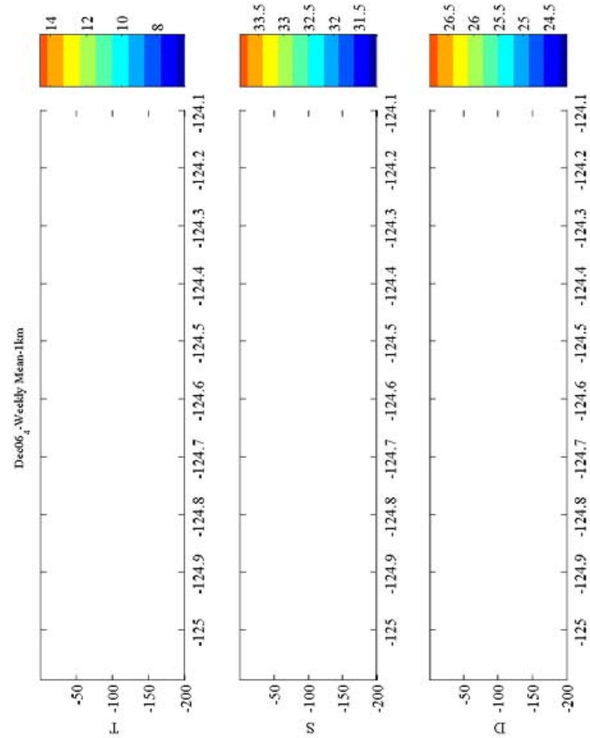

Dec06_4-Weekly Mean-1km
T
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-200
-125
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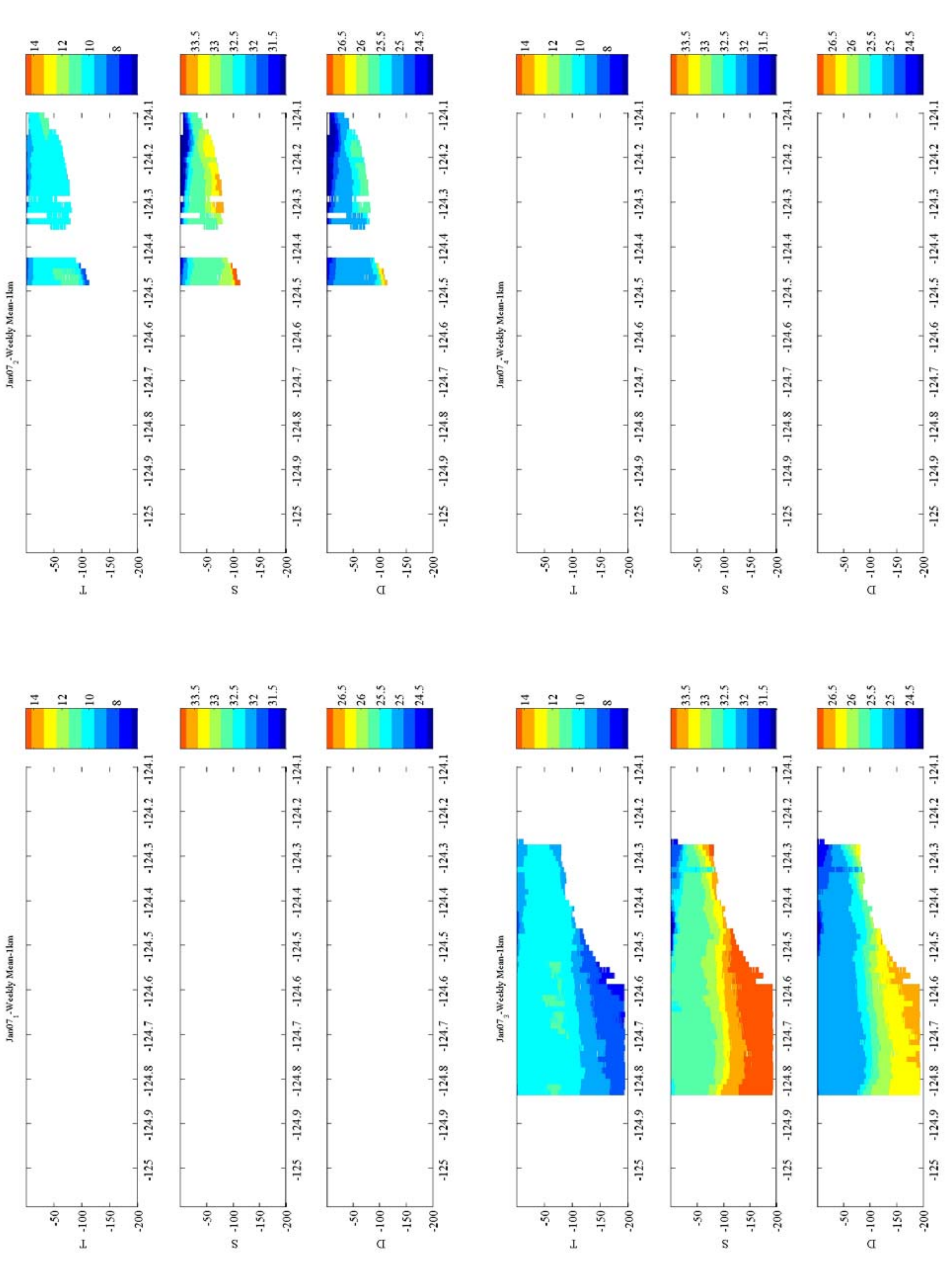

Jan07_1-Weekly Mean-1km
Jan07_2-Weekly Mean-1km
Jan07_3-Weekly Mean-1km
Jan07_4-Weekly Mean-1km
T
S
D
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
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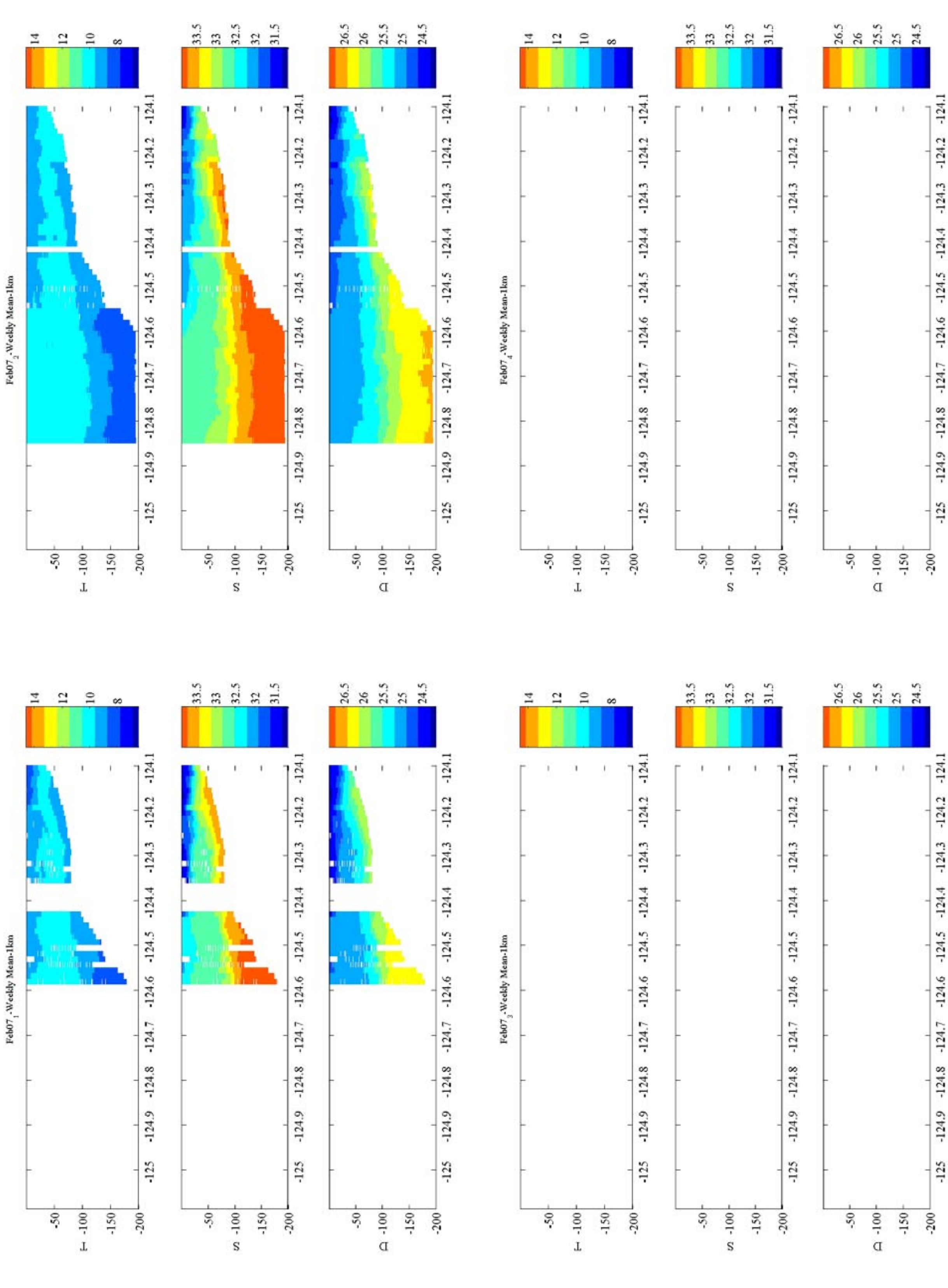
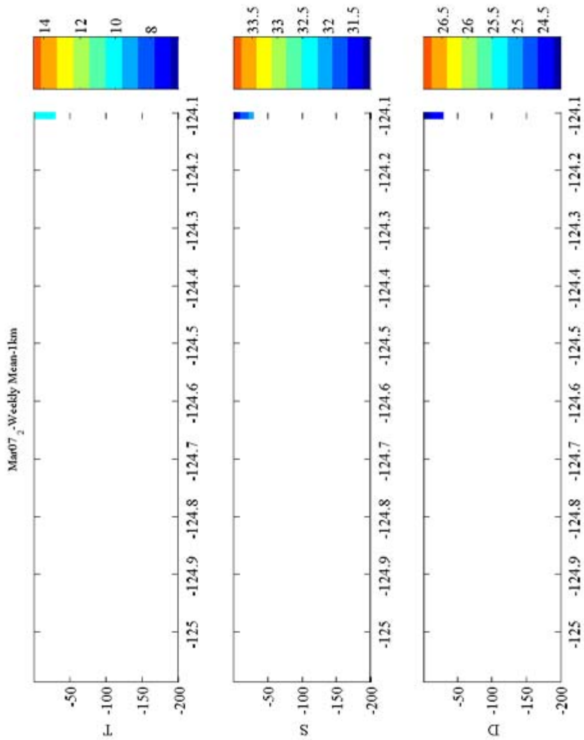
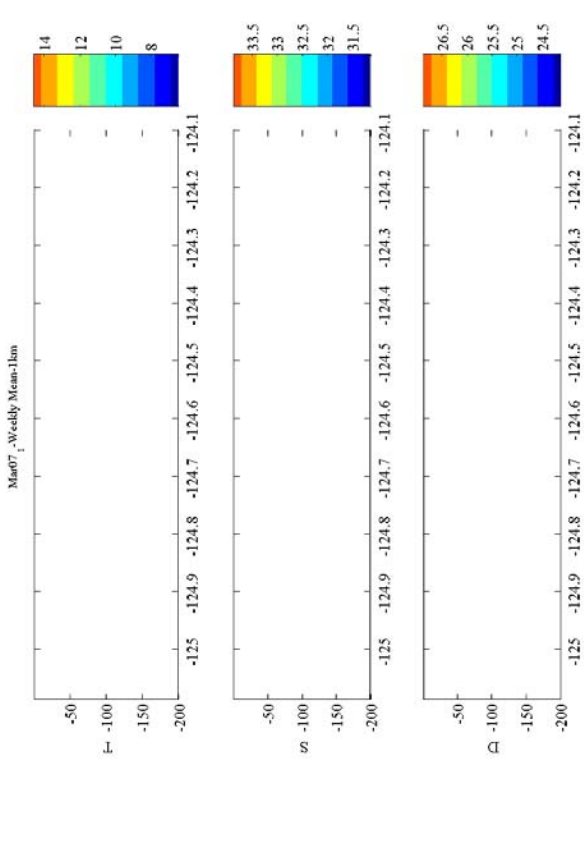
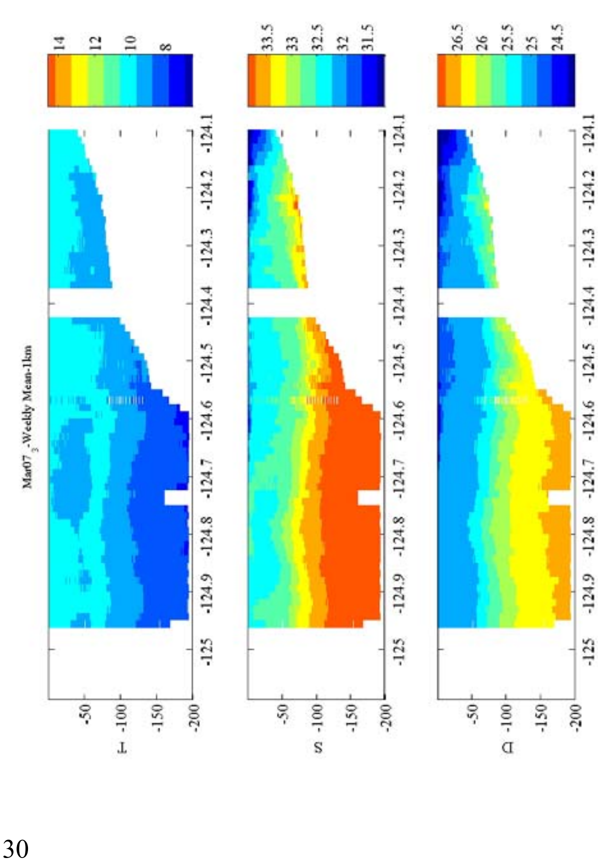

Feb07_1 -Weekly Mean-1km
Feb07_2 -Weekly Mean-1km
Feb07_3 -Weekly Mean-1km
Feb07_4 -Weekly Mean-1km
T
S
D

