AN ABSTRACT OF THE THESIS OF

HU ERNEST LUNG for the MASTER OF SCIENCE
(Name of student) (Degree)

in OCEANOGRAPHY presented on 30 April 1973
(Major) (Date)

Title: COMPUTER ANALYSIS OF THE SURFACE CURRENT FIELD OFF OREGON BASED ON DRIFT BOTTLE DATA

Abstract approved: Redacted for Privacy

The fall-winter surface current field off Oregon was determined by analysis of ten years of drift bottle data. Computer programs were developed for generating bottle tracks on a numerical grid, for interpolating bottle velocity components to fill void grid points and for smoothing irregularities in the velocity fields. Charts are presented showing the spatial distribution of surface currents determined in the study area of 5^{o} latitude by $2\text{-}1/2^{o}$ longitude.

The mean currents for the fall-winter season have a predominantly northerly flow with speeds increasing from the south to the north (from 0.01 to 0.35 knots). This probably is a consequence of the increase in speed of southerly winds from south to north in the study area during the fall-winter season. The northly flow in October during the years 1961-70, when compared with the dominant southerly flow during this month from measurements prior to 1935, may indicate

a major change of Davidson-California Current System within the past forty years. Apparent onshore flow may be introduced by bottle diffusion; this flow is prominant at all latitudes along which bottle releases are concentrated. An offshore flow component north of $46^{o}30'$N may be related to the Columbia River discharge and the westward extension of land.

Computer Analysis of the Surface Current Field off Oregon Based on Drift Bottle Data

by

Hu Ernest Lung

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1973

APPROVED:

Redacted for Privacy

Research Associate in Oceanography
in charge of major

Redacted for Privacy

Dean, School of Oceanography

Redacted for Privacy

Dean of Graduate School

Date thesis is presented 30 April 1973

Typed by Brenda Fadness for Hu Ernest Lung

ACKNOWLEDGMENT

This research was initiated and guided by Dr. Henry Crew, my major professor. I am grateful for his advice and encouragement during the analysis of data and the editing of the manuscript. Without his assistance my study in oceanography would never have been successful.

Sincere thanks go to Dr. Victor T. Neal for all his help in arranging my study in the School of Oceanography, Oregon State University. He also devoted much of his time to review the thesis and made many valuable comments.

Appreciation is extended to Mr. William E. Gilbert for providing me the ten years of drift bottle data, to Mr. Godfrey D. Waston and Mr. Neng-chun Yao for their assistance in computer programming, and to Mr. Donald F. Keene for providing me valuable suggestions on researching and English writing.

The understanding and encouragement of my wife, Pu-ching Sheng, in Taiwan during the long period of my study in the United States, is highly appreciated.

My studies in the past two years have been supported by the Ministry of National Defense, Republic of China.

TABLE OF CONTENTS

LIST OF FIGURES

COMPUTER ANALYSIS OF THE SURFACE CURRENT FIELD OFF OREGON BASED ON DRIFT BOTTLE DATA

INTRODUCTION

This research was motivated by the desire to represent drift bottle data in a form more useful than a chart of assumed bottle tracks and release-recovery statistics. In this analysis, ten years of drift bottle data were used to chart the mean surface current field off Oregon during the fall-winter season.

The determination of surface currents by use of drift bottle data is limited by the accuracy of the data. Errors are undoubtedly introduced in the present analysis through the processes of data rejection, linear interpolation and smoothing. It is felt, however, that the surface current field obtained will be of practical use in navigation, planning for waste disposal, air-sea rescue and other practices affected by surface currents.

The method of analysis employed here is described, and the computer programs used are included as appendices. The errors inherent in drift bottle data and those possibly introduced in the analytical technique are discussed. The results obtained are compared with other determinations of the current field off Oregon. Improvements in the analytical technique and special uses of the technique are suggested.

THE DATA

Oregon State University has been conducting a long-term drift bottle project since 1961. In the period of 1961 through 1970, a total of 21,615 bottles were released within 165 nautical miles of the Oregon Coast during 87 cruises. The major release points were 5, 15, 25, 35, 45, 65, 85, 105, 125, 145, and 165 nautical miles west of Brookings (42°00'N), Coos Bay (43°20'N), Newport (44°39'N), and Astoria (46°14'N). Of the bottles released, 2,938 were eventually recovered along the west coast of the United States and Canada. The high return rate (13%), the highest among drift bottle studies off the west coast of North America, may be attributed in part to the large fraction of nearshore releases. About one-fourth of all the bottles were released within 25 nautical miles of the coast, and the return rate of these bottles was 33%. A general offshore flow in spring-summer and onshore in fall-winter is reflected in the smallest return rate during June (4.2%) and greatest during September (28.5%) (see Table 1).

Statistics of the 1961-1970 drift bottle data and monthly charts of straightline tracks between the points of release and recovery have been presented by Wyatt, *et al.* (1971). Those bottle data have been employed by Burt *et al.* (1964) and Wyatt *et al.* (1972) in analysis of the surface currents off Oregon.

Table 1. Monthly Bottle Return Rate, 1961-1970.

Year	Monthly Return Rate (%) of Releases from all Stations											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1961	7.0		30.1	46.5	2.6	1.2	8.3	4.2		18.4		46.4
1962	23.6	30.2	0*	25.8		1.6	14.0	3.3	24.2	8.3		10.5
1963	34.7	28.6	29.0				7.5	15.3	32.0		10.8	22.0
1964		0.4*	0.6				4.4			4.2*	19.7	10.4
1965		5.7	0*	36.1**		14.8**	3.3				25.0	27.3
1966	13.5		4.5	0			2.2		22.2	15.2	9.8	
1967	23.6	27.0		1.9	0	7.4	7.9	35.0**		36.3	34.8	
1968	26.7	15.5	17.7	0.5		18.1	10.1	14.5	30.3	15.9	28.4	4.2
1969	18.7	10.7			18.6	8.3		9.2	21.2	11.9	6.4	
1970	29.1	14.7			16.0	1.0					31.1	27.9
Average Monthly Return Rate	19.4	13.2	10.8	18.2	10.7	4.2	7.6	12.7	28.5	15.8	20.4	20.8

* Bottles released mostly from stations greater than 45 nautical miles offshore.

** Bottles released mostly from nearshore stations less than 25 nautical miles or a small number of bottles released.

ANALYTICAL METHOD

The analysis performed here involves the following steps:

1. Selecting the data and numerical grid to be employed by: sorting data for time of year; rejecting suspicious data; and selecting numerical grid coverage and spacing to warrant best resolution of available data.

2. Computing the current components at grid intersections by: determining eastward (u) and northward (v) velocity components of each bottle; associating these values with those intersections of the two-dimensional grid which lie along the straightline track between the bottle release and recovery points; and averaging the velocity components at grid intersections lying along two or more tracks.

3. Applying two-dimensional interpolation to assign velocity components to those intersections not lying along any tracks.

4. Smoothing the velocity component fields and forming the fields of speed and direction.

5. Forming divergence and vorticity fields.

6. Forming meridional and zonal averages.

These steps are described and discussed below. The computer programs used are included as appendices.

Selection of Data and Grid

In selecting data to be employed, existing knowledge of the currents should be taken into consideration. The surface waters of the west coast of the United States of America are dominated by a slow and broad equatorward flow called the California Current, and coastal currents which vary seasonally. According to Sverdrup et al. (1942), a subsurface countercurrent flowing northward along the coast breaks through to the surface as the Davidson Current in the winter months when the winds are southeasterly to southwesterly. Off Oregon the Davidson Current begins to develop in September and becomes dominant from October through February. Preceded by two months of variable flow, the southward California Current resumes in May through August (Wyatt et al., 1972). The width of the Davidson Current is not well defined. The current develops along the Washington and Oregon coast in September, first close to shore and later widening (Schwarzlose, 1964). Pilot charts for January (USNHO, 1957) show the Davidson Current to be 60 to 100 nautical miles wide off Oregon. Fall-winter hydrographic measurements have indicated a width of 105 nautical miles for northward geostrophic flow (Lee, 1967).

Bottles released from stations within 105 nautical miles of the coast during October-February were selected for this analysis. Month to month variations in current can be presumed small in this period and onshore drift during this period results in a high percentage of returns (average monthly return rate in this period is around 20%, higher than spring-summer season as shown in Table 1).

Data for bottles not recovered within 60 days of their release (or until after March 30) were not included in the analysis. By rejecting these data (38% of the returns for the period) some of the bottles which had lain on the beach some time before being picked up were eliminated, as were some bottles which had taken circuitous routes. The effect of this data rejection is to increase apparent mean current speeds, especially at locations far from shore. Other rejection schemes might involve an elapsed time criterion that increases linearly with distance of release point from shore, or criterion that varies so as to eliminate the same percentage of returns from every release point. In view of the under-estimation of current speed due to the assumption of straight line tracks, the data rejection scheme employed here is considered satisfactory. The spatial distribution of release stations and the 920 data selected by this method are shown in Figure 1.