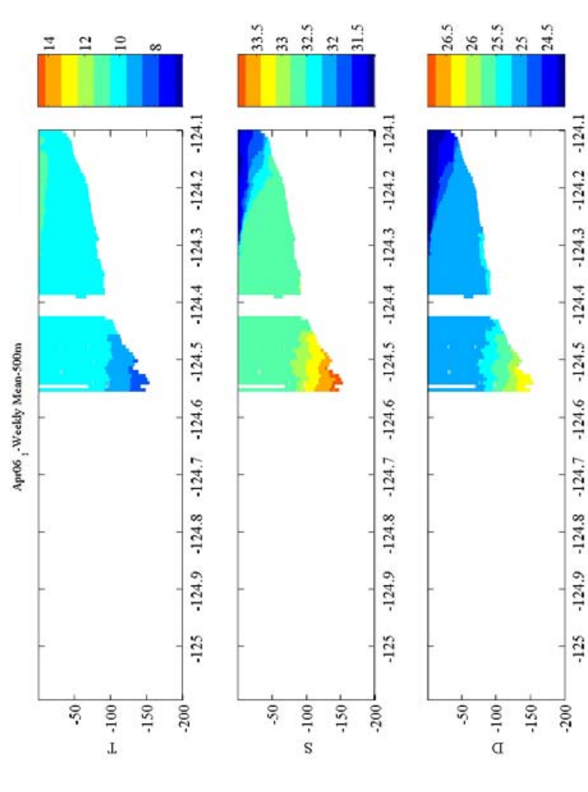

Mar07_2-Weekly Mean-1km

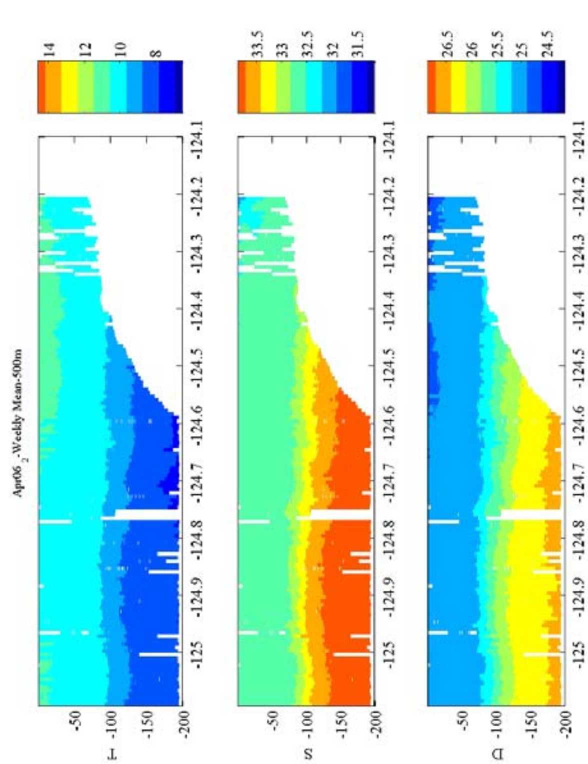

Mar07_1-Weekly Mean-1km

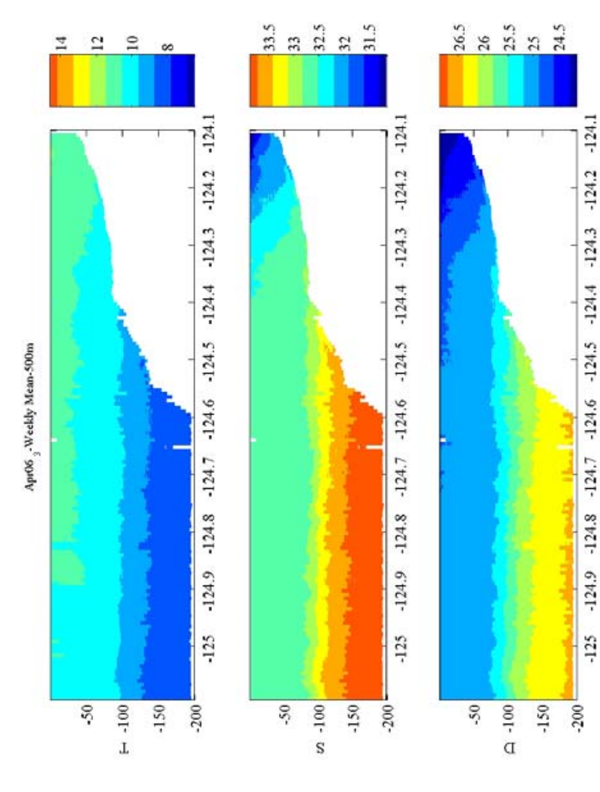

Mar07_3-Weekly Mean-1km

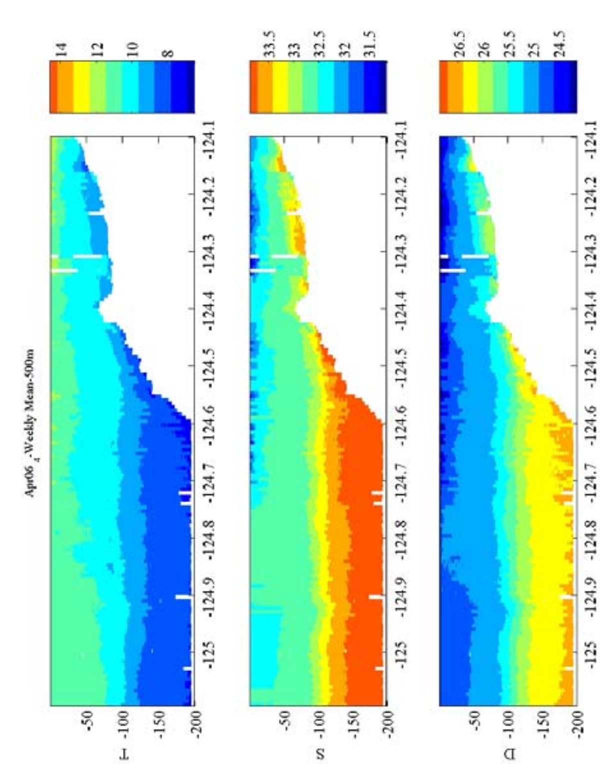
ISOBATH BINNING
500 m bin resolution
1 week timescale