The area selected for computation of the current field is bounded on the east by the coast, on the west by longitude $126^{\circ}30'$W, and north and south by latitudes $47^{\circ}00'$N and $42^{\circ}00'$N. The area was selected because it is most densely crossed by tracks during the October-February period (Wyatt, et al, 1971). It should be noted that while

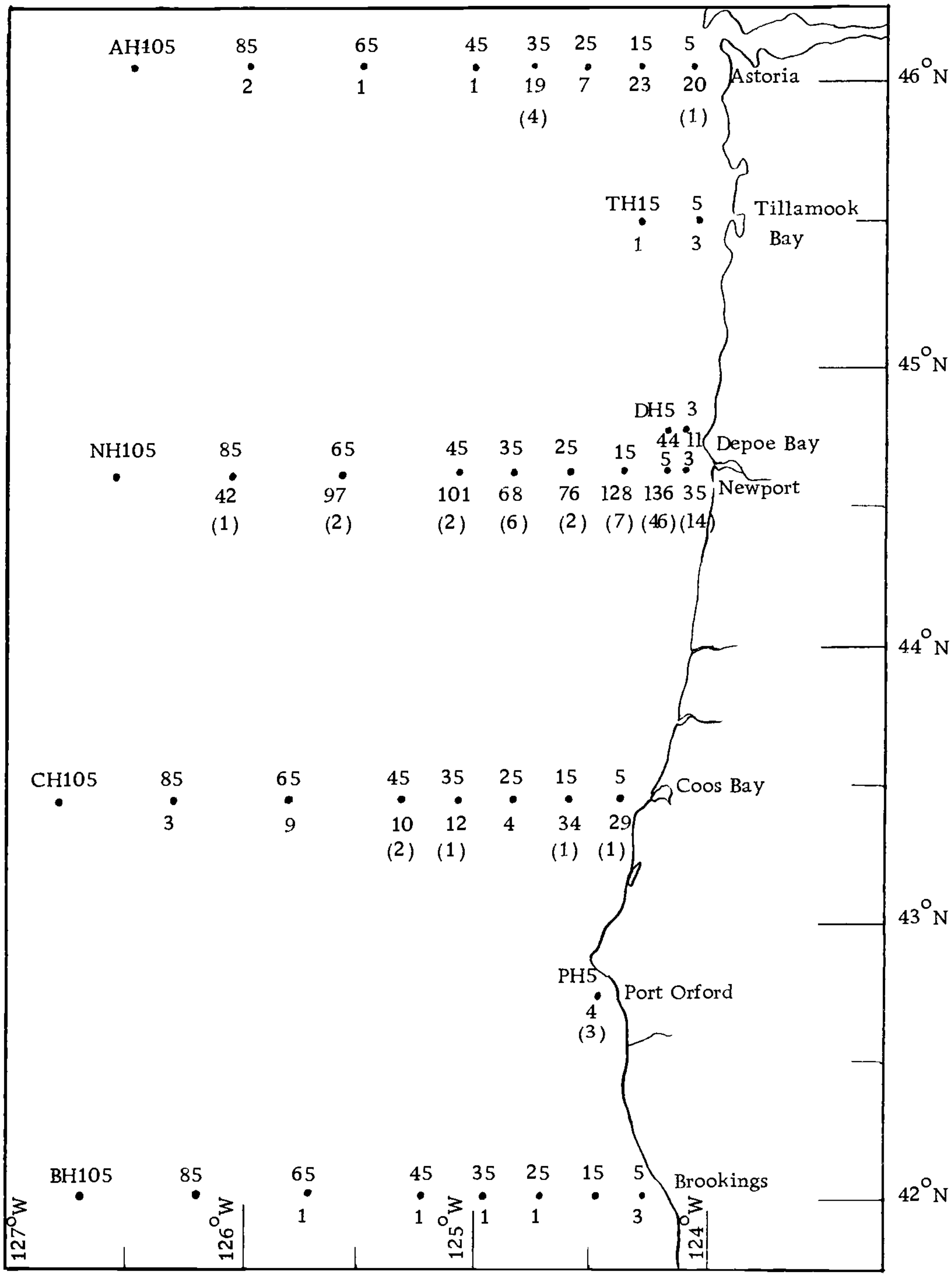


Figure 1. Distribution of Bottle Release Stations and Number of Returns Used in This Study.

the current analysis is limited to this area, data from returns outside the area are included in the computation.

The selected area is partitioned by a 30X60 numerical grid consisting of squares 5 minutes on a side (see Figure 2). The grid spacing was chosen even smaller than the density of data appeared to warrant in order that small features, such as quasi-stationary shear zones, might be resolved. With such a dense mesh there will be some grid points without data and the amount of data at each grid point is small, but these problems can be eliminated by interpolation and smoothing. If computer storage were a problem, a uniform rectangular grid with the long sides parallel to merdians might be used with little loss of resolution as the gradient of velocity in the direction of mean flow is usually small. In view of decreasing density of tracks with distance offshore, a second solution to a computer storage problem would be a grid that expands offshore. This last solution, however, would require more sophisticated programming and distort spatial scales of the currents.

Computation of Mean Currents Distributed in Study Area

There are three steps involved in calculating mean currents in the study area. They are: a) computation of speed, direction and velocity components for each bottle, b) assignment of the velocity components to those grid points lying along the straight line track

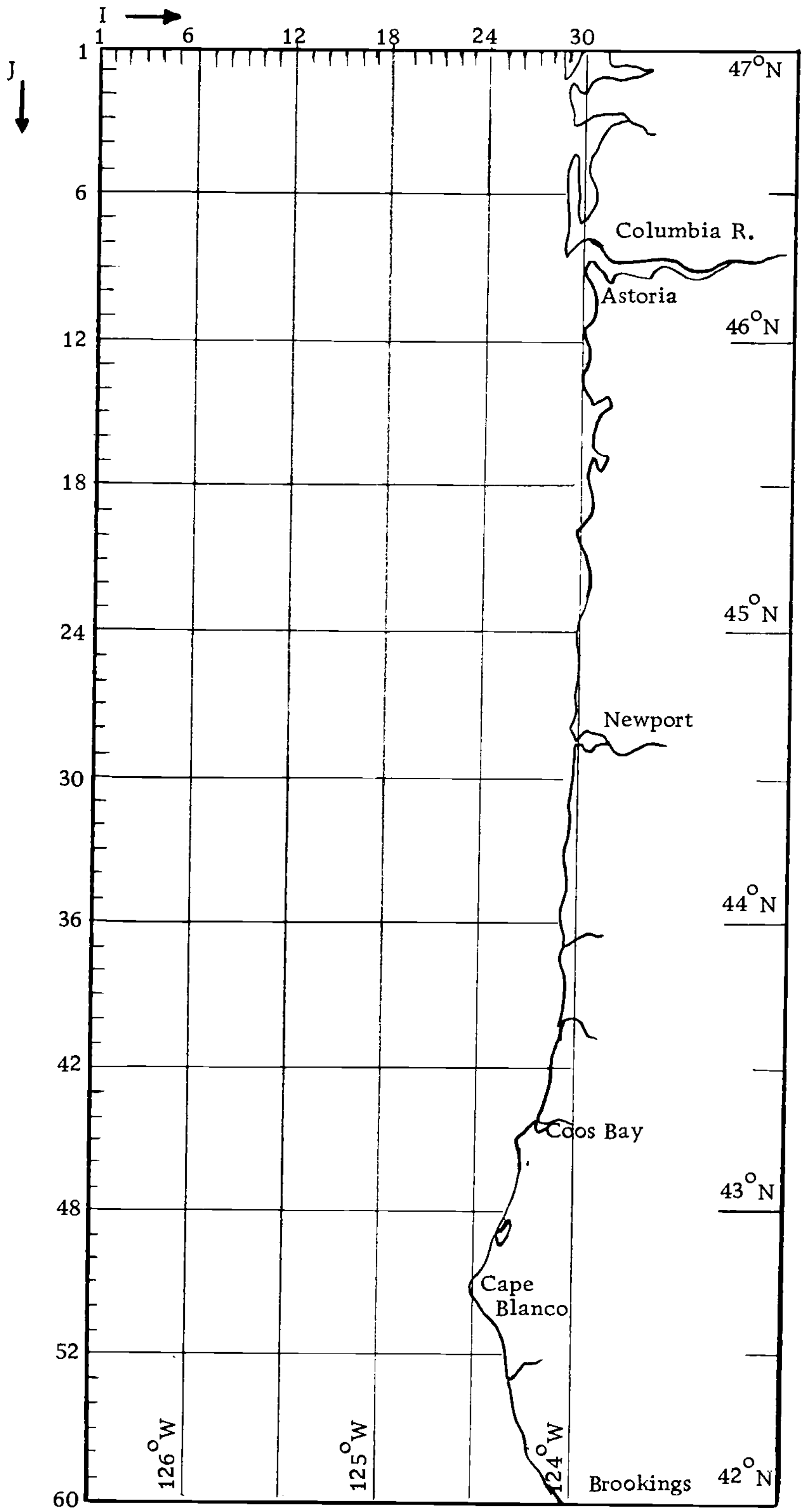


Figure 2. Numerical Grid Used in the Study

between the release and recovery locations of each bottle and c) determination of the mean velocity components associated with each grid point passed by more than one bottle track. These steps are described in detail below.

Computation of Bottle Speed, Direction and Velocity Components

The Mercator Sailing Method (Bowditch, 1962) was used for computing direction and speed between release and recovery points. Denoting the latitude and longitude of the release point by L_1 and λ_1, respectively, and of the recovery point by L_2 and λ_2, the distance D in nautical miles and course angle C in radians (with respect to one of four cardinal points of the compass) are given by

$$D = |(L_1 - L_2) \sec C|$$

$$C = \arctan((\lambda_1 - \lambda_2)/(M_1 - M_2))$$

where L_1, L_2, λ_1 and λ_2 are in minutes, and M is the number of meridional parts between the equator and a given parallel on a Mercator chart. Meridional parts are calculated, with latitude in degrees, by

$$M = (\mathrm{Log}_e 10 \,\mathrm{Log} \tan(45^\circ + L/2) - (\epsilon^2 \sin L + \frac{\epsilon^4}{3} \sin^3 L + \frac{\epsilon^6}{5} \sin^5 L + \ldots))\, 21600/2\pi$$

The appropriate compass point is determined from the signs of the differences between release-recovery latitudes and longitudes. The course angle is converted into direction from true north by the subroutine of Appendix Ia and meridional parts for the release and recovery latitudes are calculated by the subroutine of Appendix Ib. The speed S of a bottle in knots is computed by

$$S = D/TH$$

where TH is the elapsed time in hours between release and recovery.

The zonal and meridional velocity components are computed by

$$U = S\sin C \quad \text{and} \quad V = S\cos C.$$

The above computations are made in lines 29 to 53 of the main program (listed in Appendix I), and involve the subroutines of Appendices Ia and Ib.

Generating Tracks and Assigning Velocities to Grid Points

This step involves identifying the grid points lying along each bottle track and assigning the bottle's u and v components to these points. In the numerical grid shown in Figure 2 the index I increases eastward from 1 to 30 in 5-minute increments from $126^{\circ}30'$W to $124^{\circ}05'$W, and index J increases southward from 1 to 60 in 5-minute increments from $47^{\circ}00'$N to $42^{\circ}05'$N.