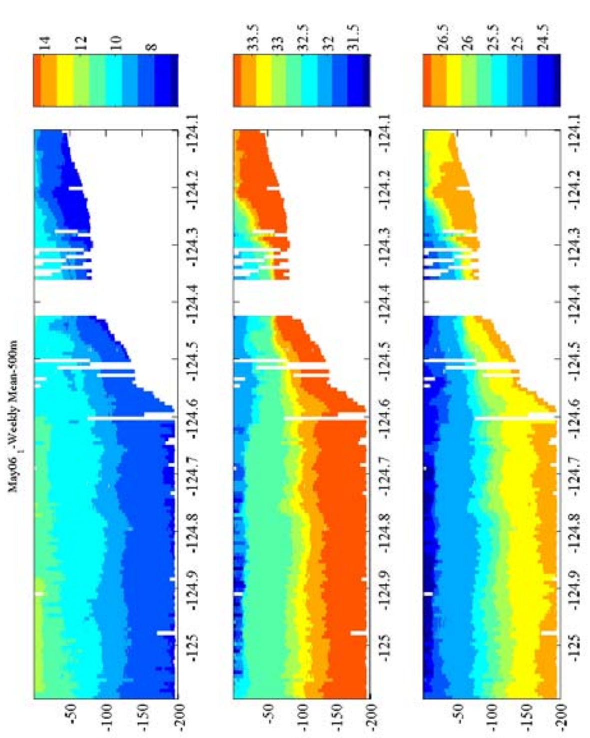
Apr. 2007 – Nov. 2007
Not Shown

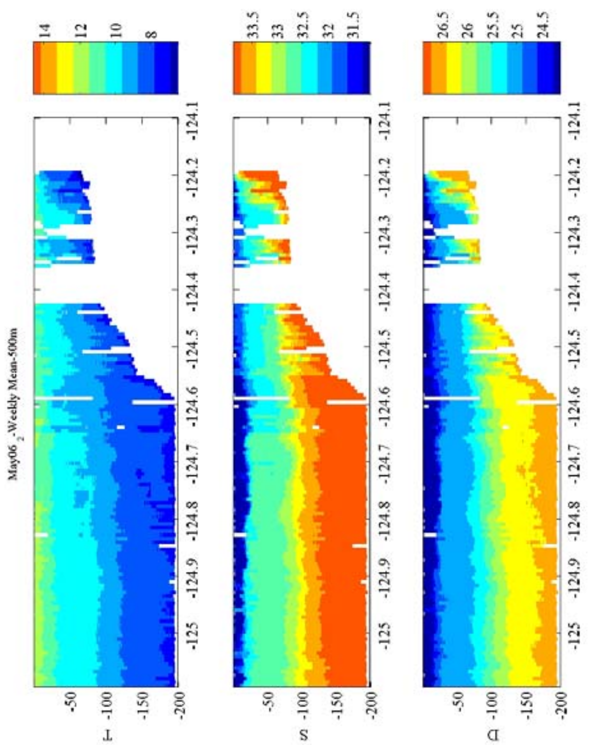

Apr06_1 -Weekly Mean-500m
T
S
D

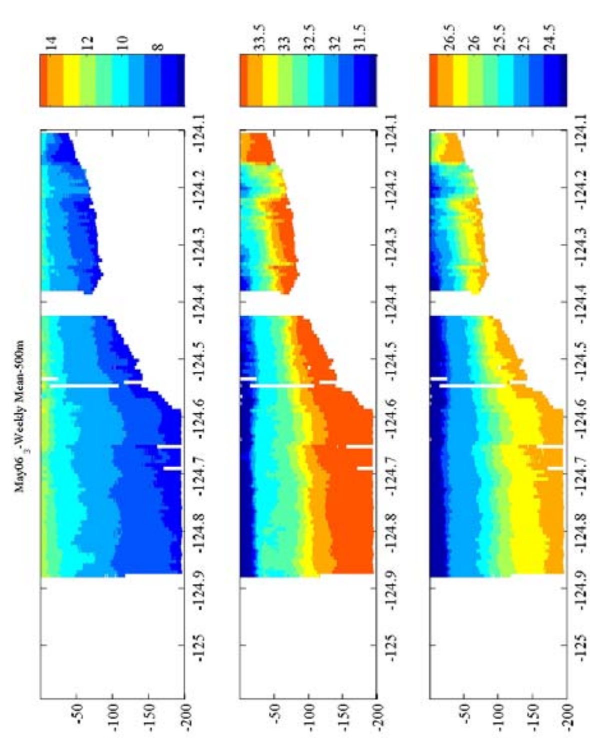

Apr06_2 -Weekly Mean-500m
T
S
D

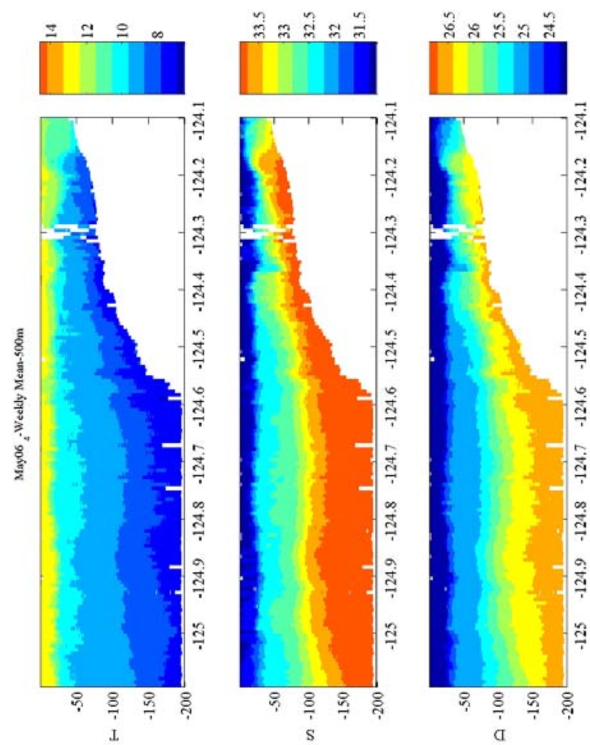

Apr06_3 -Weekly Mean-500m
T
S
D

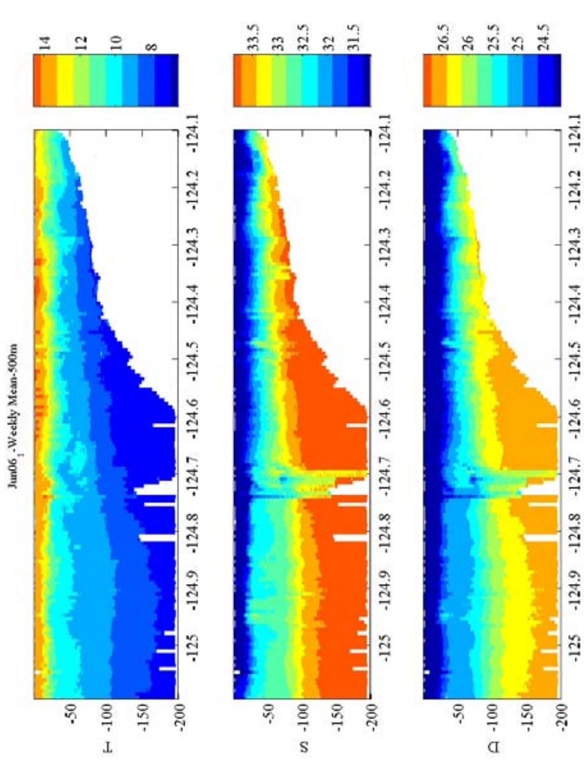

Apr06_4 -Weekly Mean-500m
T
S
D

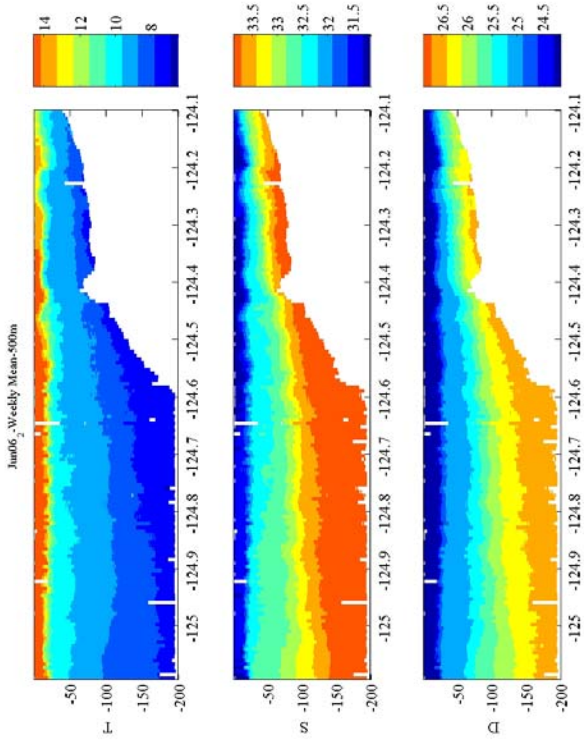

May06_1-Weekly Mean-500m
T
S
D

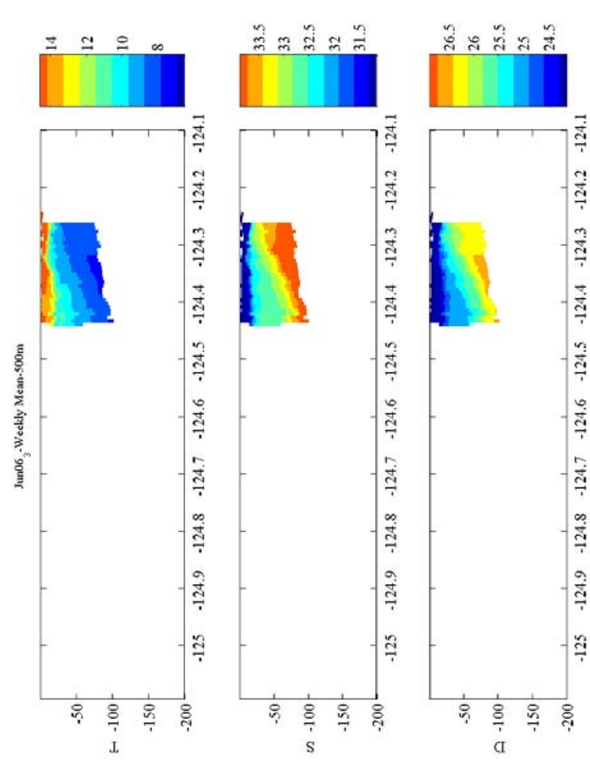

May06_2-Weekly Mean-500m
T
S
D

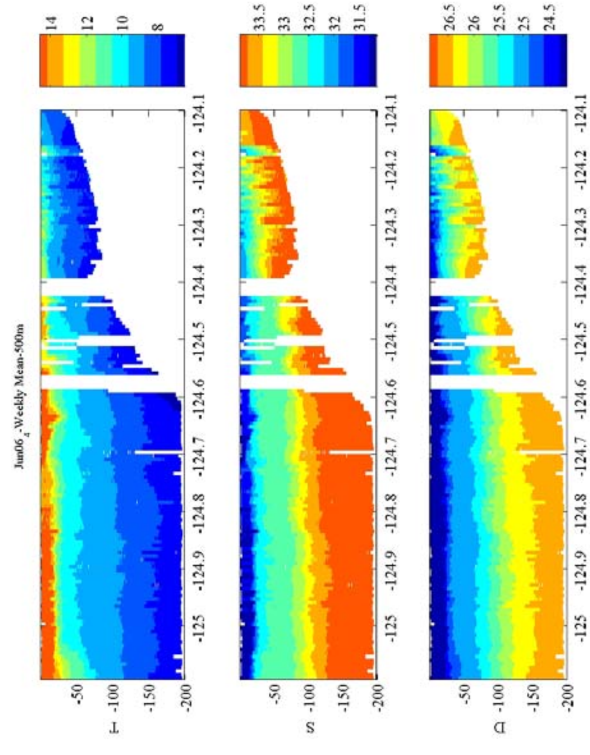

May06_3-Weekly Mean-500m
T
S
D

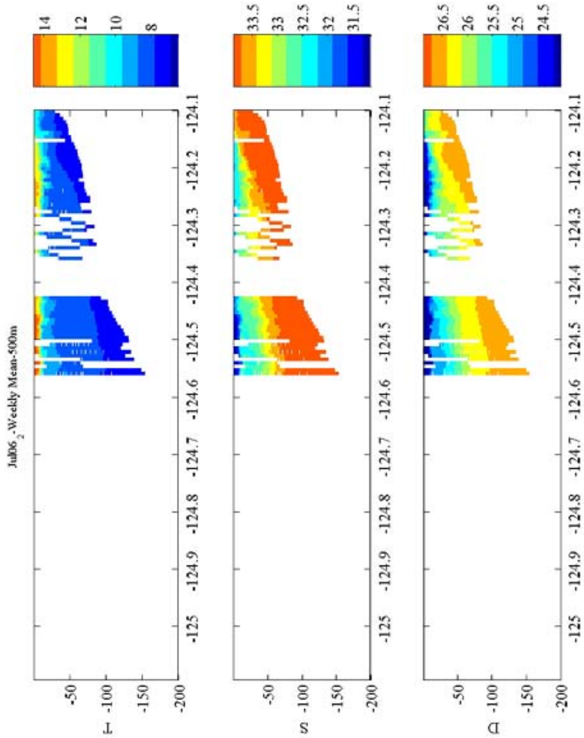

May06_4-Weekly Mean-500m
T
S
D

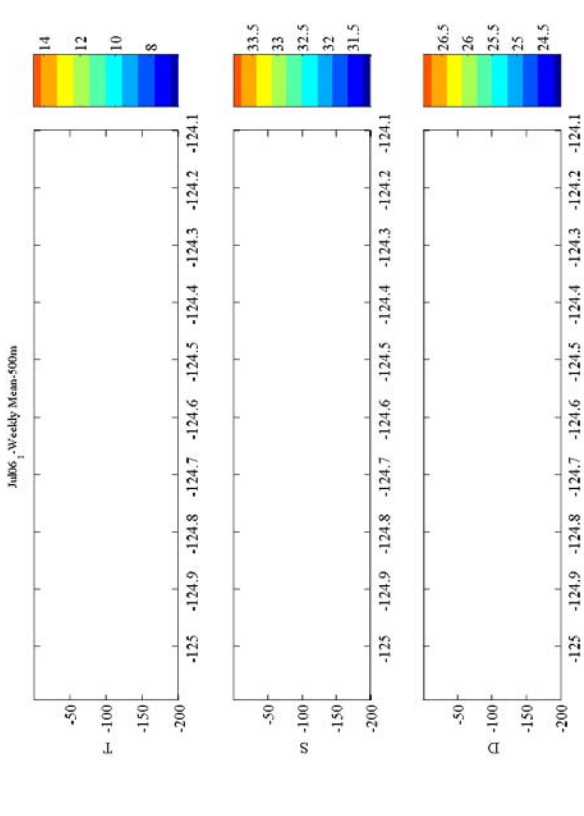

Jun06_1 -Weekly Mean-500m

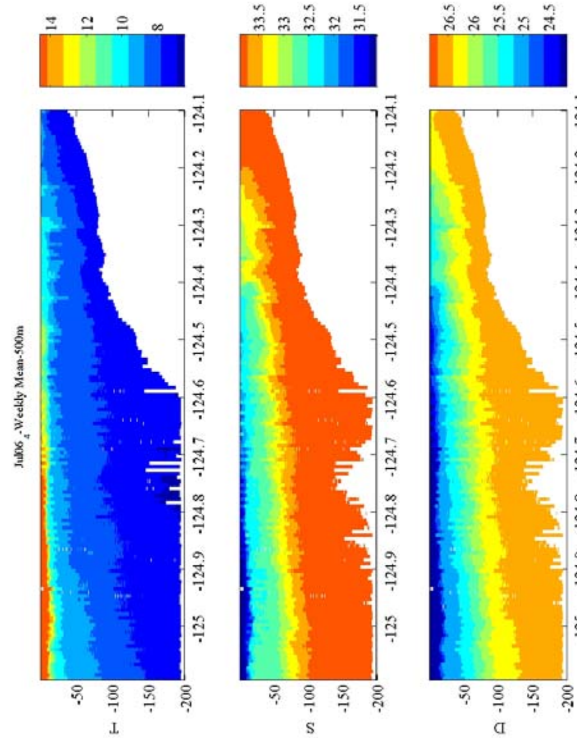

Jun06_2 -Weekly Mean-500m

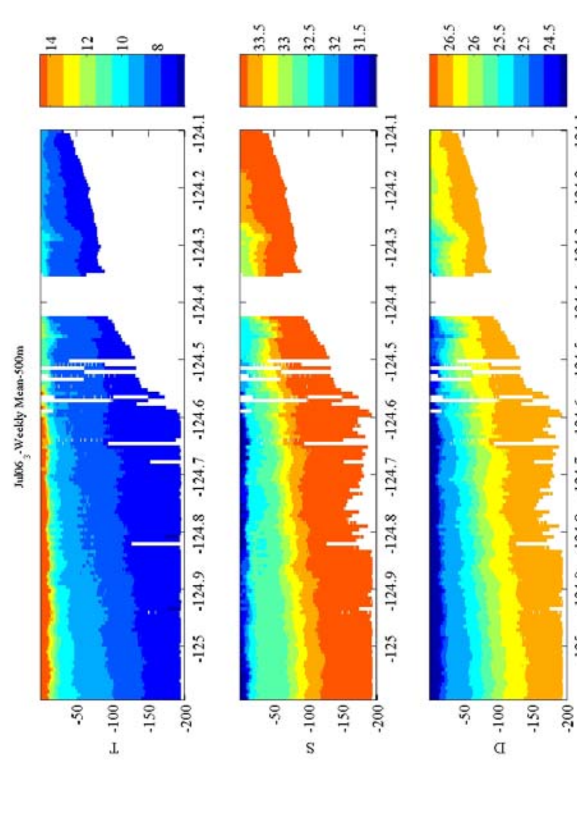

Jun06_3 -Weekly Mean-500m

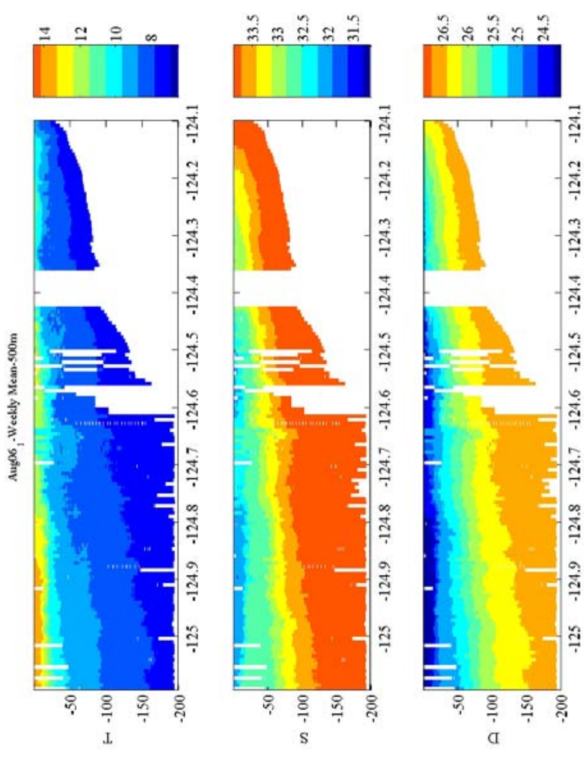

Jun06_4 -Weekly Mean-500m

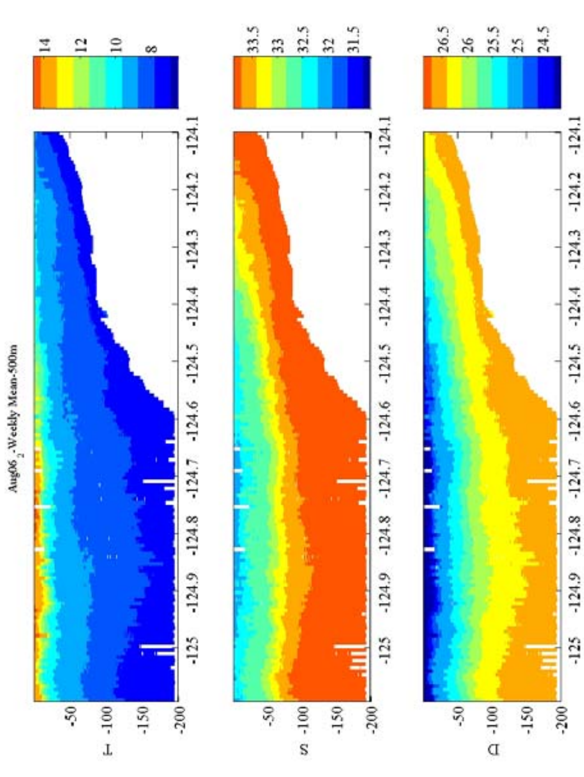

Jul06$_2$ -Weekly Mean-500m
T
S
D


Jul06$_1$ -Weekly Mean-500m
T
S
D


Jul06$_4$ -Weekly Mean-500m
T
S
D


Jul06$_3$ -Weekly Mean-500m
T
S
D


Aug06_1 -Weekly Mean-500m
T
S
D
-125 -124.9 -124.8 -124.7 -124.6 -124.5 -124.4 -124.3 -124.2 -124.1
-50 -100 -150 -200
14 12 10 8
33.5 33 32.5 32 31.5
26.5 26 25.5 25 24.5


Aug06_2 -Weekly Mean-500m
T
S
D
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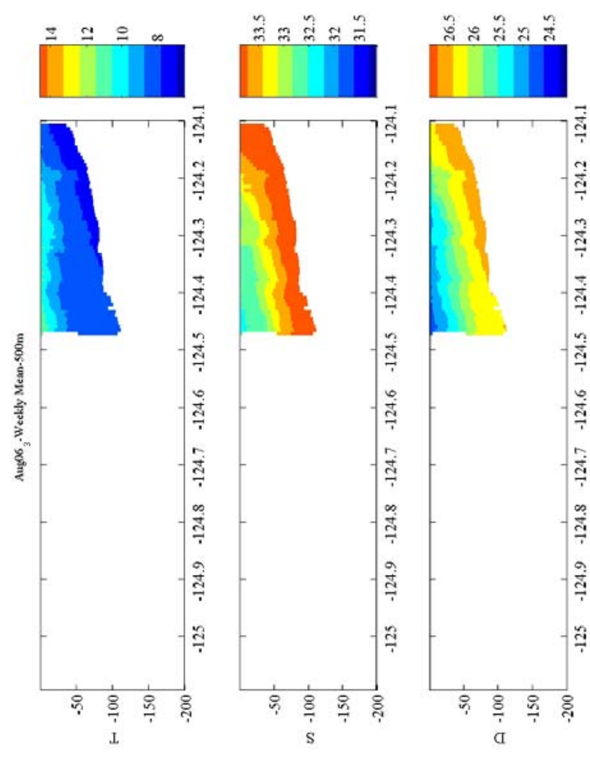
-50 -100 -150 -200
14 12 10 8
33.5 33 32.5 32 31.5
26.5 26 25.5 25 24.5


Aug06_3 -Weekly Mean-500m
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S
D
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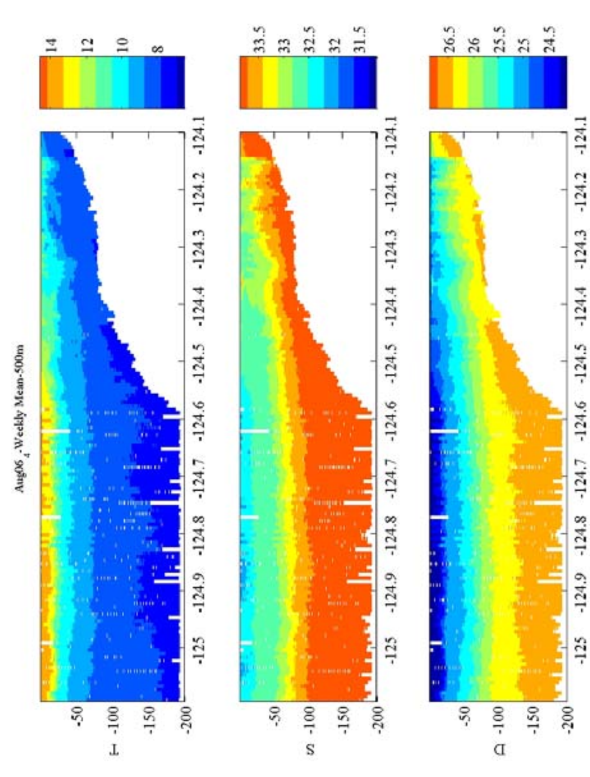
26.5 26 25.5 25 24.5


Aug06_4 -Weekly Mean-500m
T
S
D
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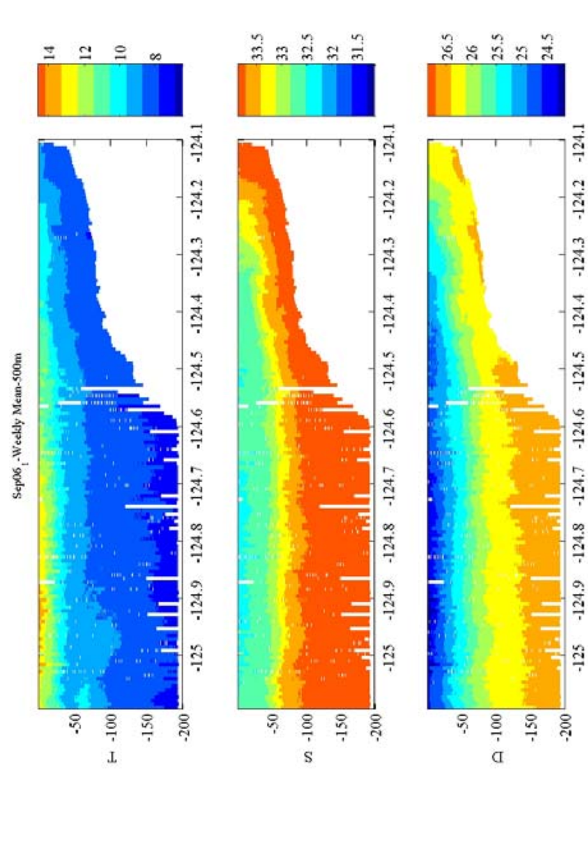
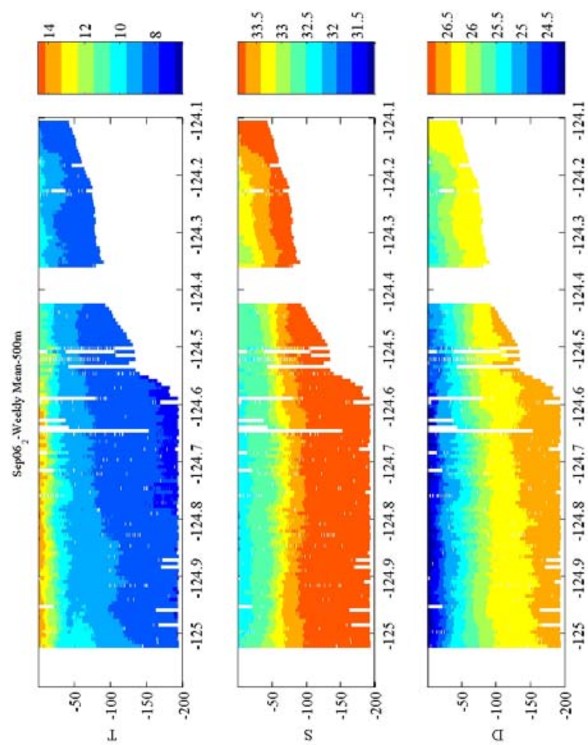
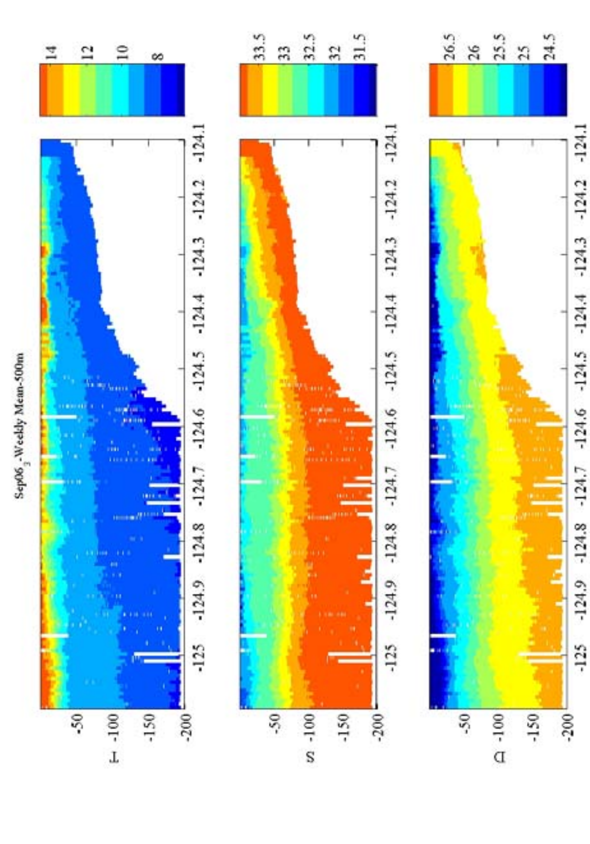
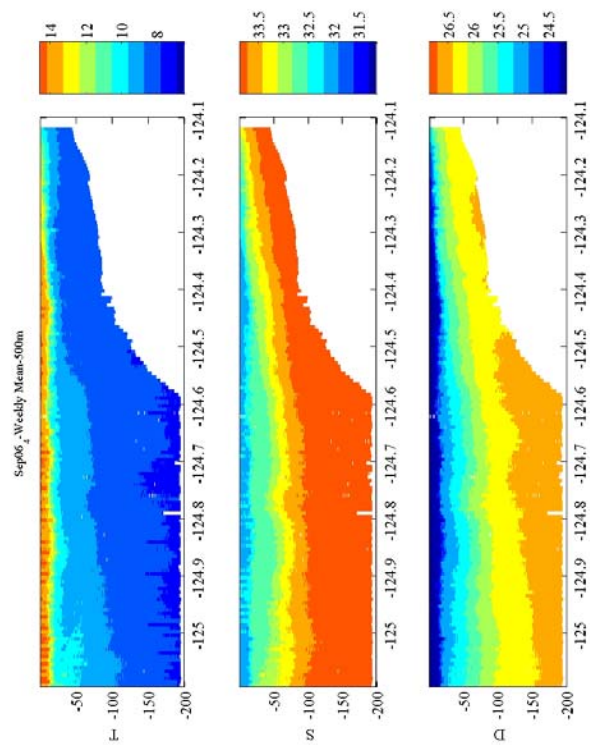
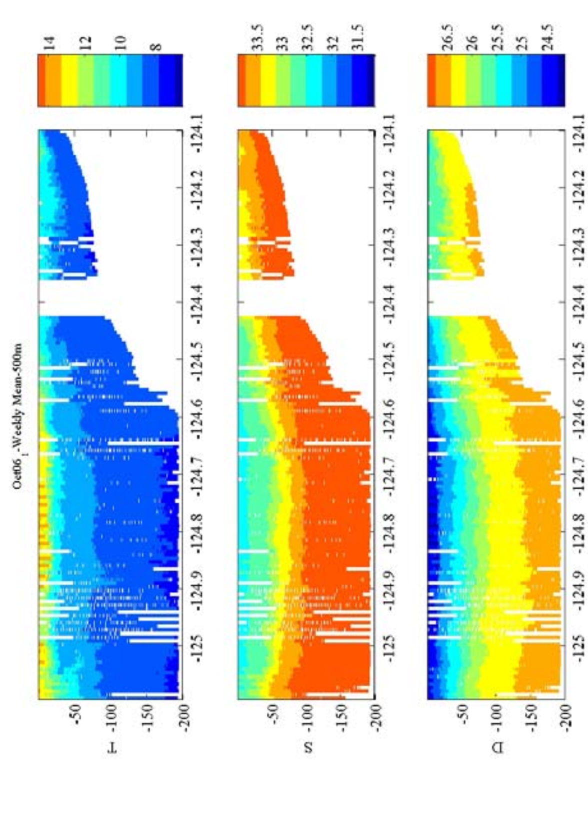
26.5 26 25.5 25 24.5