The method employed to identify grid points (I, J) lying along a bottle track depends on the bottle's trajectory. Due to the configuration of the coast in this area, no bottles have trajectories predominantly westward or toward the southwest. To insure all points lying along a track are identified, tracks are divided into three categories as shown in Figure 3. The courses are categorized, in part, by the slope of the straight line between release and recovery

$$R = (L_1 - L_2)/(\lambda_1 - \lambda_2)$$

If a bottle's trajectory is predominantly eastward, the absolute value of R is less than unity and the grid points (I, J) lying along the track are generated by

$$J = J_1 + R(I - I_1),$$

$$I = I_1,\ I_1+1,\ I_1+2,\ \cdots,\ 30,$$

where the bottle release point indices are given by

$$I_1 = (126 \times 60 + 30 - \lambda_1)/5,$$

$$J_1 = (47 \times 60 - L_1)/5.$$

When the generated grid points (I, J) have I values greater than I_2, these points are discarded, where

$$I_2 = (126 \times 60 + 30 - \lambda_2)/5.$$

This case is shown in Figure 3(a).

A bottle's trajectory is predominantly northward when $L_2 > L_1$ and $|R| > 1$, and for this case grid points lying along the tracks are generated by

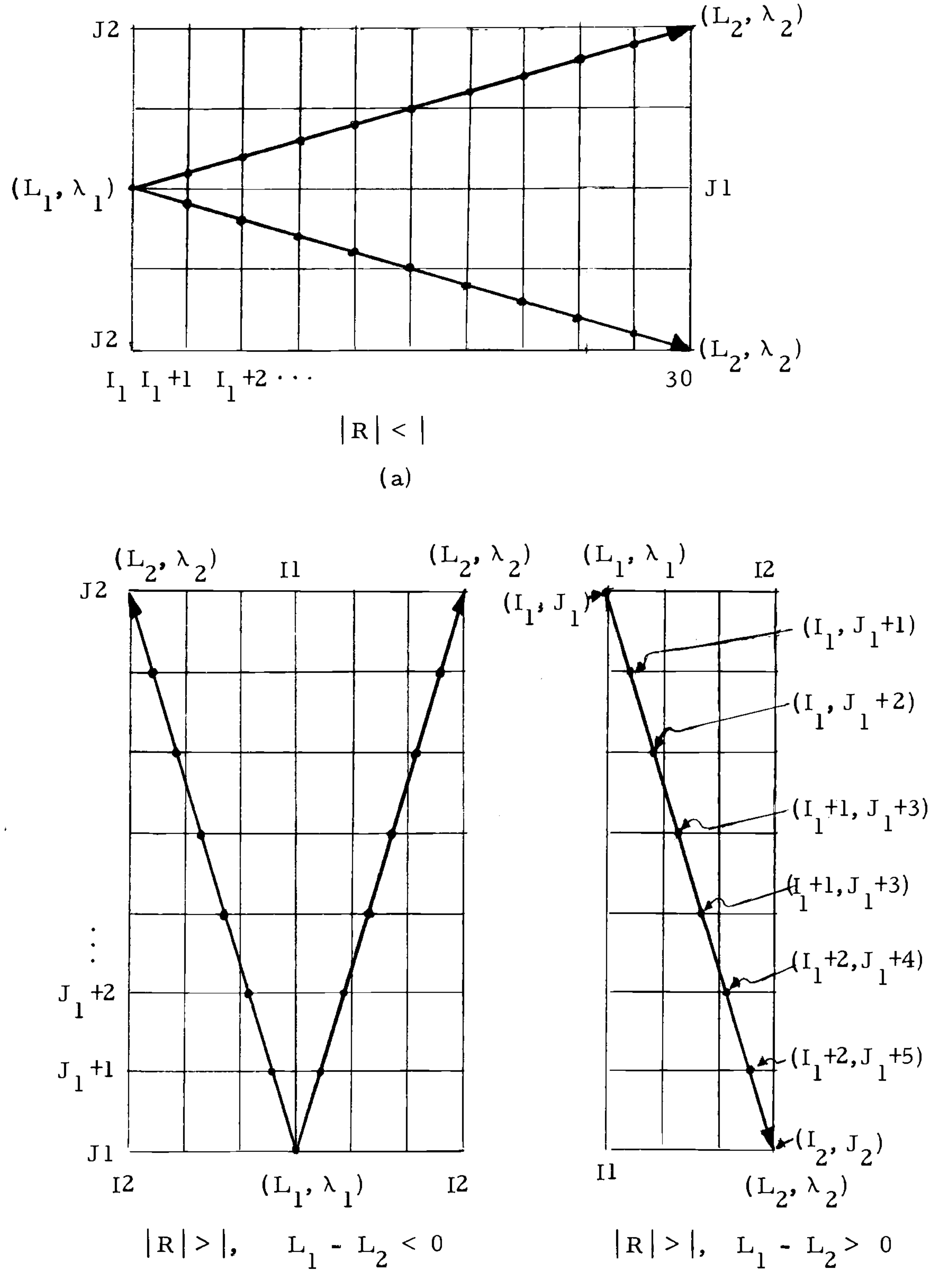


Figure 3. Grid Points Along Tracks

$$I = I_2 + (J - J_2)/R ,$$

$$J = J_2, J_2+1, J_2+2, \cdots, J_1$$

where the bottle recovery point indices are

$$I_2 = (126 \times 60 + 30 - \lambda_2)/5$$

$$J_2 = (47 \times 60 - L_2)/5$$

This case is shown in Figure 3(b).

A bottle's trajectory is predominantly southward when $L_1 > L_2$ and $R > 1$; for this case (as shown in Figure 3(c)) grid points lying along the track are generated by

$$I = I_1 + (J - J_1)/R,$$

$$J = J_1, J_1+1, J_1+2, \cdots, J_2.$$

Grid points which may be generated outside the study area in the last two cases are discarded; these have negative indices or indices greater than 30 for I and greater than 60 for J.

At all grid points the parameters U, V and track counter N are initially set to zero. For all grid points lying along the track of a bottle, the parameters U and V are increased by the bottle's u and v components, respectively, and the counter N is augmented by unity.

The preceding step of the analysis is performed by lines 57 through 94 of the main program (see Appendix I).

Averaging the u, v Components at Each Grid Point

After performing the previous two steps for all bottles, the mean velocity components at each grid point for which $N > 0$ is determined through division of parameters U and V by N. In the southern portion of the area, especially south of $43^{o}30'$N, the percentage of grid points that lie along any track is small (see Figure 4). The highest density of tracks is off Newport; one point lies along 167 tracks. As expected, the density of tracks decreases with distance offshore (see Figure 5).

Two Dimensional Interpolation

Some grid points do not lie along any bottle track (i e. have $N = 0$, see Figure 6), and must be assigned velocity components. If such a point lies in a row between grid points having $N > 0$, it receives velocity components by horizontal linear interpolation. If to one side of the point in the row there are no points having $N > 0$, the point receives velocity components of the nearest point in the row having $N > 0$. The point similarly receives velocity components based on data from the column within which it lies. Then the point is assigned velocity components which are means of these row-based and column-based computations. Both meridional and zonal interpolations are performed, and the mean of interpolated values is used

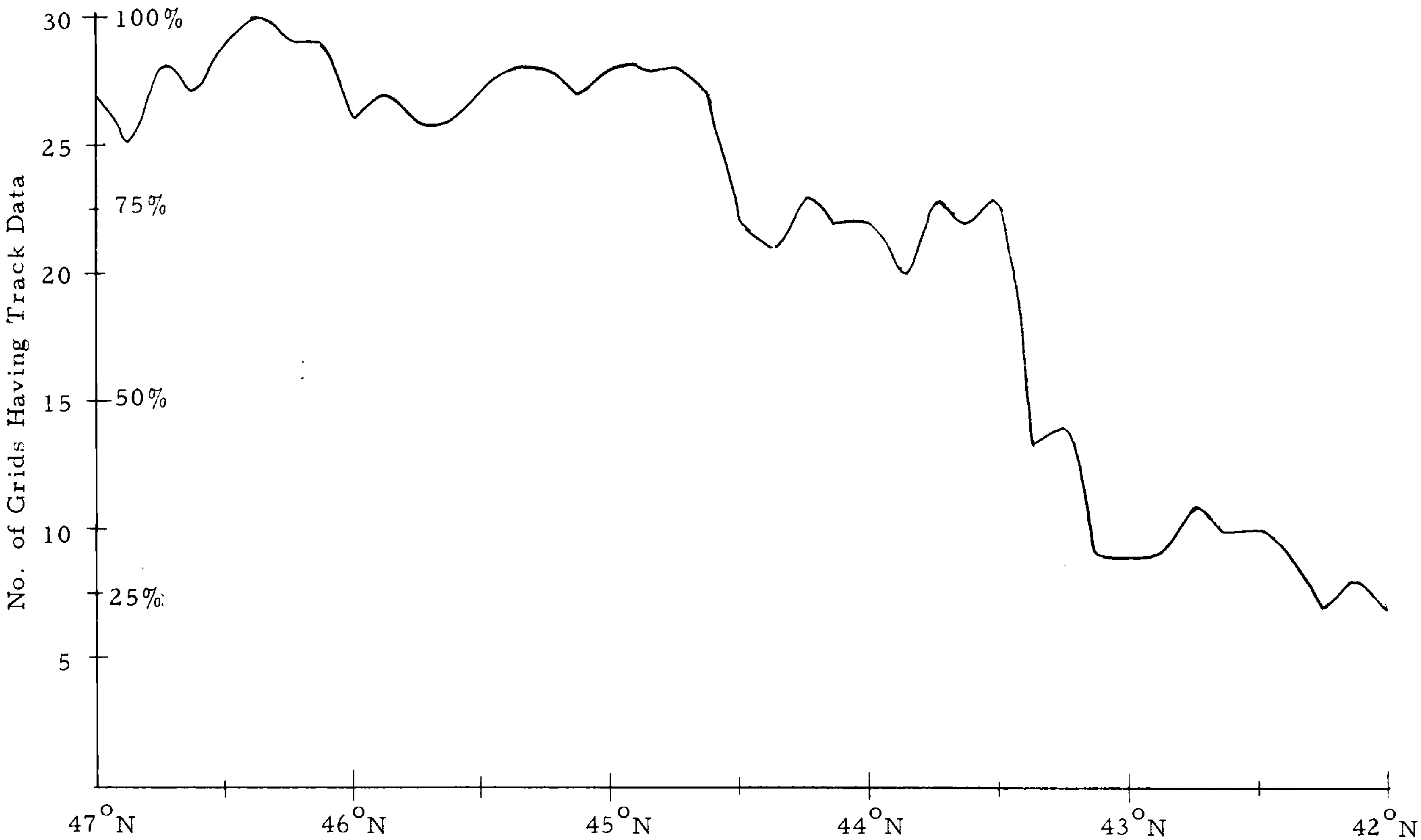


Figure 4. Zonal Distribution of Grids Having Track Data.

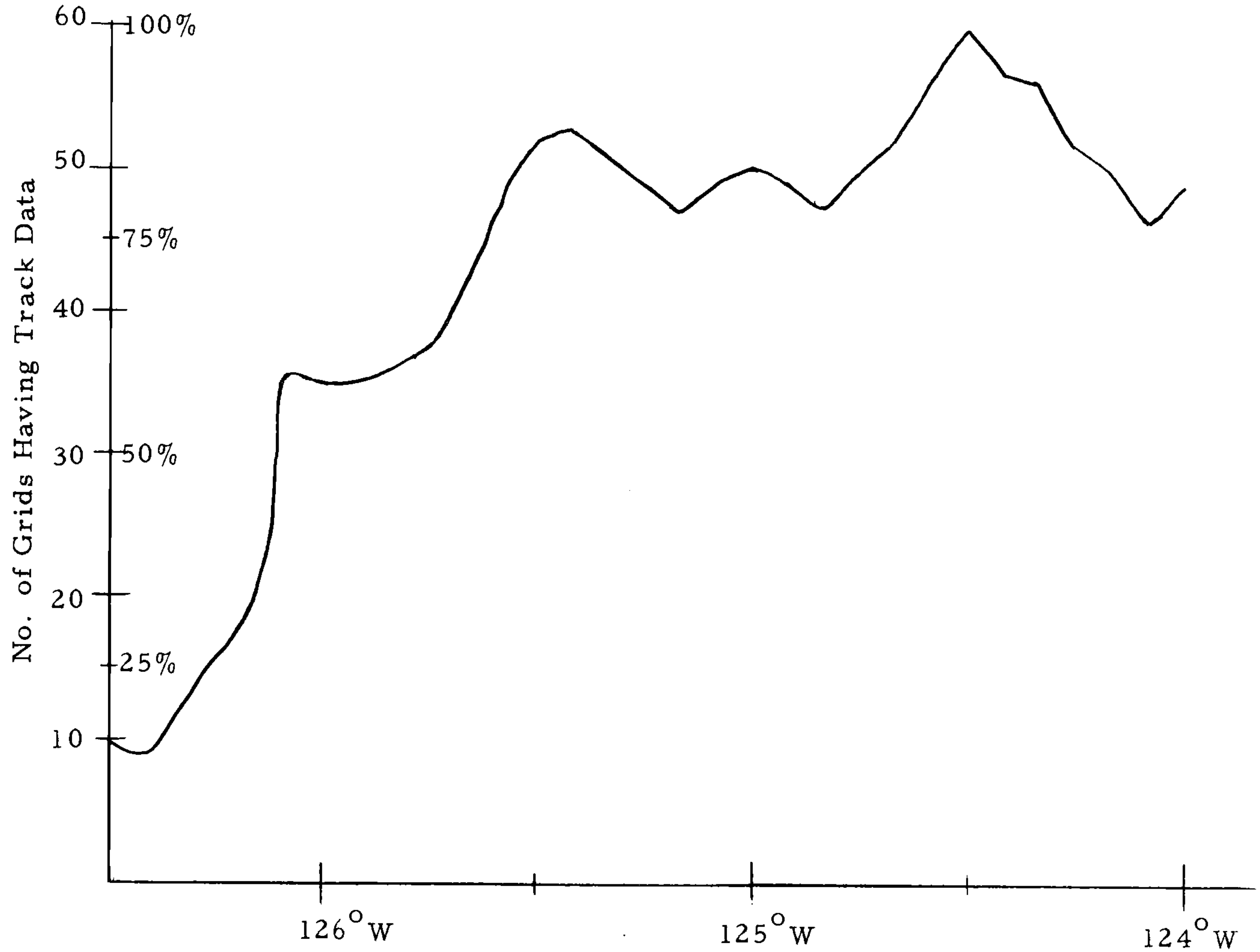


Figure 5. Meridional Distribution of Grids Having Track Data.

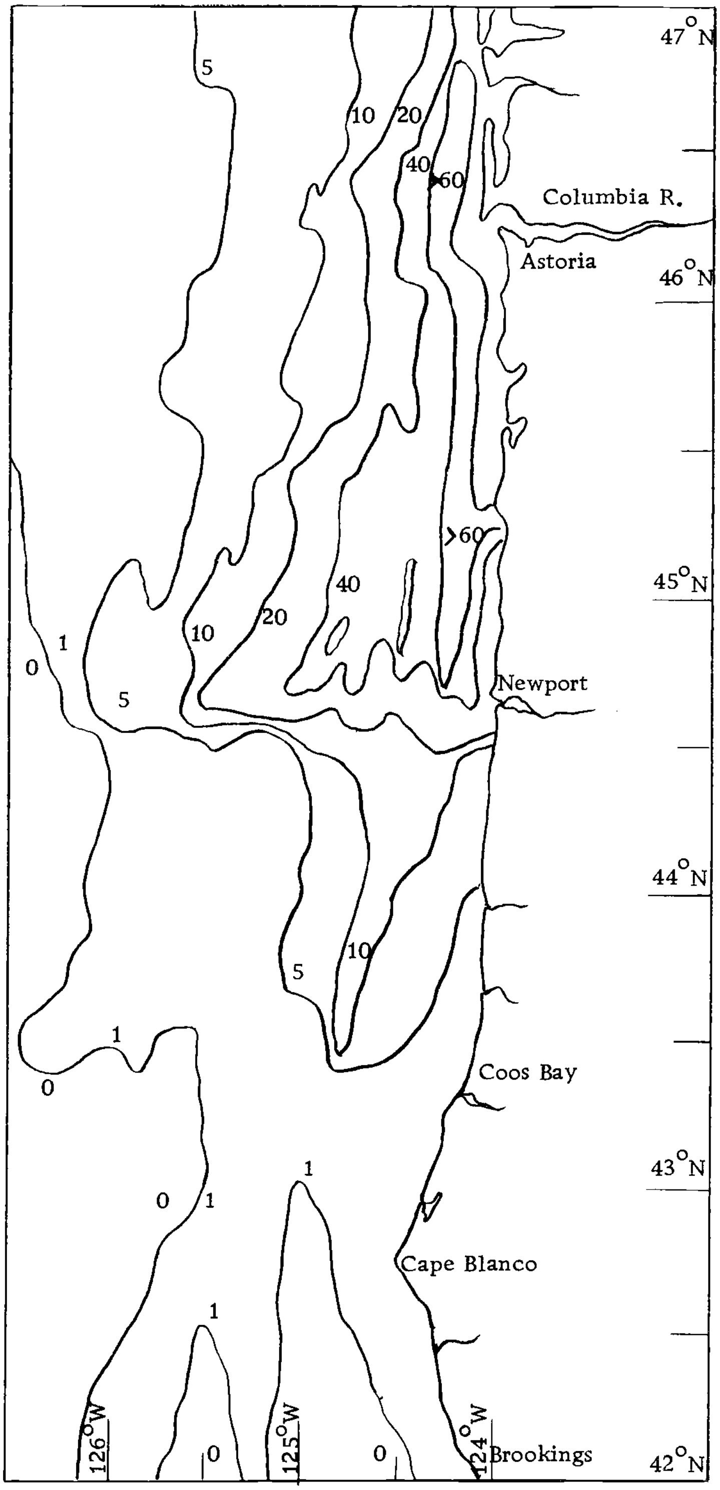


Figure 6. Isolines of Number of Tracks at Grid Points.

to fill a void point.

A large part of the main program, lines 130 through 266, is devoted to performing these two-dimensional interpolations.

Smoothing the u, v Fields

The mean current field obtained after interpolation showed obvious small scale discontinuities in both speeds and directions. These discontinuities are due to sparsity of data, variation in the currents over the data period, and 'bad' data that was not rejected. The following 5-point smoothing operator is applied to smooth the u and v components

$$X_{ij}^{k+1} = (X_{ij}^{k} + (X_{i+1,j}^{k} + X_{i-1,j}^{k} + X_{i,j+1}^{k} + X_{i,j-1}^{k})/4)/2$$

where X is either the u or v component, and k indicates the number of smoothing pases $k = 0, 1, 2, \cdots$. The 5-point smoothing operator is not applicable at the boundaries, and a 3-point operator is used at the northern and southern boundaries, namely,

$$X_{i1}^{k+1} = (X_{i1}^{k} + (X_{i+1,1}^{k} + X_{i-1,1}^{k})/2)/2$$

$$X_{i60}^{k+1} = (X_{i60}^{k} + (X_{i+1,60}^{k} + X_{i-1,60}^{k})/2)/2$$

Similar 3-point operators are applied to the meridional boundaries and at the corner points.

The spatial filtering resulting from the application of such operators is described by Dingle and Young (1965). It was found that three passes with the filter were sufficient to remove features considered spurious. The program applying these operators is given in Appendix II.

Divergence and Vorticity Fields

The finite-difference relation used to compute horizontal divergence is

$$(\mathrm{Div}_h \vec{V})_{ij} = (U_{i+1,\,j} - U_{i-1,\,j})/2\Delta X + (V_{i,\,j-1} - V_{i,\,j+1})/2\Delta Y$$

where distance between adjacent grid points in the y (northward) and x (eastward) directions are $\Delta Y = 5.0$ nautical miles and $\Delta X = \Delta Y \cos L = 3.5$ nautical miles respectively. Using smoothed values of the u, v field, the mean divergence computed for the entire grid is $3.8 \times 10^{-4}\,hr^{-1}$. Assuming a mixed layer depth of 100 meters, this divergence corresponds to a mean upward velocity through the thermocline of nearly 1 meter/day. This result is probably meaningless, however, as over this large area the divergence should be nearly zero or perhaps slightly negative due to the coast lying to the right of the winds during this fall-winter season.