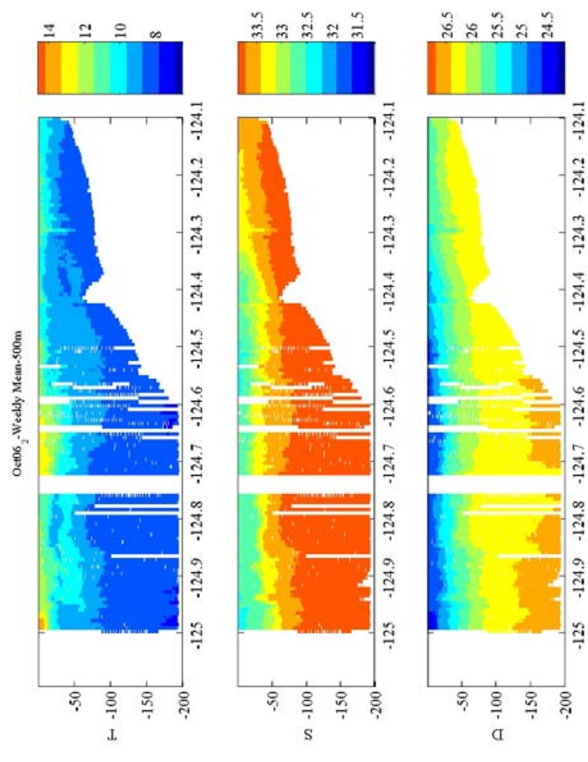

Sep06_1 -Weekly Mean-500m

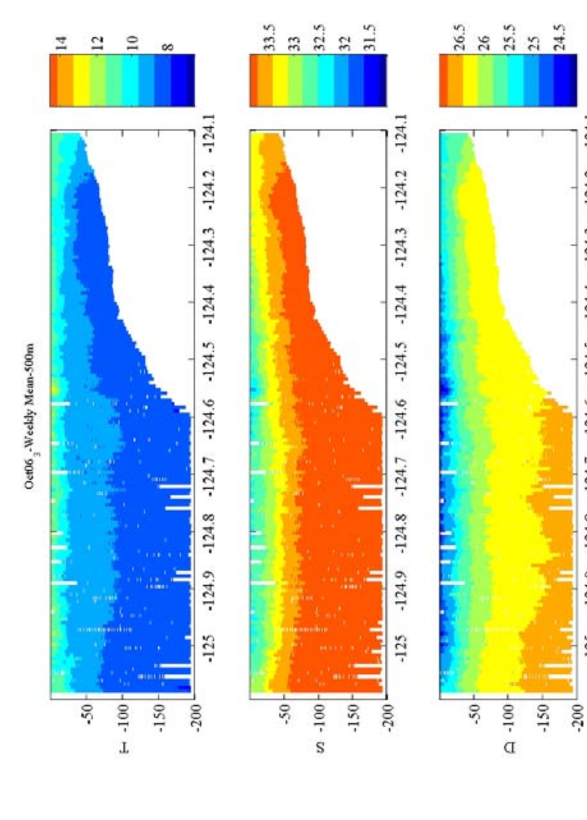

Sep06_2 -Weekly Mean-500m

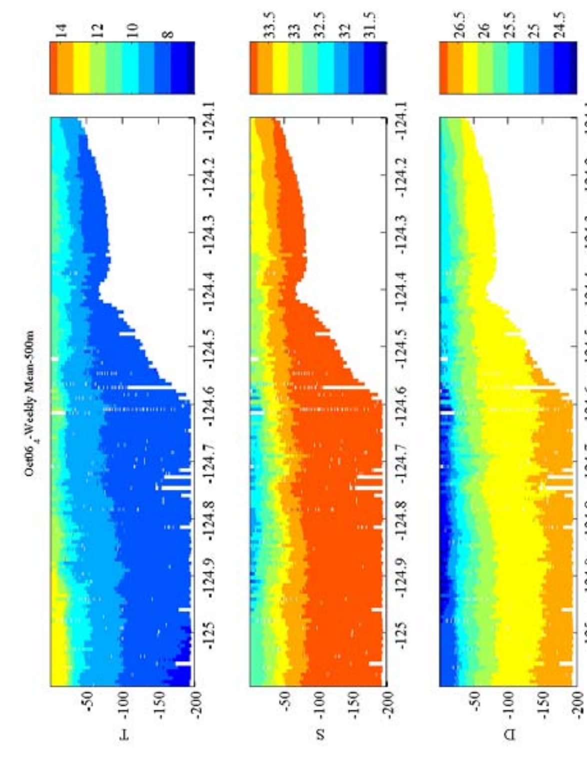

Sep06_3 -Weekly Mean-500m

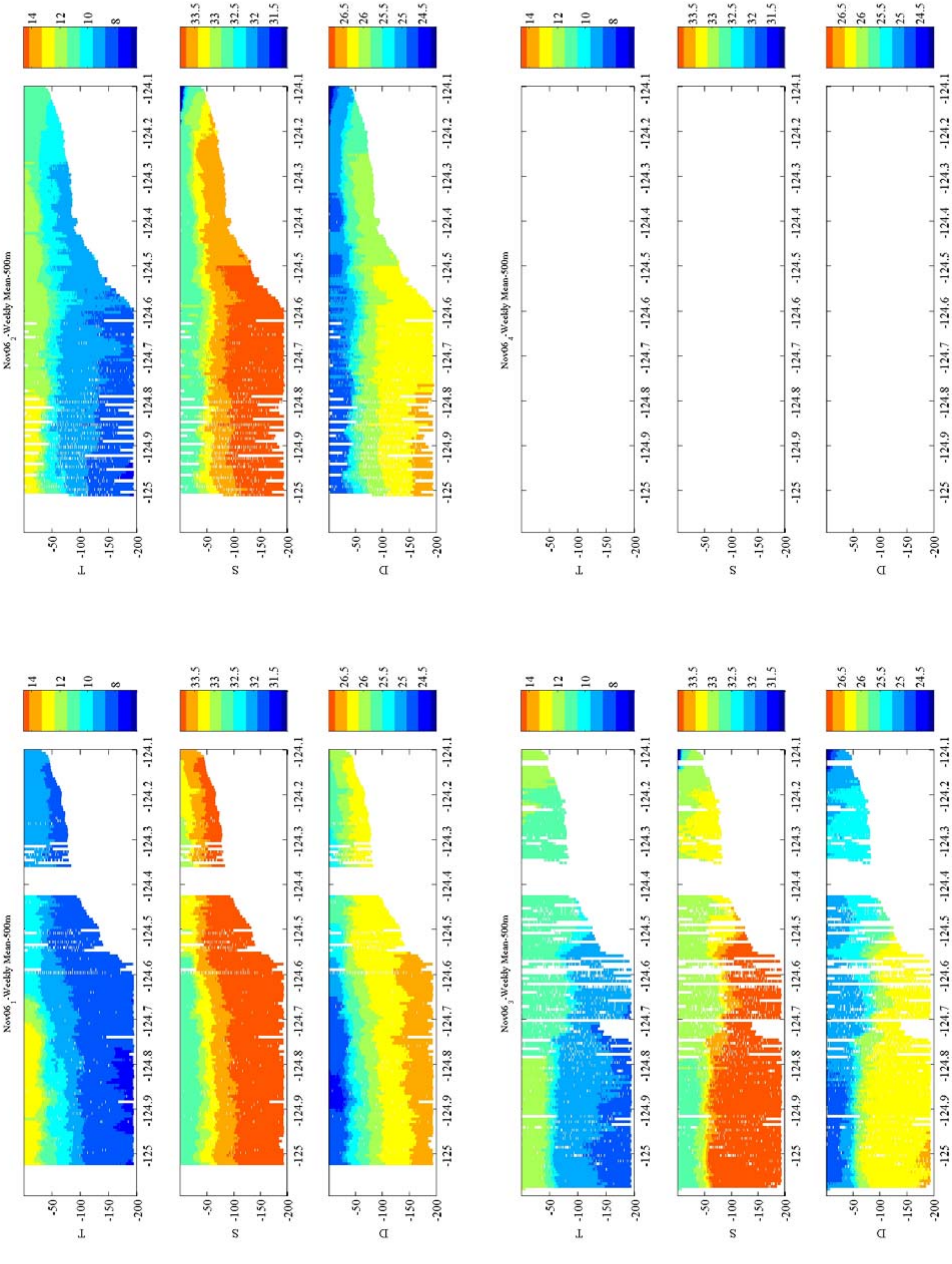

Sep06_4 -Weekly Mean-500m


Oct06_1-Weekly Mean-500m


Oct06_2-Weekly Mean-500m


Oct06_3-Weekly Mean-500m


Oct06_4-Weekly Mean-500m


Nov06_1 -Weekly Mean-500m
Nov06_2 -Weekly Mean-500m
Nov06_3 -Weekly Mean-500m
Nov06_4 -Weekly Mean-500m
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-50
-100
-150
-200
-125
-124.9
-124.8
-124.7
-124.6
-124.5
-124.4
-124.3
-124.2
-124.1
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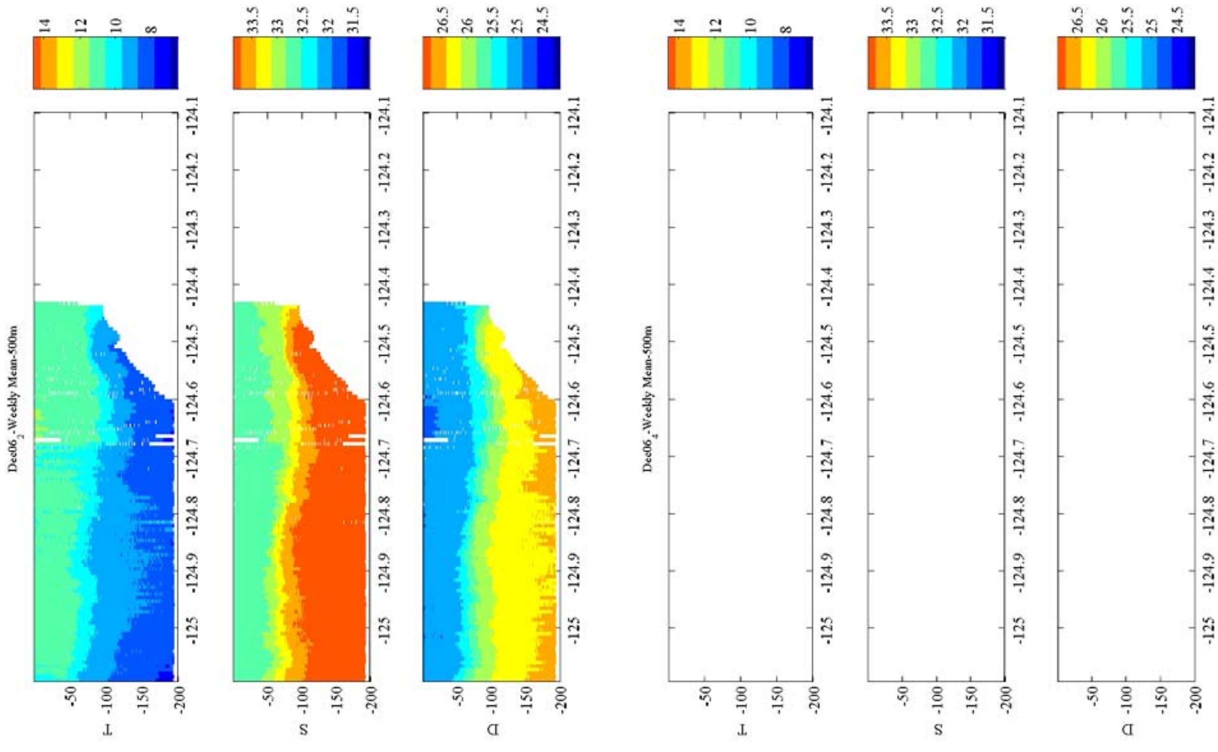
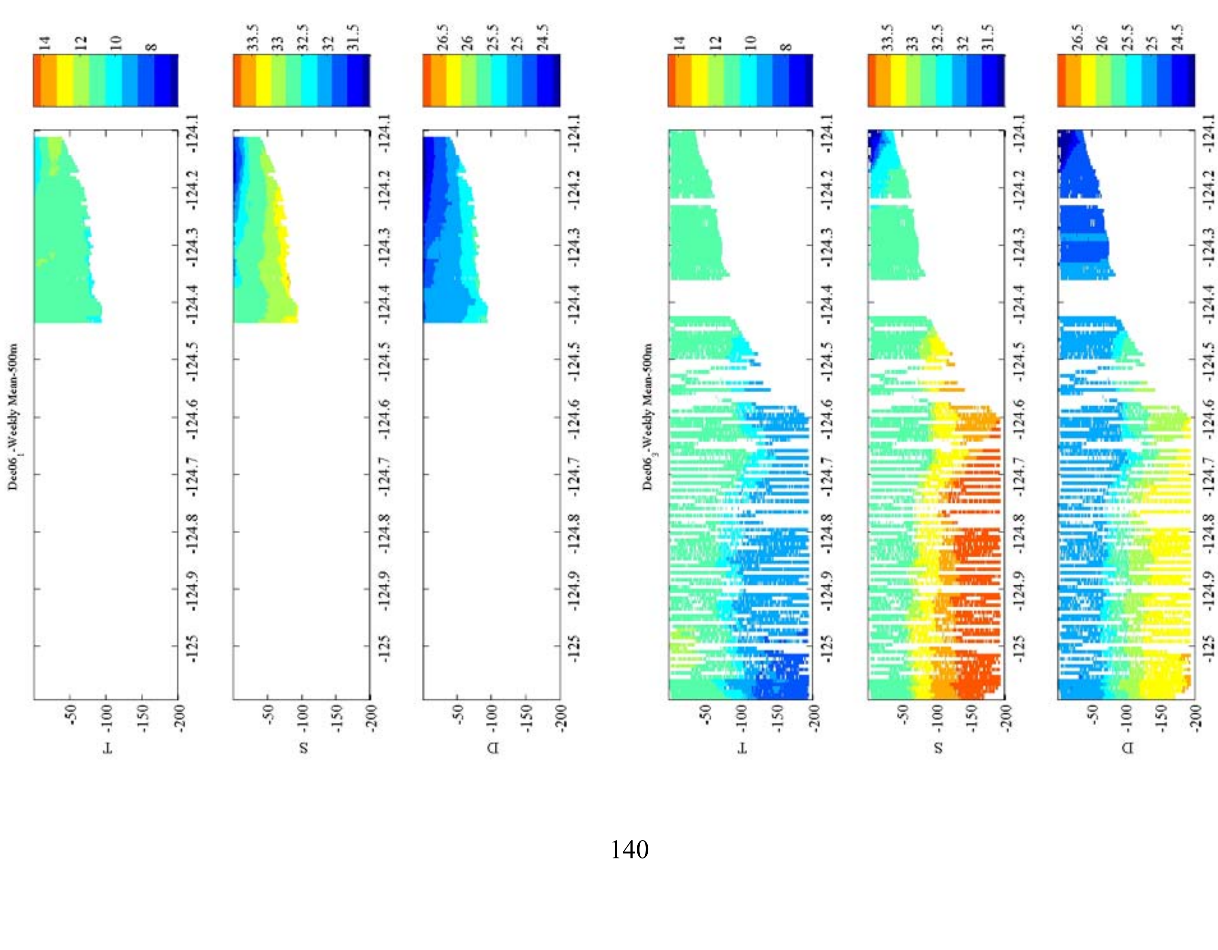
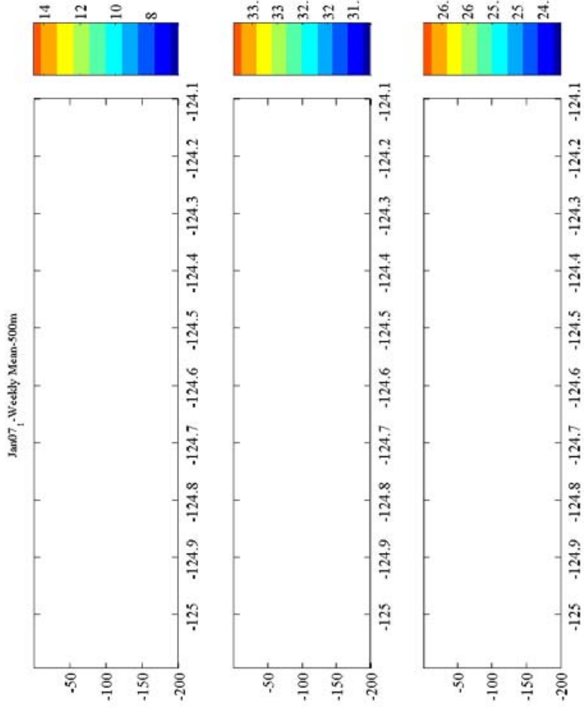
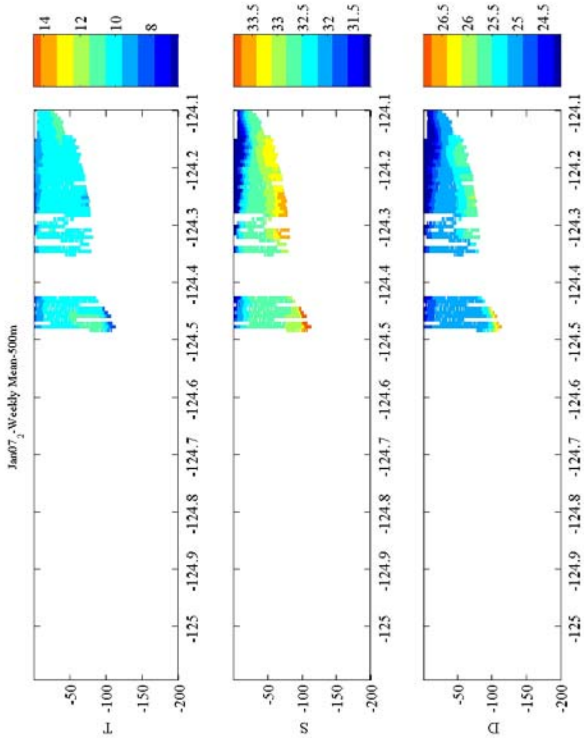
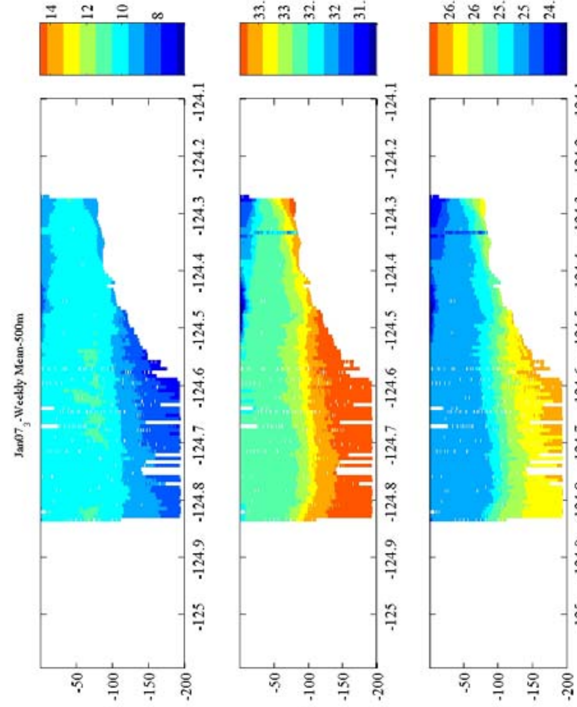
25.5
25
24.5

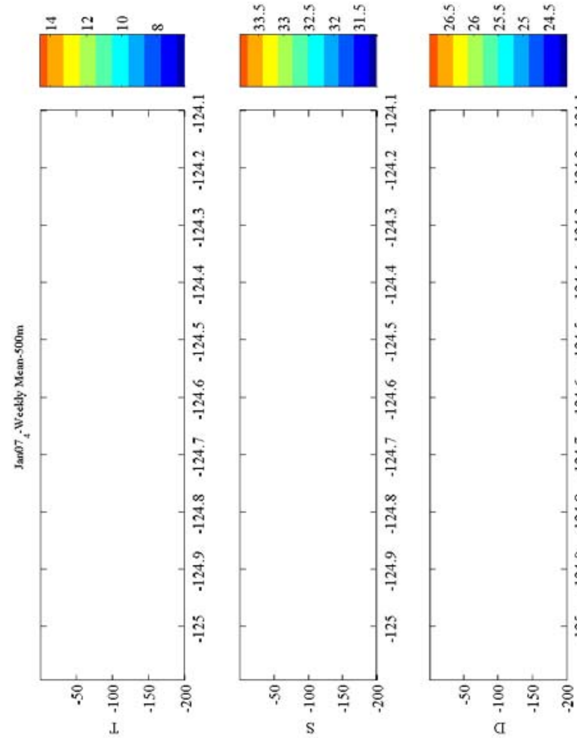

Dec06_2 -Weekly Mean-500m
Dec06_4 -Weekly Mean-500m

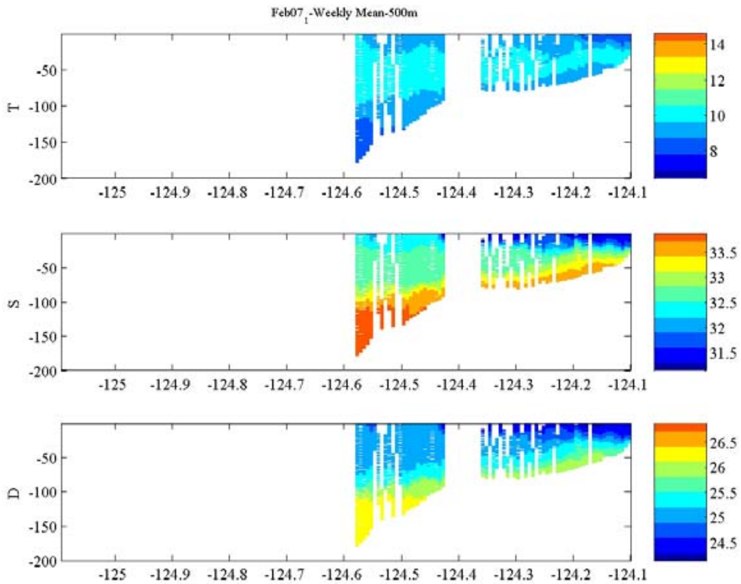

Dec06_1 -Weekly Mean-500m
Dec06_3 -Weekly Mean-500m


Jan07_1 -Weekly Mean-500m


Jan07_2 -Weekly Mean-500m


Jan07_3 -Weekly Mean-500m


Jan07_4 -Weekly Mean-500m


Feb07$_1$-Weekly Mean-500m
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-50
-100
-150
-200
-125
-124.9
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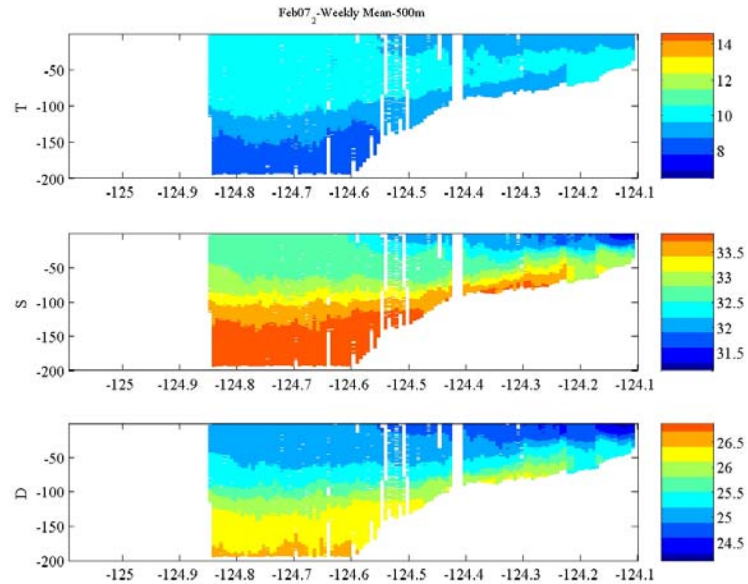
Feb07$_2$-Weekly Mean-500m
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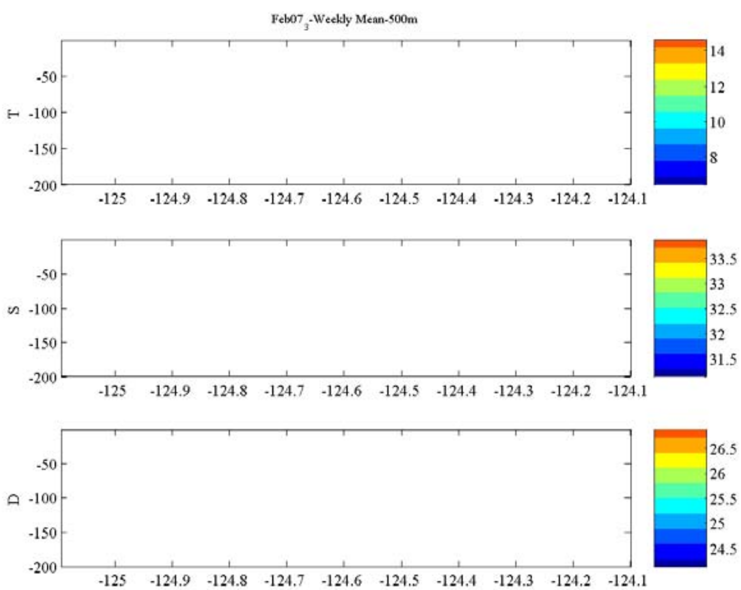
Feb07$_3$-Weekly Mean-500m
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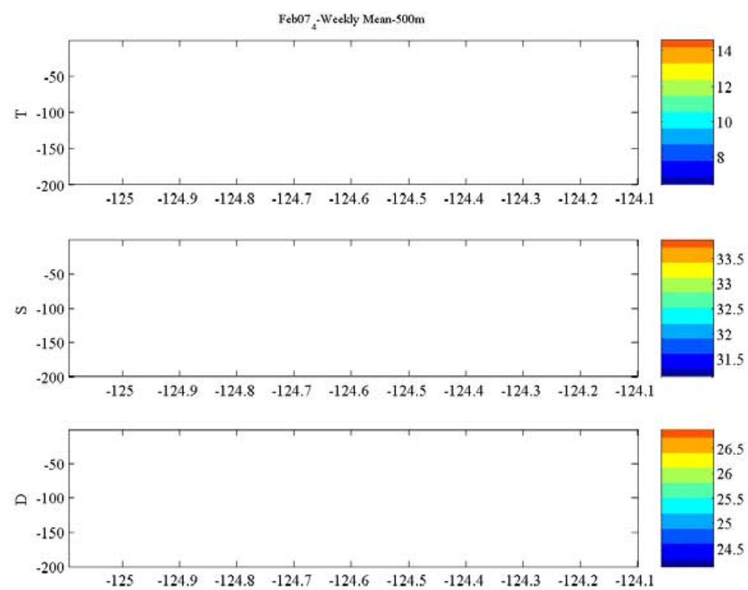
Feb07$_4$-Weekly Mean-500m
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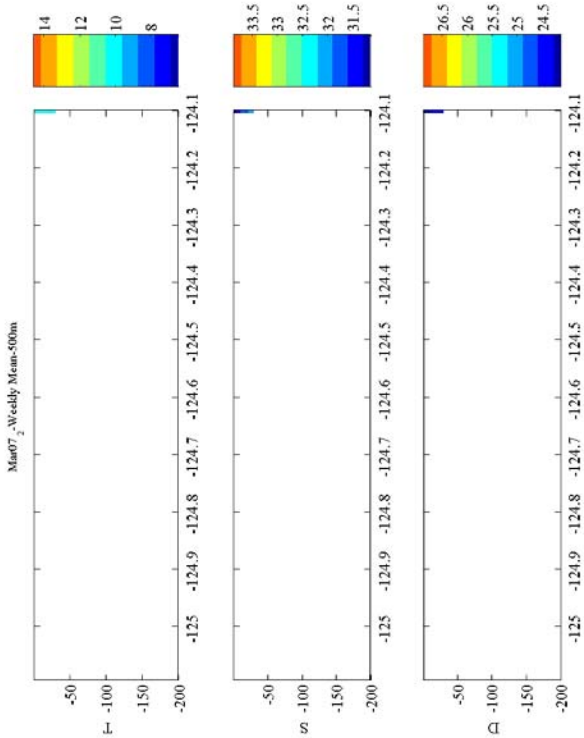
Mar07_2-Weekly Mean-500m
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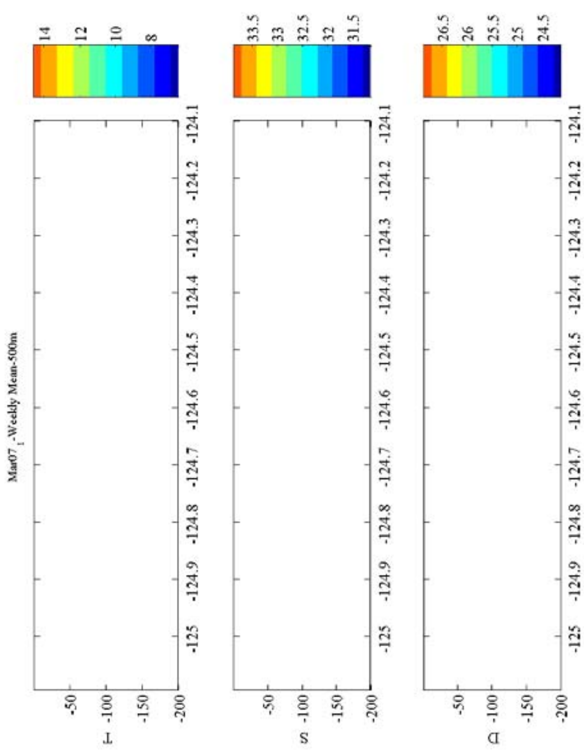
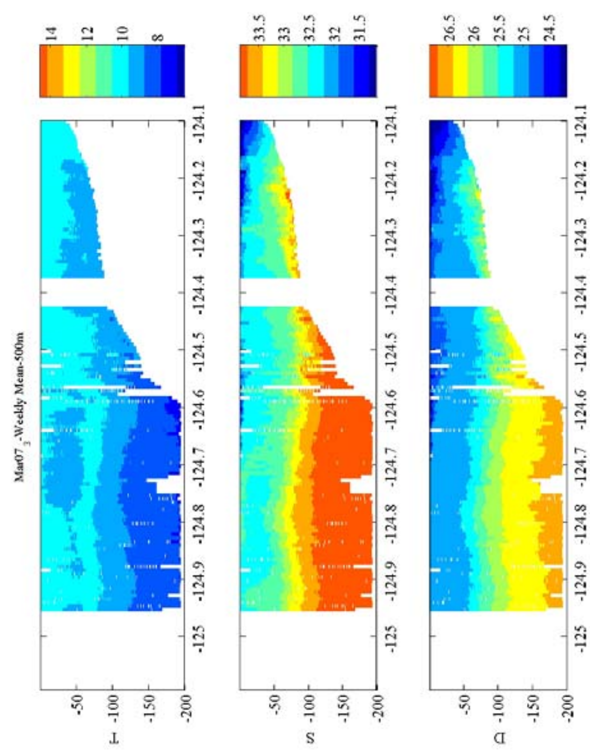
S
D