Since the magnitude of horizontal divergence in the ocean is typically an order of magnitude smaller than either term in the horizontal divergence expression (Arthur, 1965), an error of only 10%

in the u and v components may result in meaningless values for the calculated divergence. The erroneous result may also be due in part to the fact that the bottles were released within a small area of the total grid so as they disperse with a "random walk" component (i. e. spread throughout the total grid area), they appear to indicate the presence of positive divergence of the current field. The apparent divergence due to diffusion can be roughly calculated as follows. If bottles are released off a meridional coast between 42°N and 47°N, a distance $Y = 300$ nautical miles, then due to Joseph and Sendner type diffusion (Joseph et al., 1962) they will be located along a distance increased by about $\delta Y = 4p\delta t$ after a time interval δt. The apparent divergence (with p = 1.5 cm/sec) is therefore

$$\frac{\partial V}{\partial Y} = \frac{1}{Y}\frac{\delta Y}{\delta t} = \frac{4P}{Y} = 4 \times 10^{-4}\, hr^{-1}$$

This value is fortuitously close to the calculated mean divergence of $3.8 \times 10^{-4}\, hr^{-1}$.

The vertical component of relative vorticity is calculated by the expression

$$(\mathrm{Curl}_z \vec{V})_{ij} = (V_{i+1,\,j} - V_{i-1,\,j})/2\Delta X - (U_{i,\,j-1} - U_{i,\,j+1})/2\Delta Y$$

The mean value of vorticity derived from the smoothed u, v field is approximately $8.0 \times 10^{-5}\, hr^{-1}$. The meridional distribution of vorticity is shown in Figure 7. The vorticity calculation is not

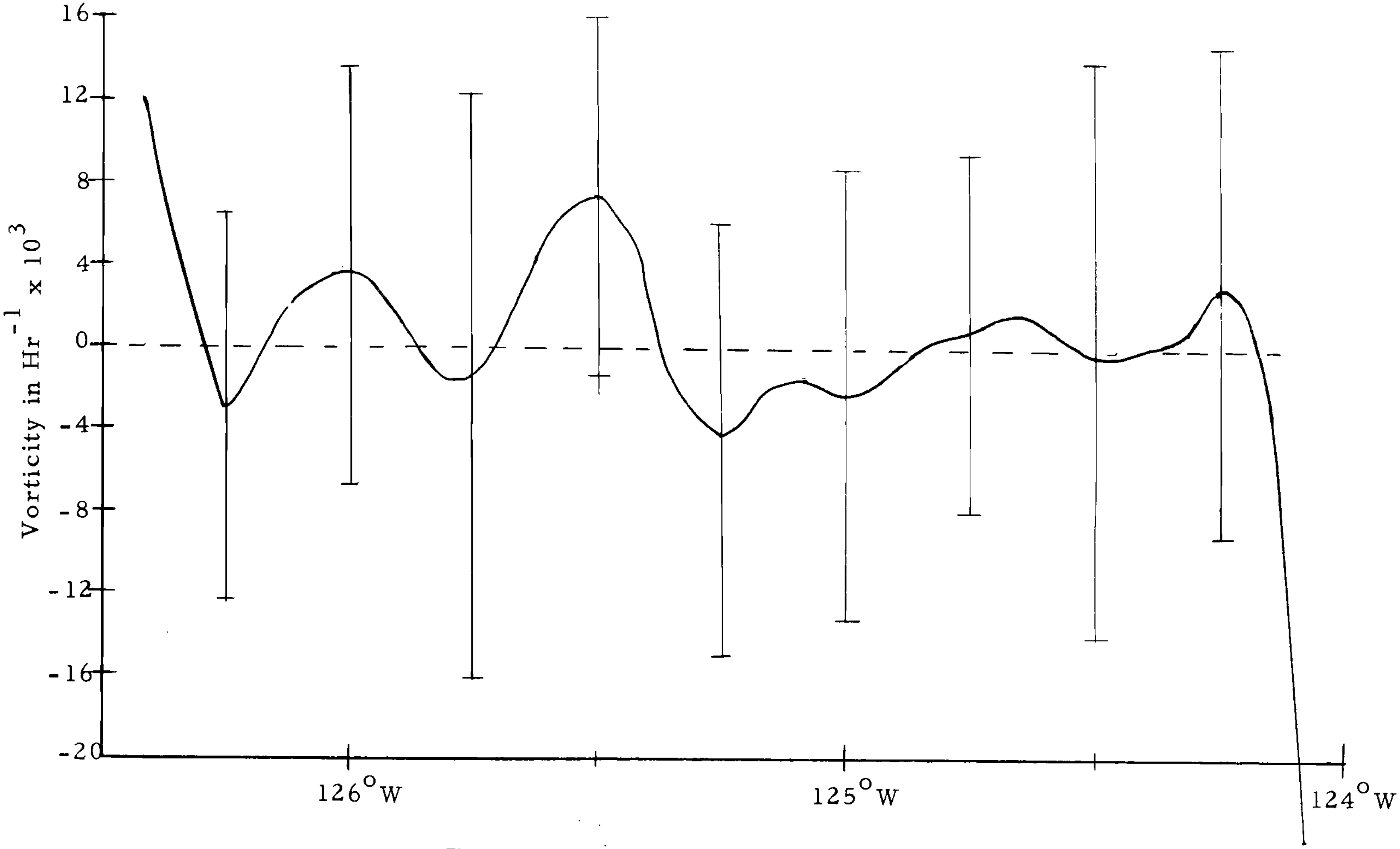


Figure 7. Meridional Mean Vorticity

subject to the errors of the divergence calculation, and the vorticity distribution obtained appears to be reasonable. It is interesting to note the large negative vorticity near the coast which may be ascribed to the frictional interaction of northward flow with the coast to the east.

Zonal and Meridional Averages

Zonal averages were computed by summing non-interpolated mean values along latitude, j, and then dividing by the number of terms in this sum. That is, they are calculated by

$$X_j = (\sum_i X_{ij}) / \sum_i 1$$

where X_{ij} denotes a smoothed grid point value (e.g., V), and the summations are only over those i for which N_{ij}, the number of tracks through the point i, j, is non-zero. If interpolated values had been included in summations, the data values on which the interpolations are based would have effectively received greater weight than other data values. While the zonal averaging employed here does not involve constant meridional weighting, the weighting is much more uniform than if each track passing latitude j had been weighted equally. That is the average formed by weighting all data equally

$$(\sum_i X_{ij} N_{ij}) / \sum_i N_{ij} \quad \text{--- (summed over all i)}$$

would, as a consequence of the higher N_{ij} nearshore (see Figures 5 and 6), weight the nearshore area more heavily.

The standard deviation about the mean is computed by

$$\sigma_{Xj} = \{[\sum_i (X_{ij} - X_j)^2] / [(\sum_i 1) - 1]\}^{1/2}$$

where summation is again only over those i for which $N_{ij} \neq 0$.

A similar method is applied for the computation of the meridional averages X_i and the standard deviation about these averages.

The computer program for the calculation of the zonal and meridional averages and their standard deviations is given in Appendix 3.

Figure 8 shows the variation with latitude of zonally averaged meridional velocity (v). Standard deviations associated with averages at intervals of 30' latitude are also shown in this figure. Figure 9 shows the variation with latitude of zonally averaged zonal velocity (u). Figures 10 and 11 show the variations of the meridionally averaged u and v components with latitude. A discussion of these variations will be given later.

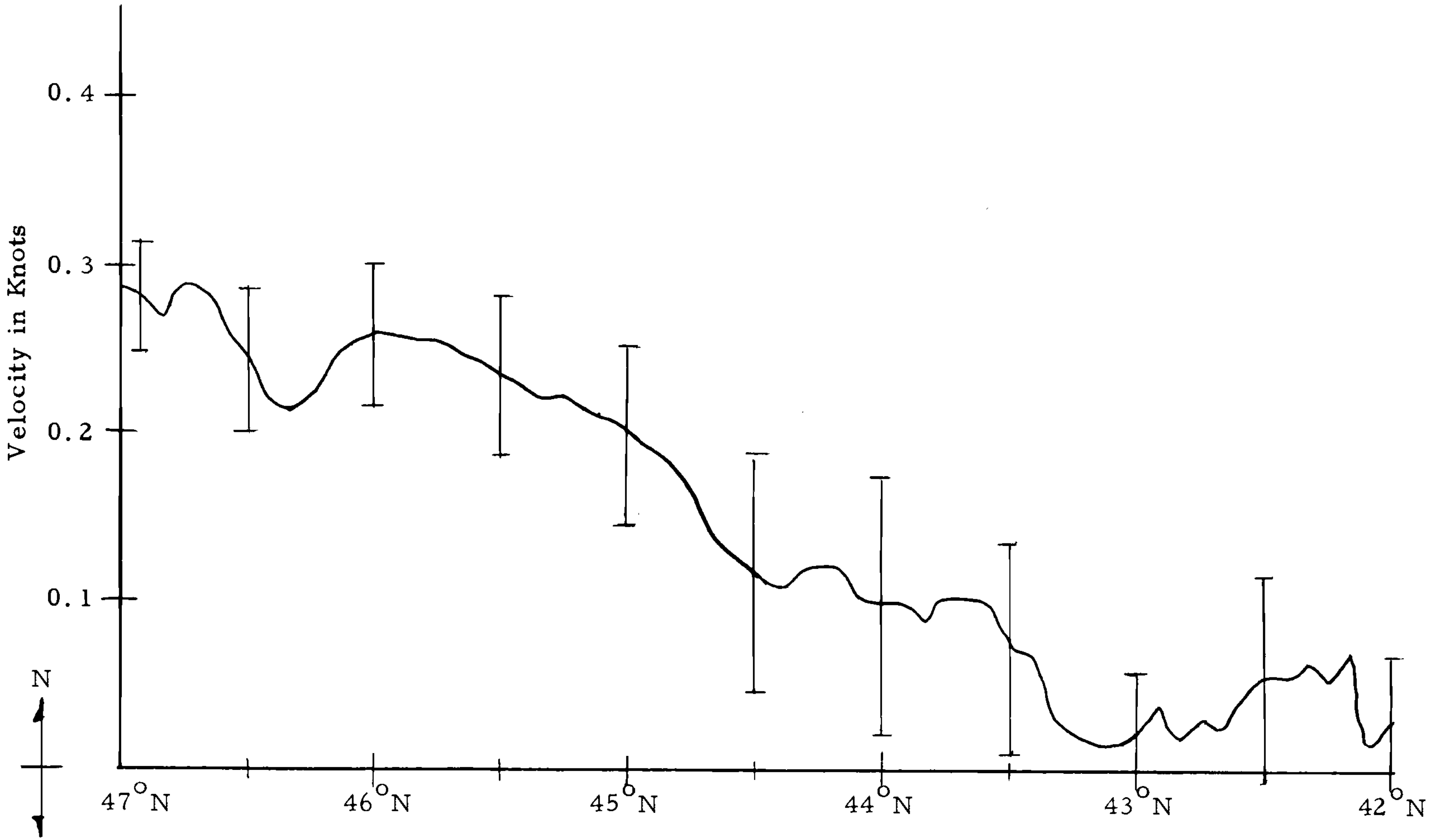


Figure 8. Distribution of Mean Meridional Velocity Component with Latitude

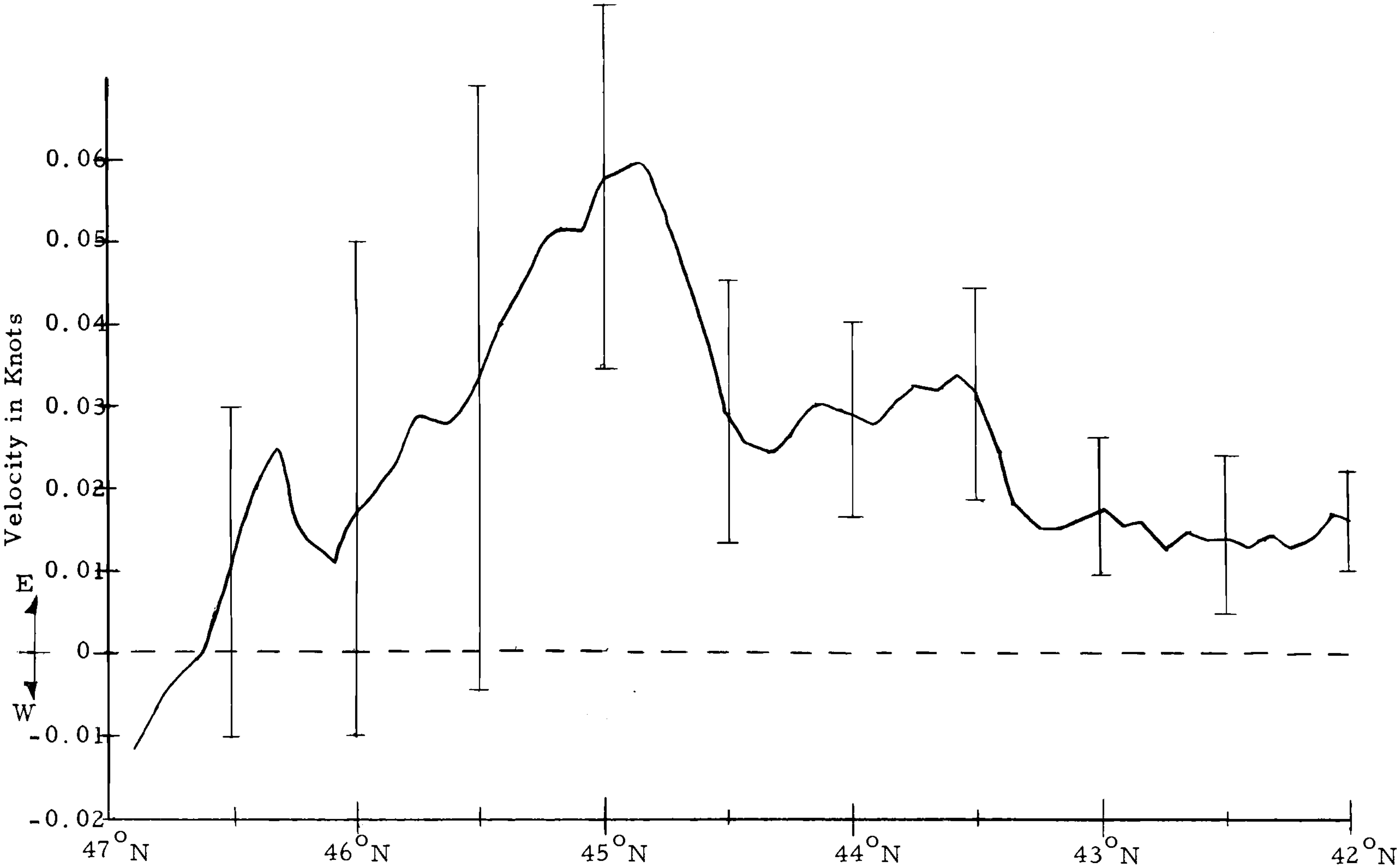


Figure 9. Distribution of Mean Zonal Velocity Component with Latitude

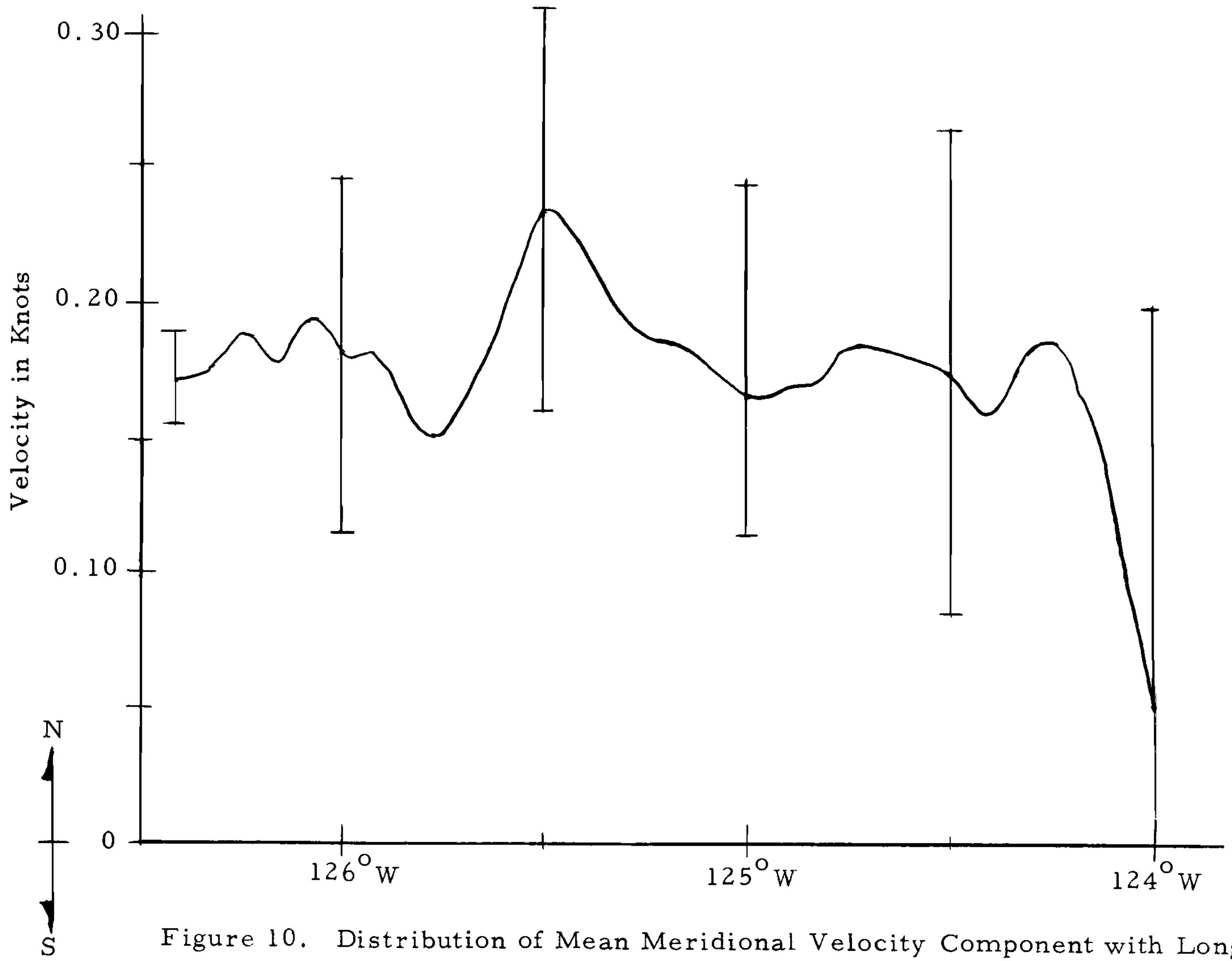


Figure 10. Distribution of Mean Meridional Velocity Component with Longitude

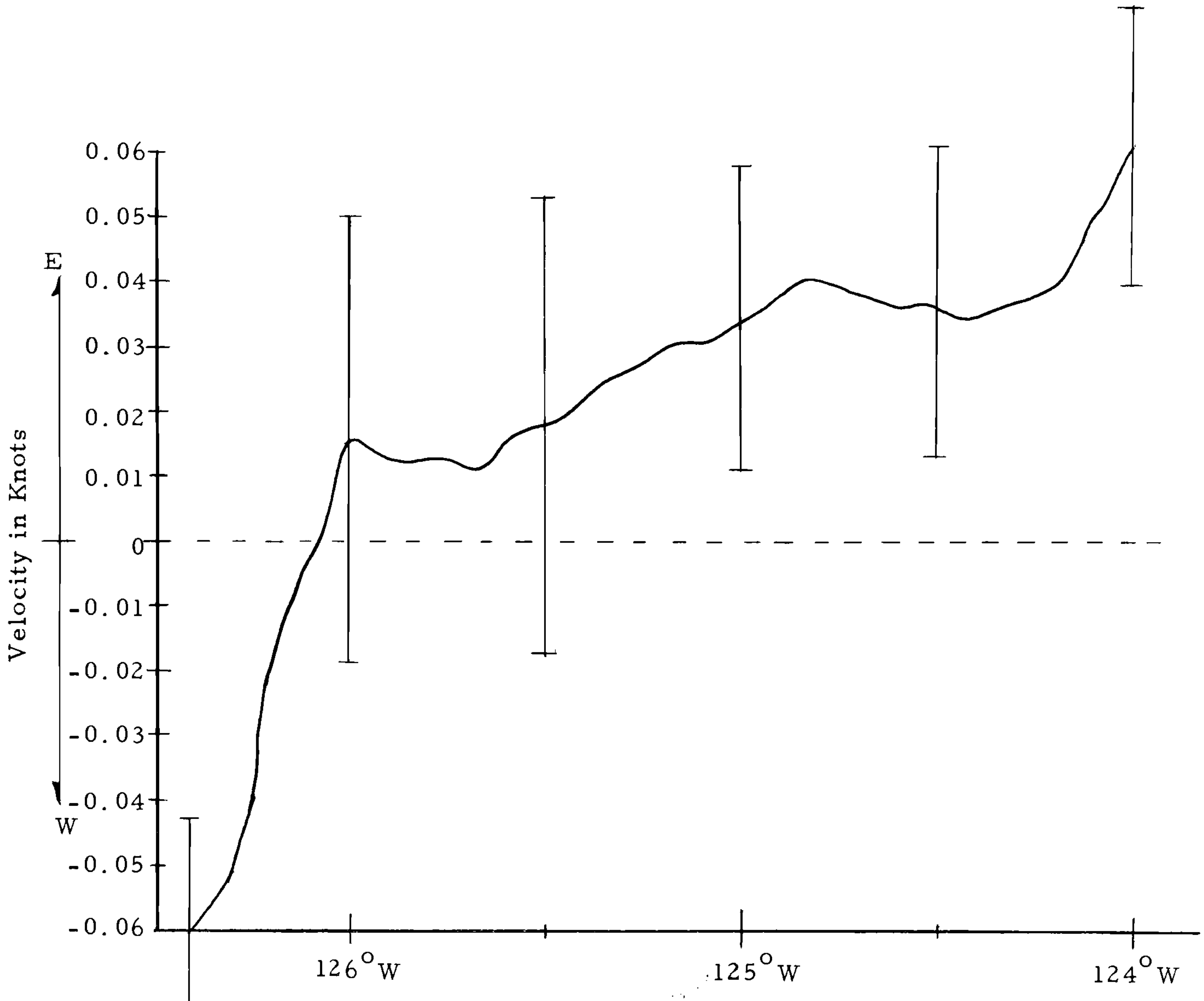
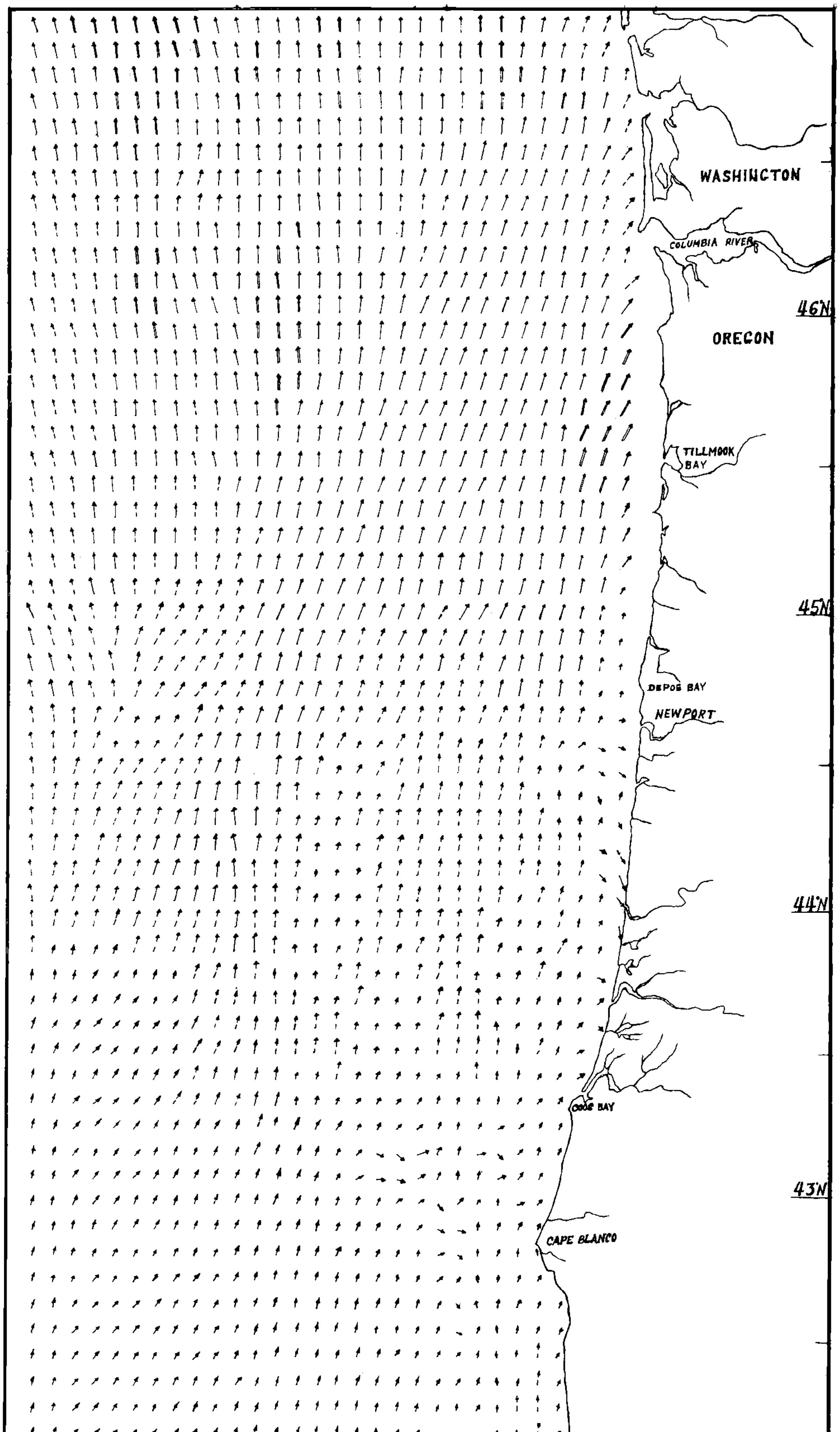


Figure 11. Distribution of Mean Zonal Velocity Component with Longitude

RESULTS AND DISCUSSION

The Mean Current

The computed mean surface flow field during the fall-winter season is shown in Figure 12. Arrows indicate the vector mean speeds and directions at the grid points. The overall flow as shown in this chart and the chart of streamlines, Figure 13, is predominantly northward. This is in agreement with tracks for each month from October through February in the years 1961-1970 (Wyatt, et al., 1971). However, dominant southward flow during October off Oregon was found prior to this drift bottle study by other measurements. The Atlas of Surface Currents of the Northeastern Pacific Ocean (USNHO, 1947) shows that southward flow is dominant off Oregon during October and northward