Mar07_1-Weekly Mean-500m
T
S
D


Mar07_3-Weekly Mean-500m
T
S
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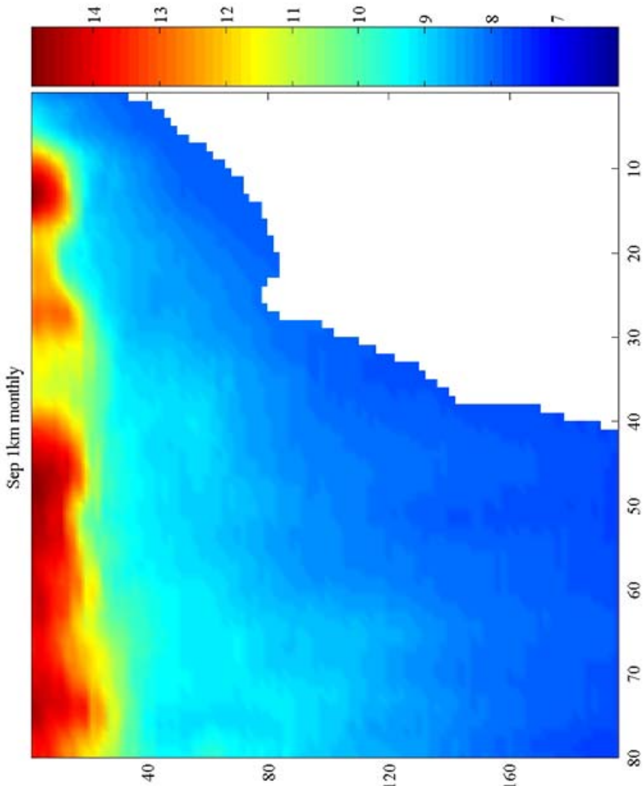
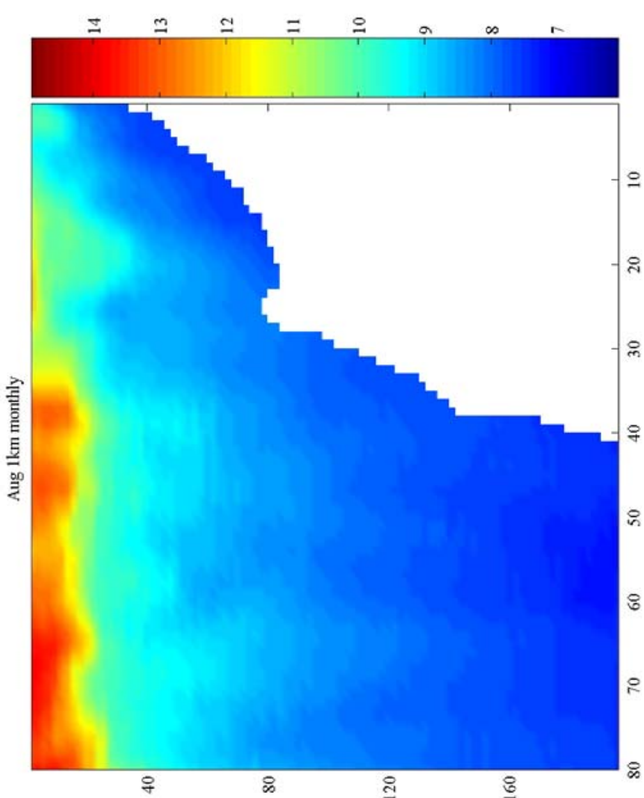
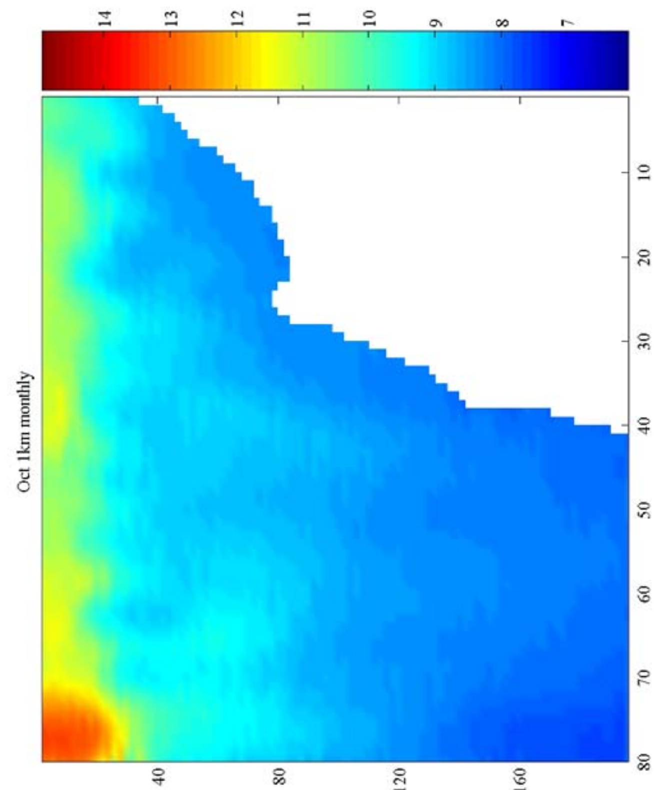
OBJECTIVE ANALYSIS
1 km resolution
1 month timescale

Apr. 2006 – Jul. 2006
Nov. 2006 – Nov 2007
Not Shown

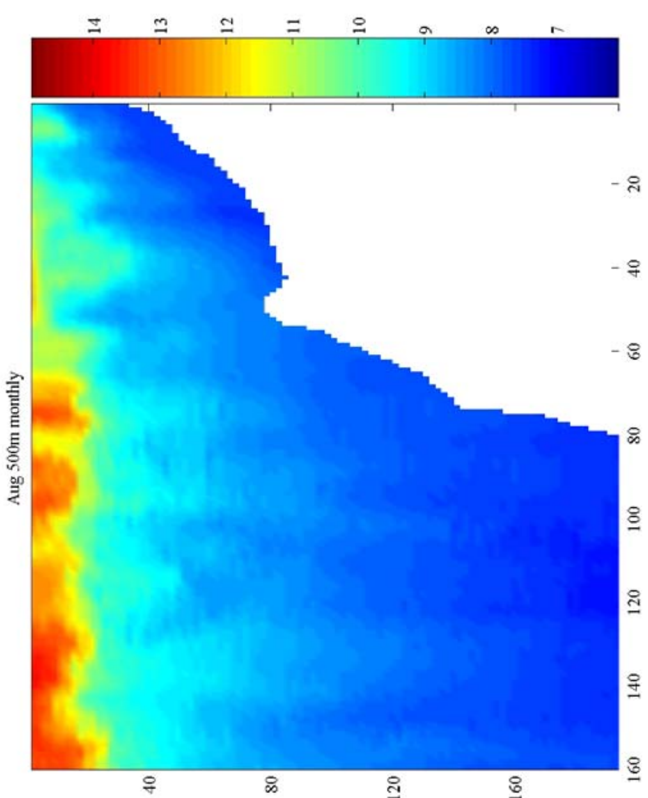

Sep 1km monthly


Aug 1km monthly


Oct 1km monthly

OBJECTIVE ANALYSIS
500 m resolution
1 month timescale

Apr. 2006 – Jul. 2006
Nov. 2006 – Nov 2007
Not Shown


Aug 500m monthly
14
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80
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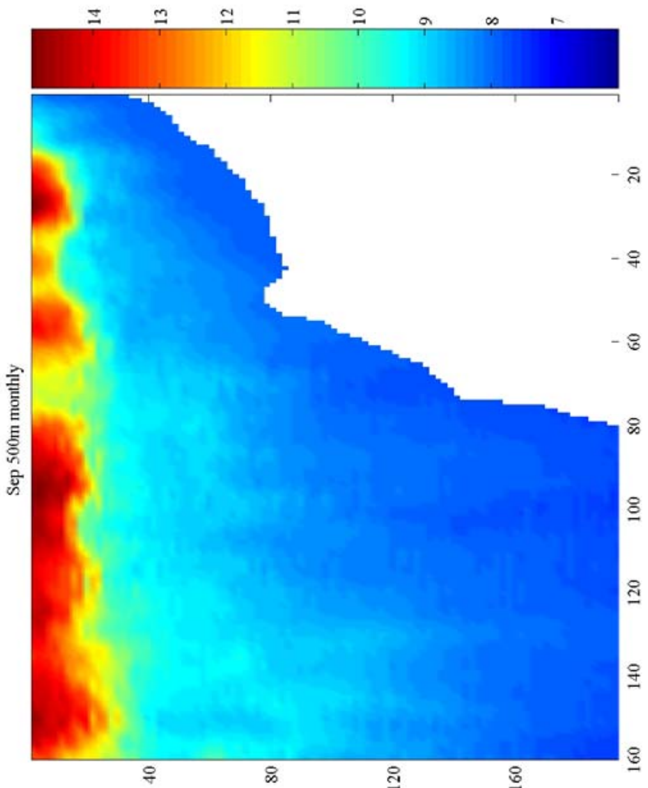
160


Sep 500m monthly
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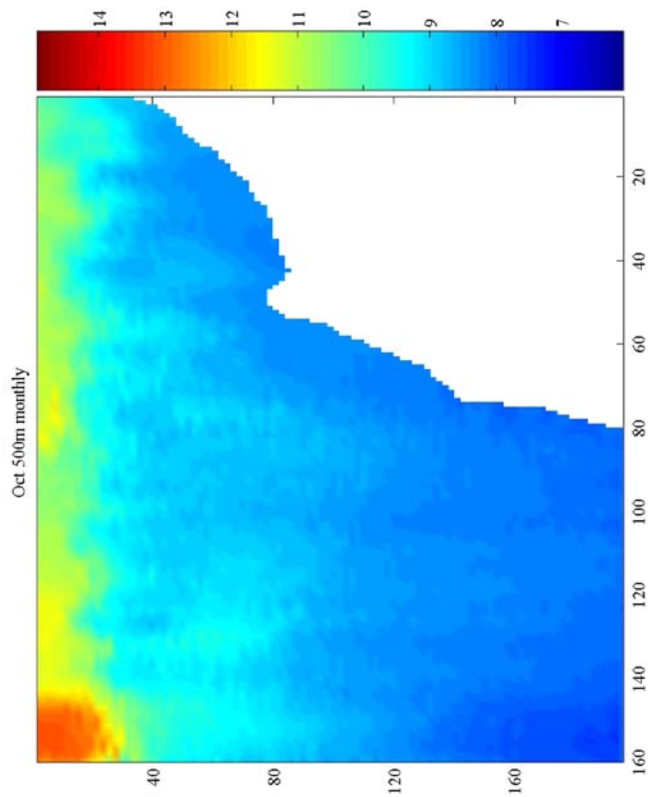
Oct 500m monthly
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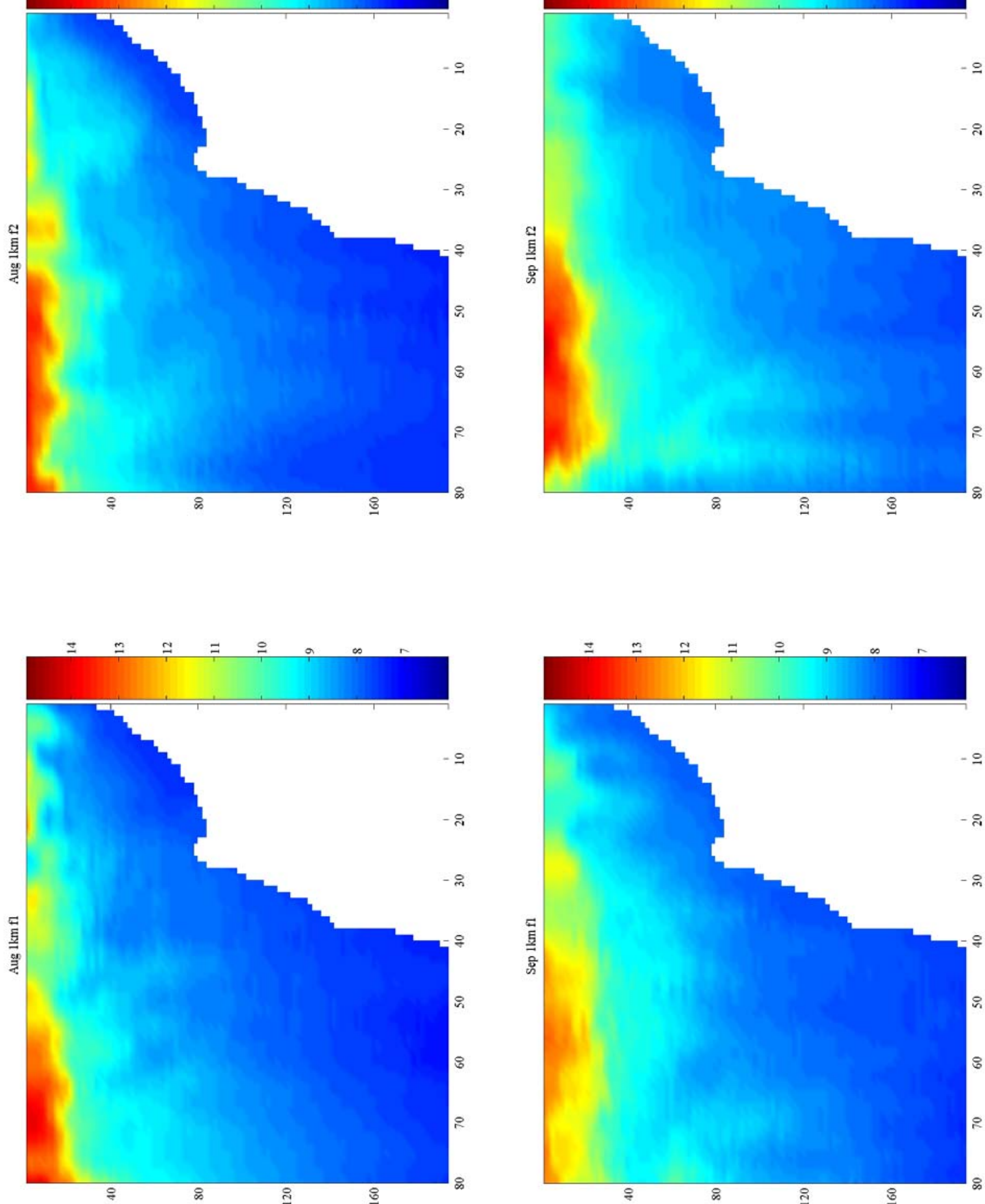
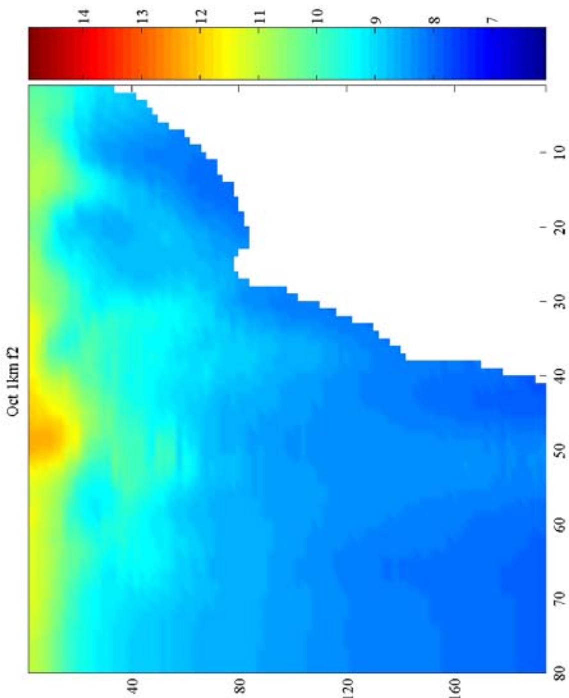
160