only from November through February. The mean currents shown in this Atlas were compiled from over a hundred years of ship reports prior to 1935. Propeller type current meter measurements made by Marmer (1926) at the Astoria Lightship and at Umatilla Reef Light Vessel during 1919 also indicate a southward flow during October. Perhaps there has been a major change of the Davidson-California Current System in the past forty years or so. Huang (1972) found significantly more eastward transport and less southward transport off California during the years 1958-59 than during the previous


WASHINGTON
COLUMBIA RIVER
OREGON
TILLMOOK BAY
DEPOE BAY
NEWPORT
COOS BAY
CAPE BLANCO
BROOKINGS
46°N
45°N
44°N
43°N
42°N
126°W
125°W
124°W

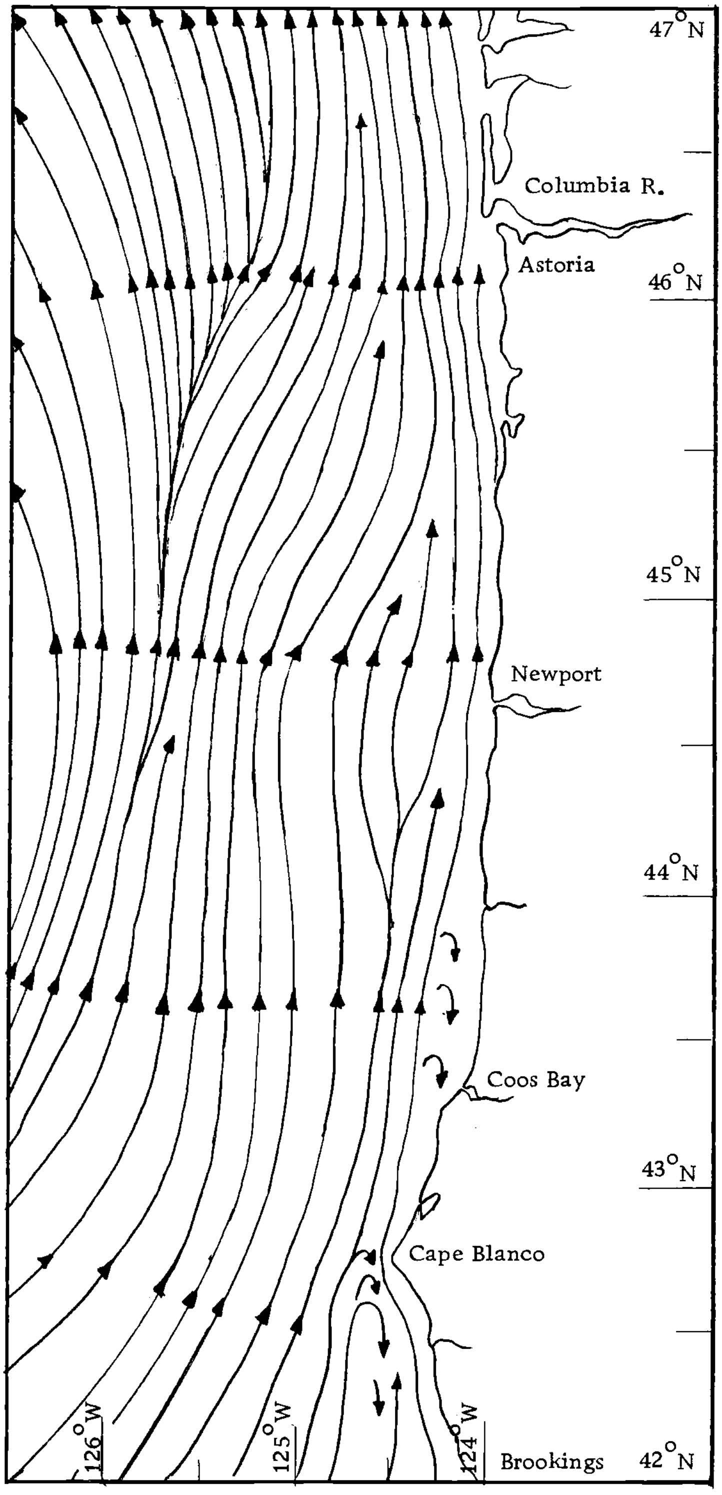


Figure 13. Stream Lines of Mean Surface Flow Field.

decade. Huang believes these decadal variations in total transport may have arisen largely from variations in the Davidson Current brought about by the anomalous atmospheric circulation during 1957-58 (Namias, 1959). It is interesting to note from Huang's calculations that the only significant change in sign of meridional transport near San Diego between these two decades occurred in September.