OBJECTIVE ANALYSIS
1 km resolution
1 fortnight timescale

Apr. 2006 – Jul. 2006
Nov. 2006 – Nov 2007
Not Shown


Aug 1km f2
Sep 1km f2
Aug 1km f1
Sep 1km f1


Oct 1km f2
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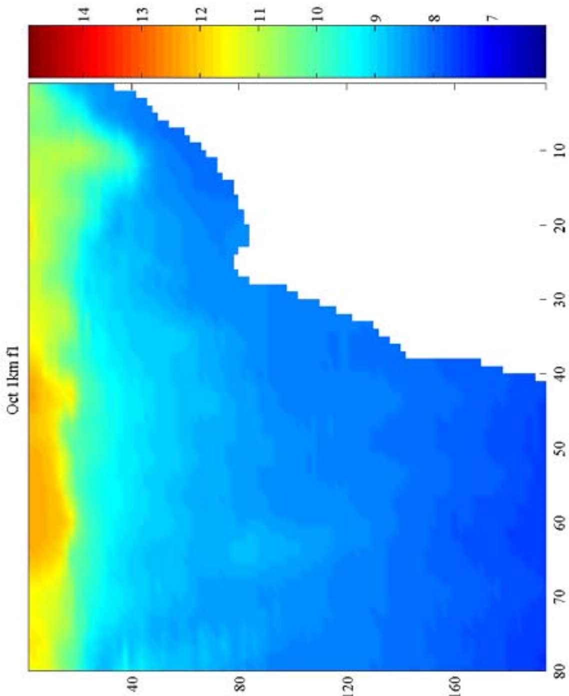
120
160


Oct 1km f1
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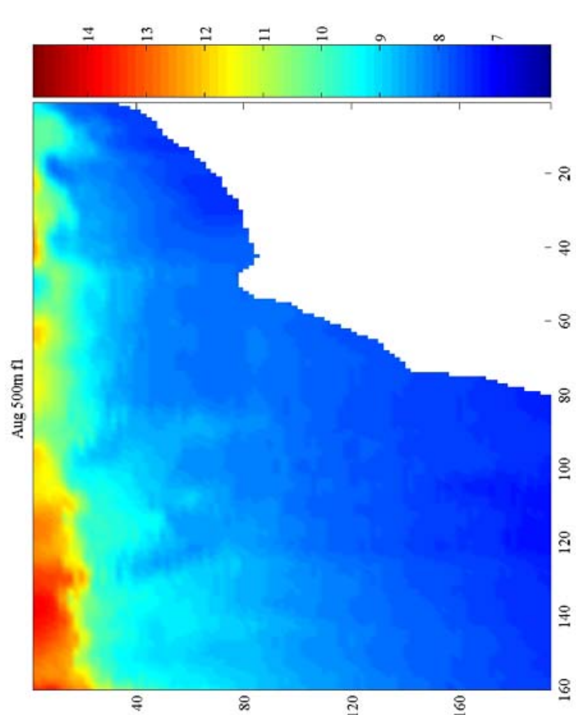
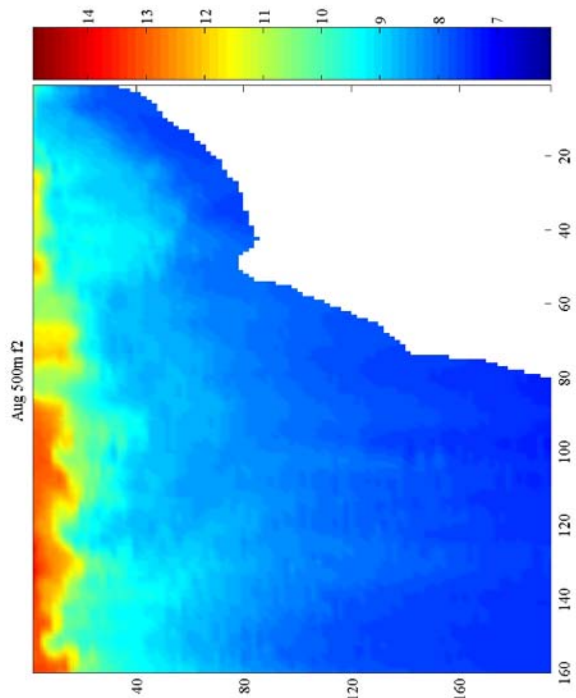
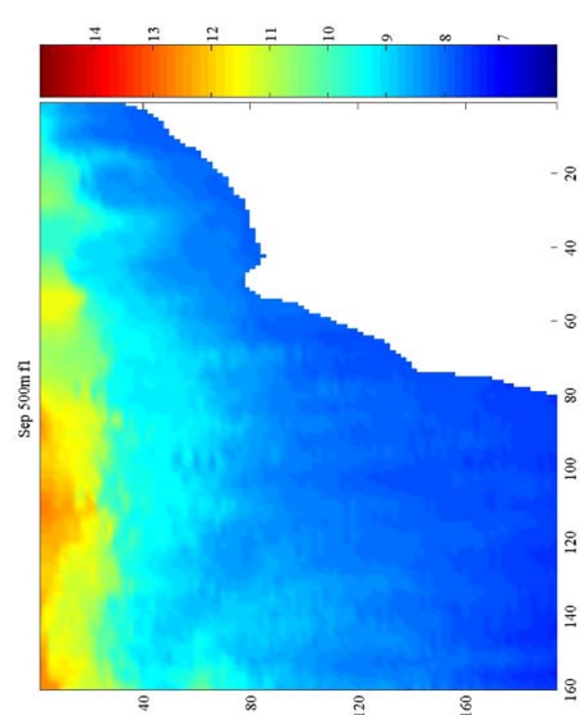
160

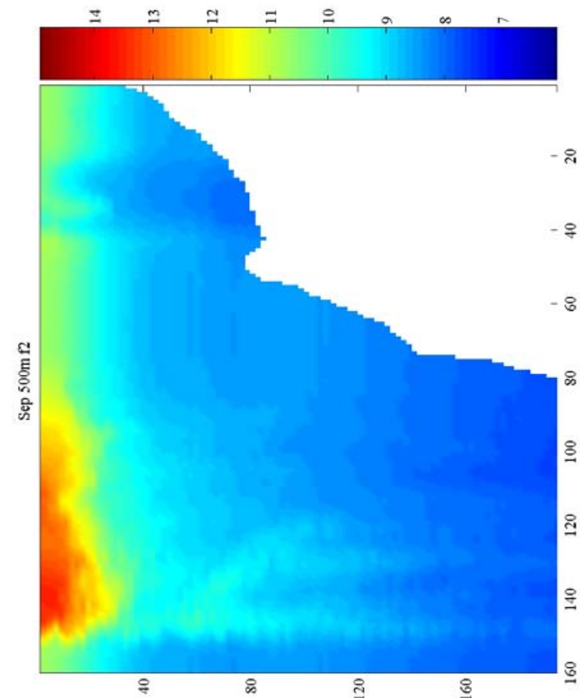
OBJECTIVE ANALYSIS
500 m resolution
1 fortnight timescale

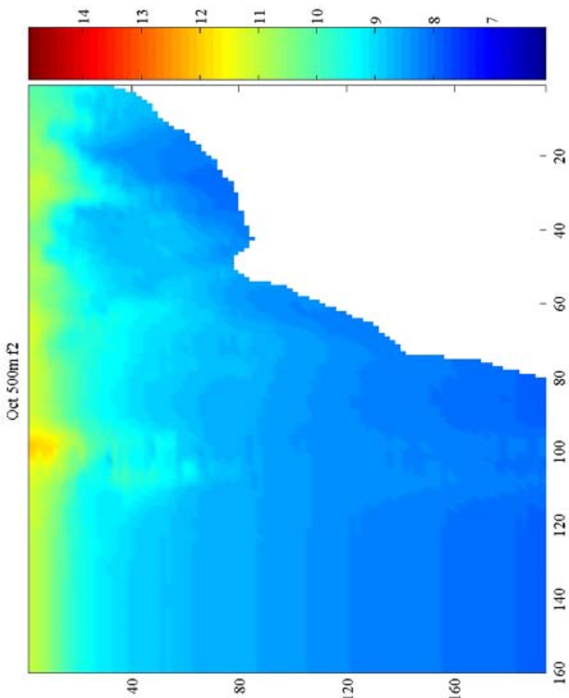
Apr. 2006 – Jul. 2006
Nov. 2006 – Nov 2007
Not Shown


Aug 500m f1
14 13 12 11 10 9 8 7
20 40 60 80 100 120 140 160
40 80 120 160


Aug 500m f2
14 13 12 11 10 9 8 7
20 40 60 80 100 120 140 160
40 80 120 160


Sep 500m f1
14 13 12 11 10 9 8 7
20 40 60 80 100 120 140 160
40 80 120 160


Sep 500m f2
14 13 12 11 10 9 8 7
20 40 60 80 100 120 140 160
40 80 120 160


Oct 500m f2
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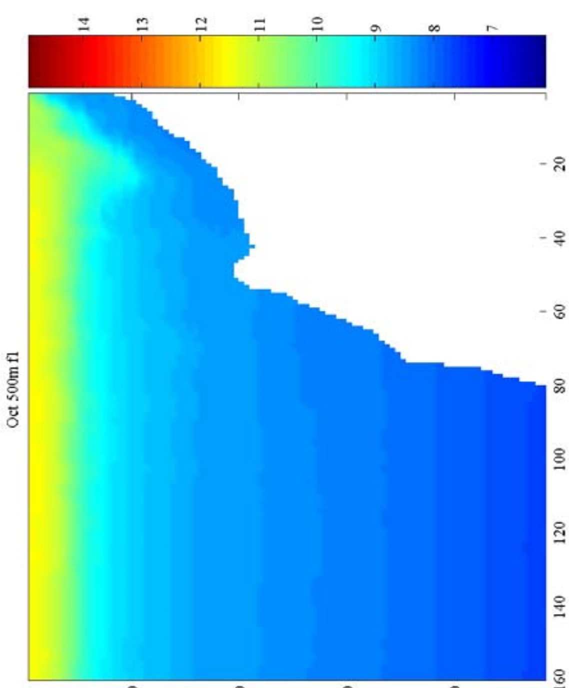
Oct 500m f1
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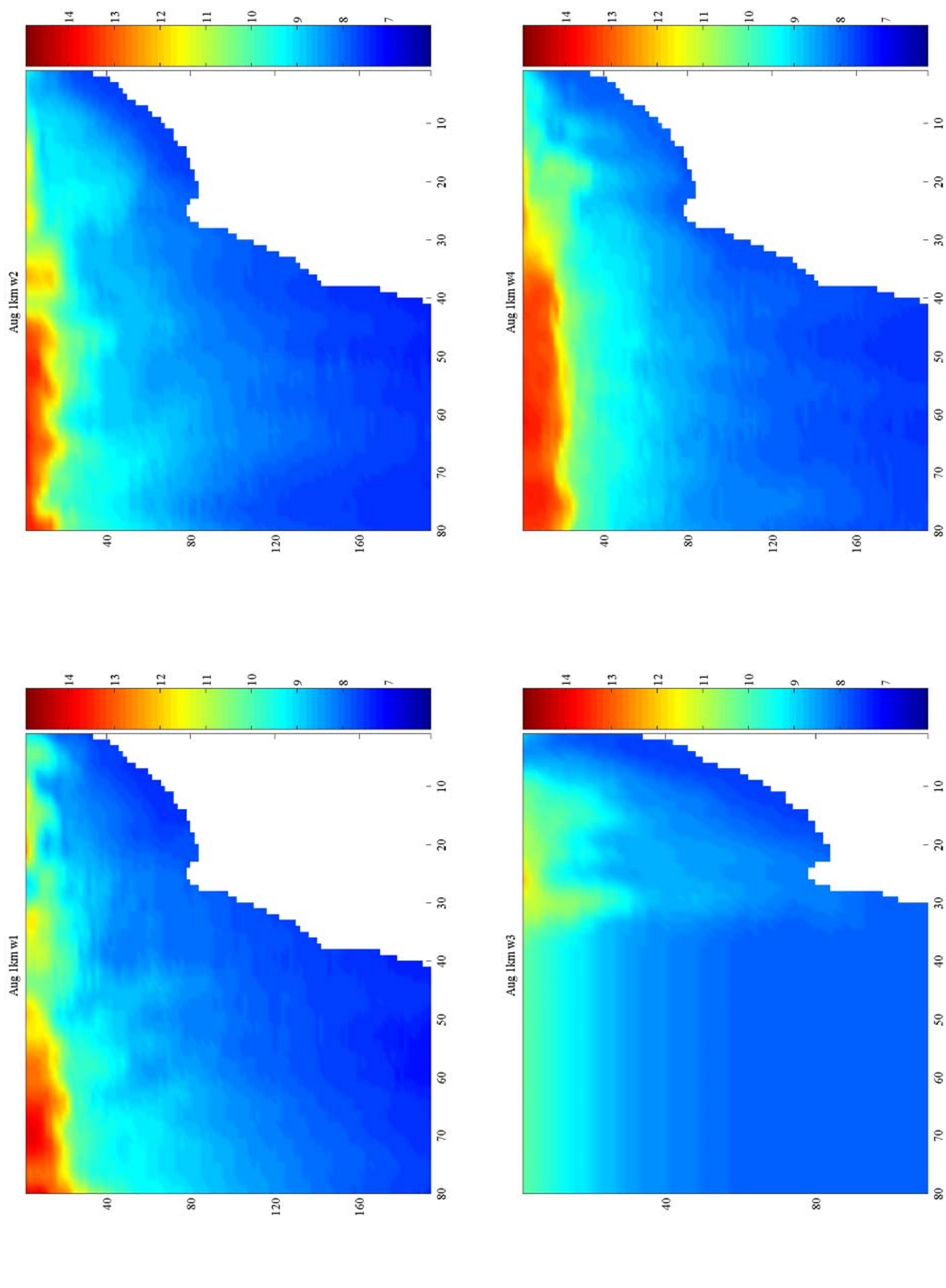
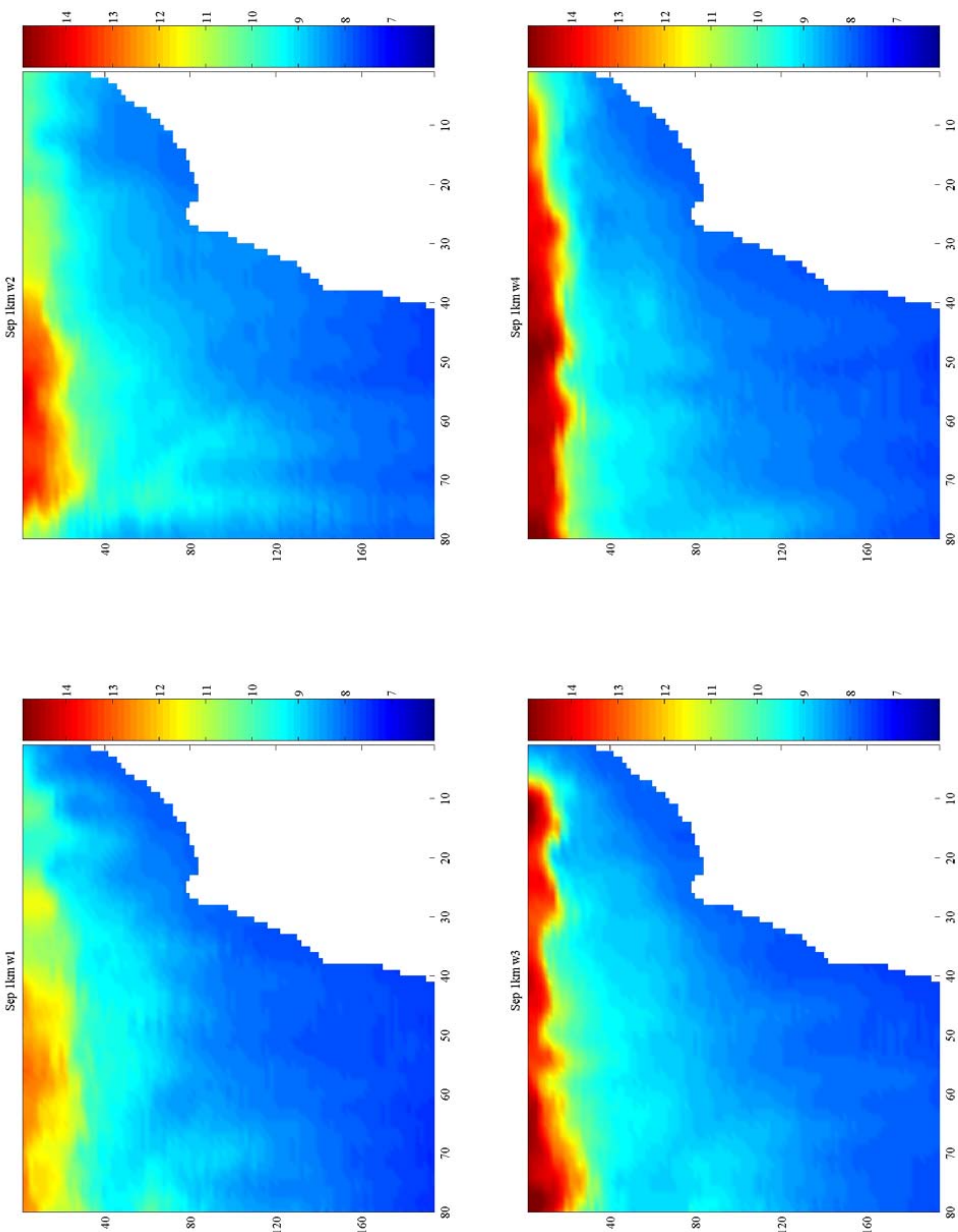
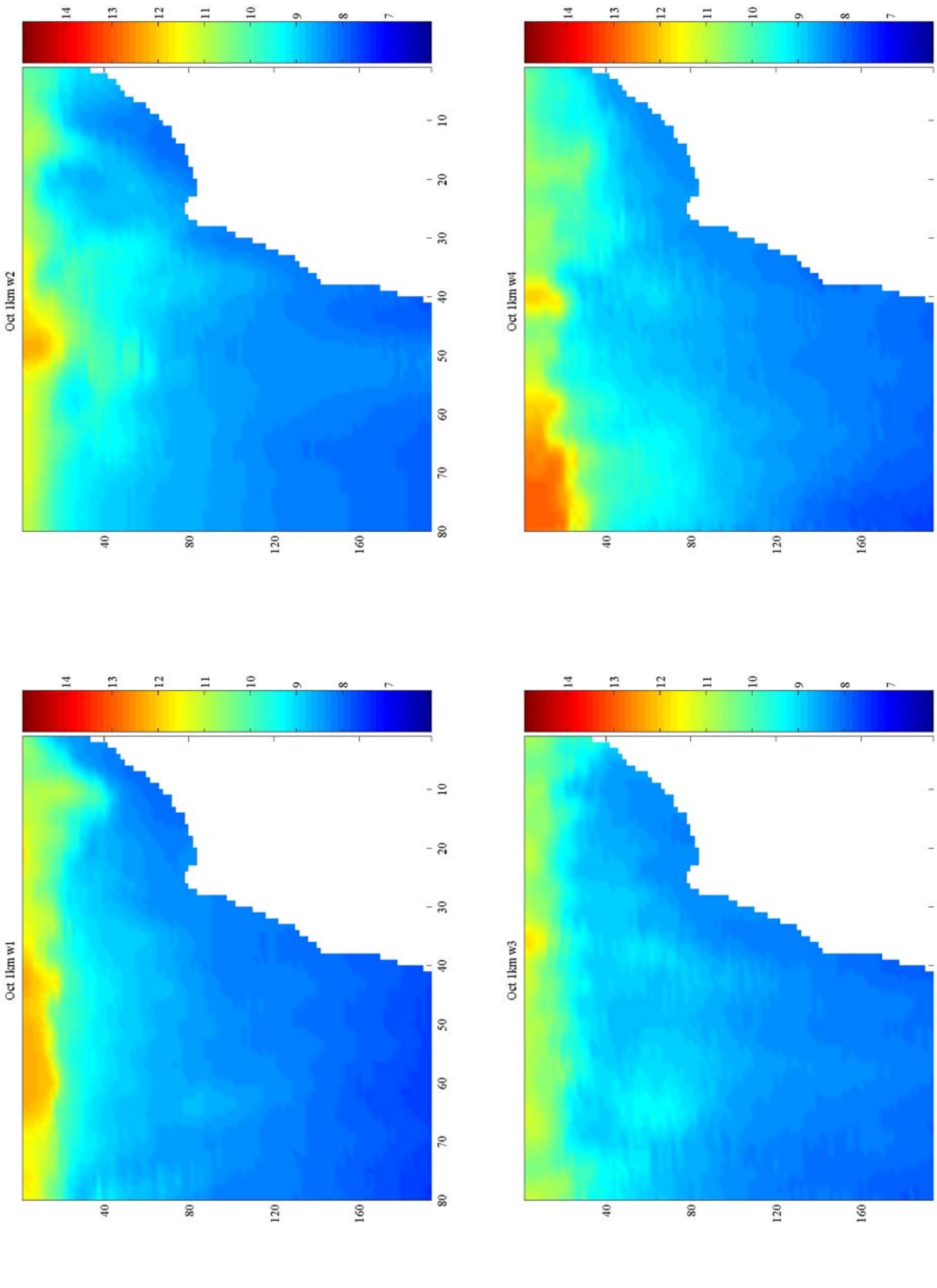
OBJECTIVE ANALYSIS
1 km resolution
1 week timescale

Apr. 2006 – Jul. 2006
Nov. 2006 – Nov 2007
Not Shown


Aug 1km w1
Aug 1km w2
Aug 1km w3
Aug 1km w4


Sep 1km w1
Sep 1km w2
Sep 1km w3
Sep 1km w4


Oct 1km w1
Oct 1km w2
Oct 1km w3
Oct 1km w4
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70
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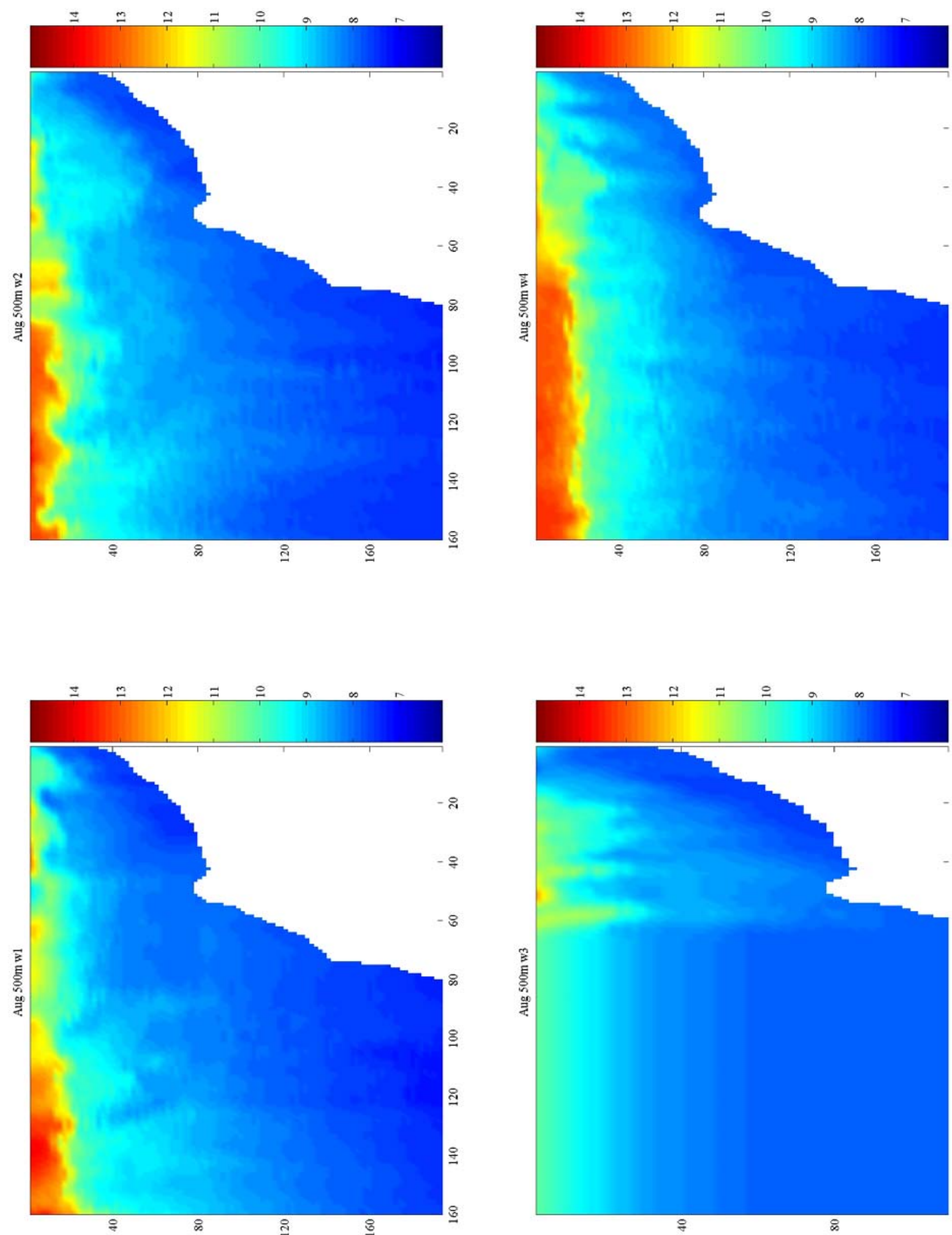
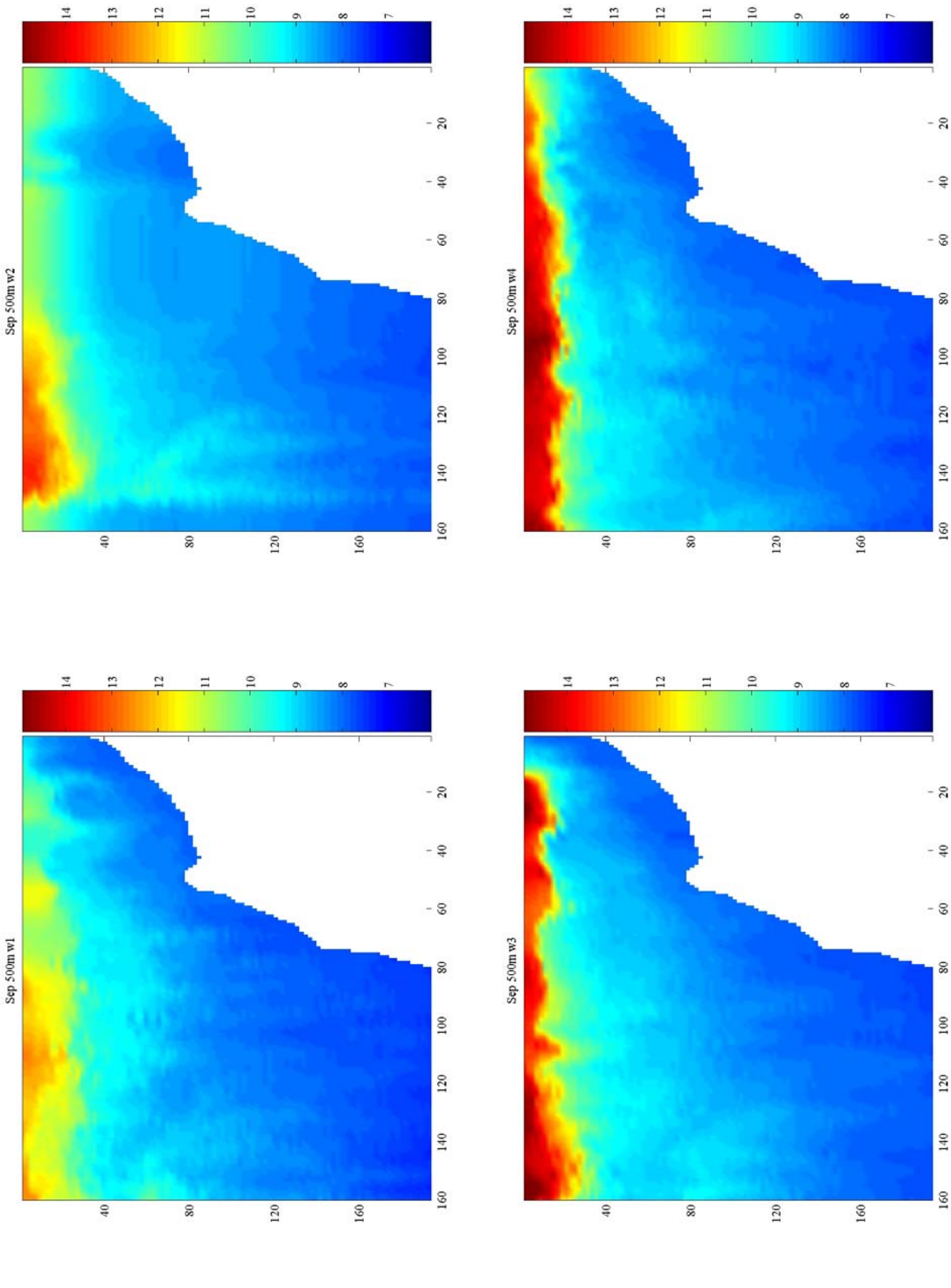
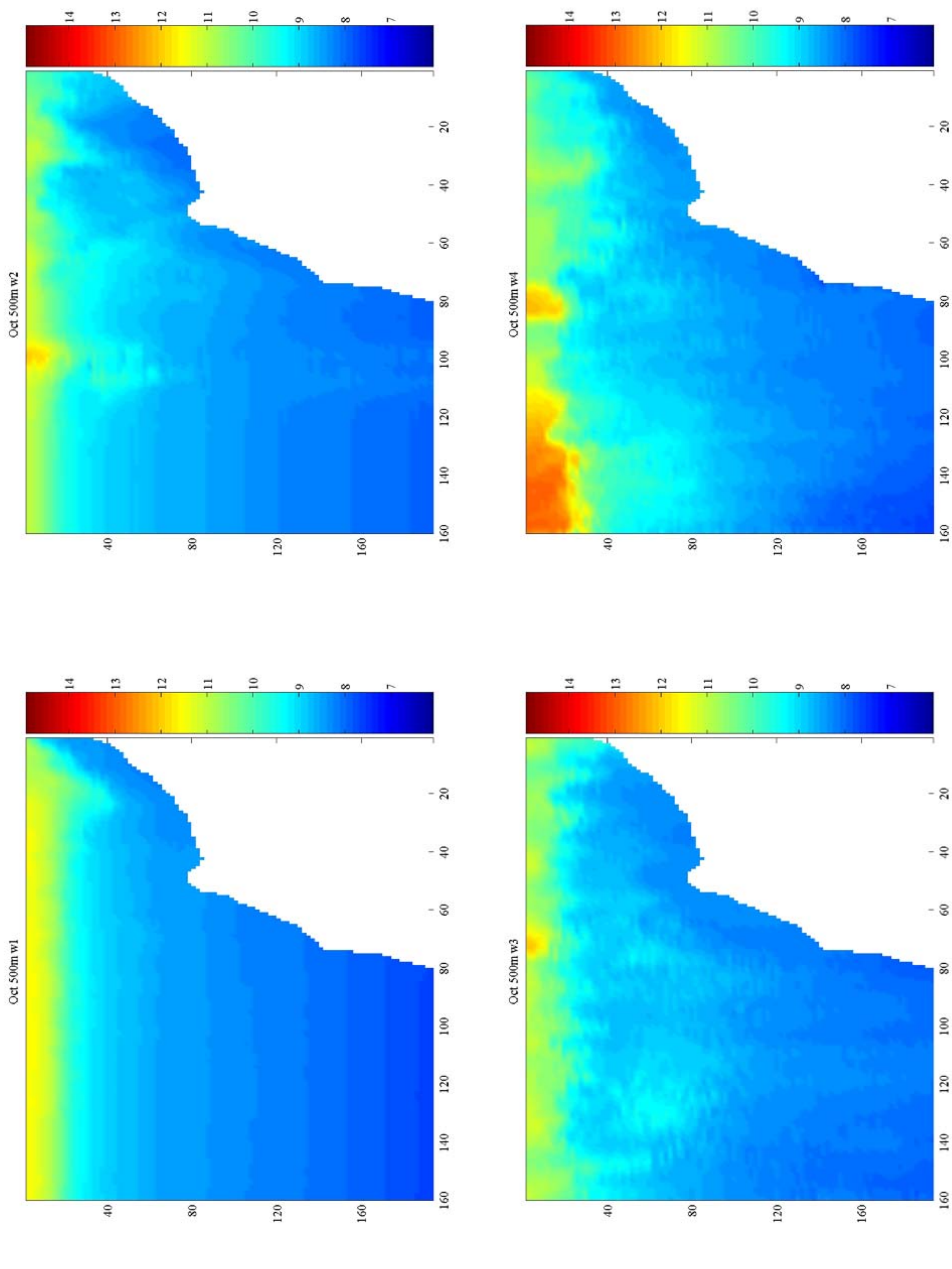
120
160

OBJECTIVE ANALYSIS
500 m resolution
1 week timescale

Apr. 2006 – Jul. 2006
Nov. 2006 – Nov 2007
Not Shown


Aug 500m w1
Aug 500m w2
Aug 500m w3
Aug 500m w4


Sep 500m w1
Sep 500m w2
Sep 500m w3
Sep 500m w4


Oct 500m w1
Oct 500m w2
Oct 500m w3
Oct 500m w4