The mean speed of the whole study area is 0.15 knots with a mean zonal component of 0.02 knots and meridional component of 0.14 knots. This vectorial mean value of the surface current is apparently lower than other measurements of current off the Oregon Coast. Collins (1968) found a mean current speed of 0.37 knots at 20 meters depth from current meter measurements off Depoe Bay in October, 1965. Stevenson's drogue measurements (1966) off Newport indicate a vector mean current speed of 0.28 knots at 10 meters depth. These drogue measurements were conducted largely within 45 miles of Newport during the period 1962-1965. The low value of mean surface current speed in the drift bottle study presented here is due in part to vectorially averaging coastal currents of variable directions during the ten fall-winter seasons. In addition, mean speeds calculated under the assumption of straight-line trajectories of drift bottle are low, as the actual routes are probably quite circuitous. The inevitable time lapse between beaching and recovery of bottles also contributes to the low computed speed.

For the reasons given above, some reservation must be placed on the interpretation of drift bottle data. Nevertheless, drift bottle data have proven valuable. For example, the atlas by Bumpus and Lanzier (1965) showing the surface circulation on the continental shelf off eastern North America between Newfoundland and Florida, the study of the Davidson Current off Oregon by Burt and Wyatt (1964) and by Wyatt et al. (1972) and numerous other fruitful current studies are based on drift bottle measurements. The limitations of other forms of surface current determination should be kept in mind. Hydrographic determinations provide only relative baroclinic currents, while the surface drift currents may be several times greater. Current meter measurements provide mean Eulerian velocities which, because Stoke's velocity is not included, may be several times smaller than the actual mean velocity of a drifting object (Longuet-Higgins, 1969). Ship drift data are plagued with large navigation and wind drag errors. Surface drogue data corrected for wind drag are valuable, but like the other types of current data they are very sparse. In fact, the only available chart showing the surface currents in the study area off Oregon in any detail is the atlas (USNHO, 1947) of 1° square averages based on ship drift data prior to 1935.

Variation of current speeds in the study area are shown in Figure 12, the chart of flow field, in Figure 14, the isolines of speed, and in Figure 15, the distribution of zonally averaged speeds with

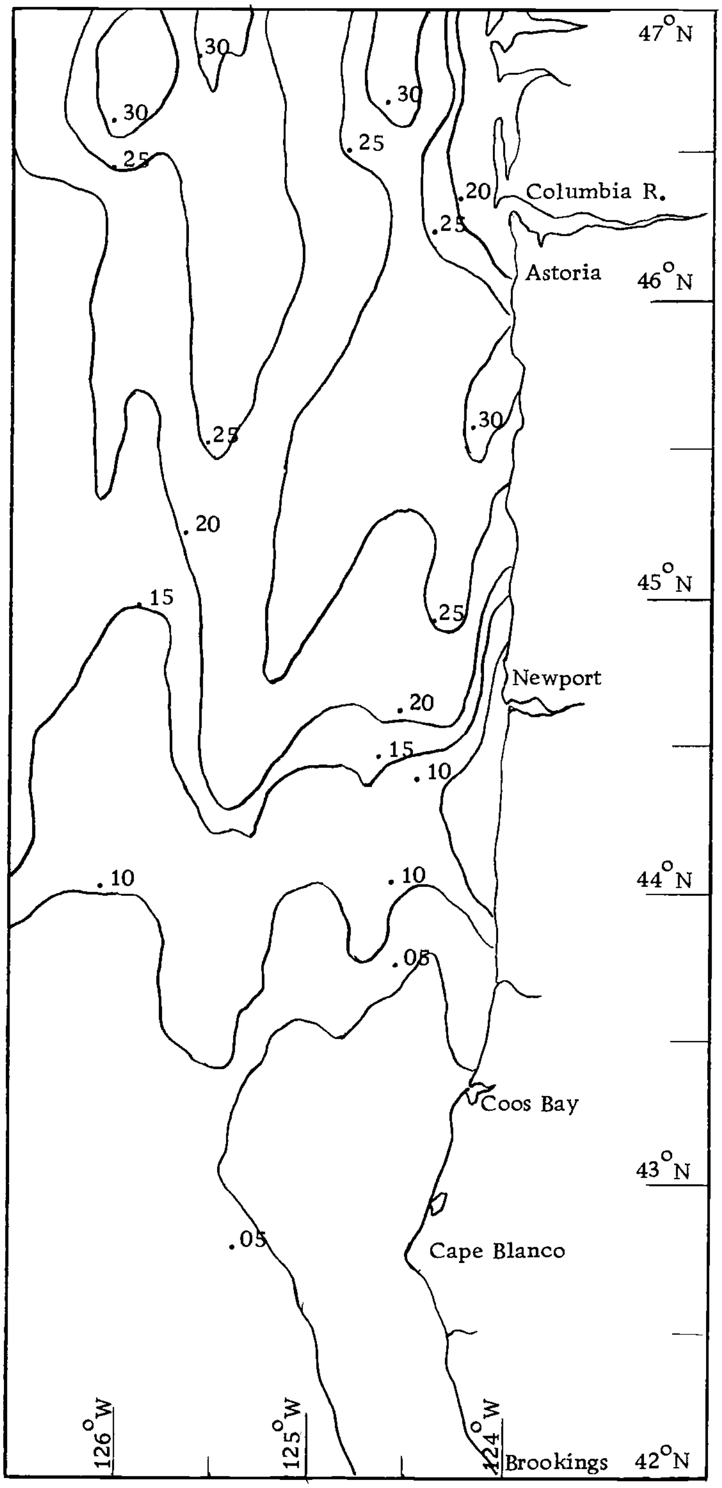


Figure 14. Isotachs of Mean Surface Currents in Knots.

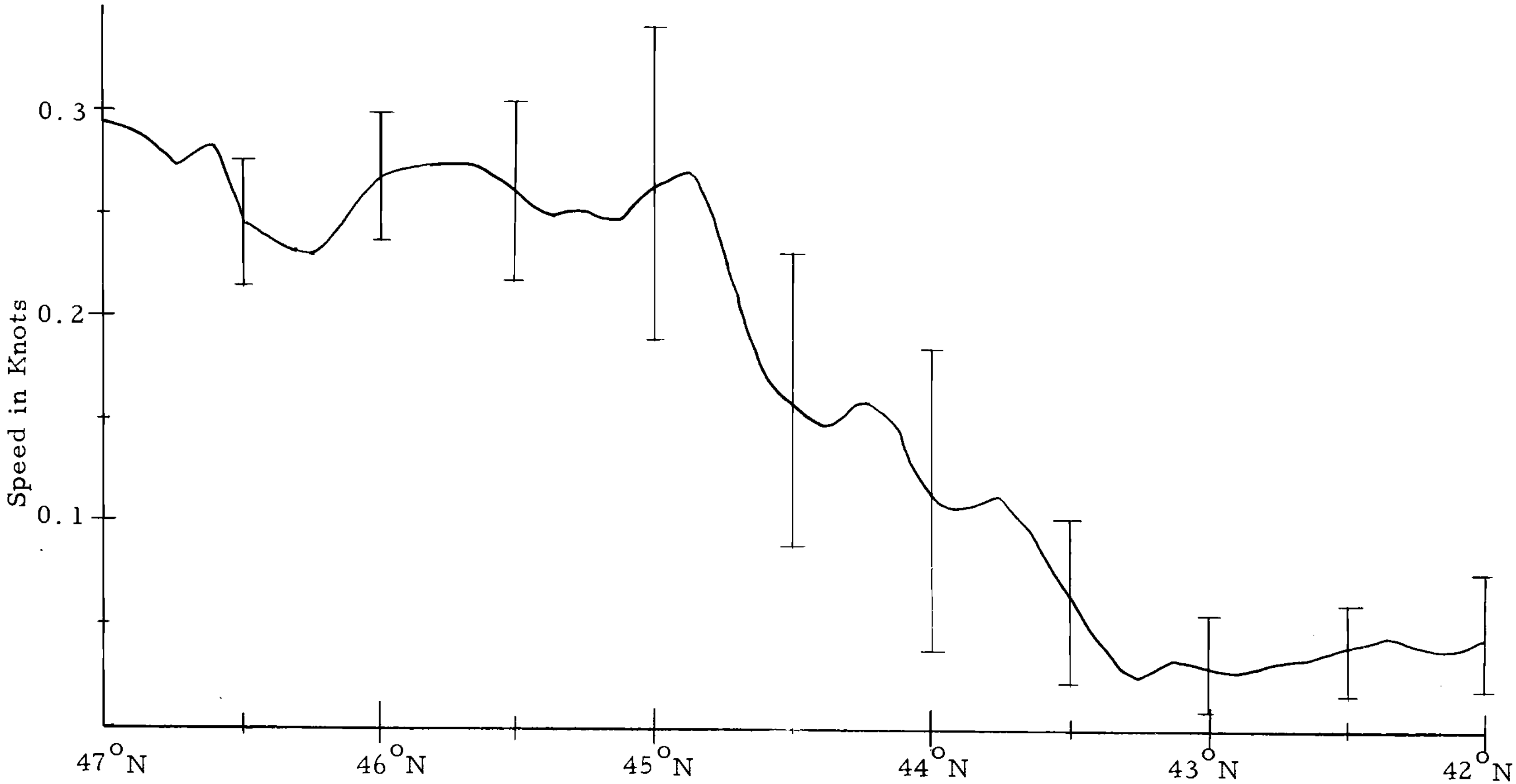


Figure 15. Distribution of Mean Speed with Latitude

latitude. The current speed increases from the south to the north off the Oregon Coast. This may be a consequence of the increase in speed of southerly winds from south to north in the study area during the fall-winter period (Duxbury, et al., 1965). The maximum speed of 0.35 knots is to the north of the Columbia River mouth, while the minimum speed of 0.01 knots is found off Cape Blanco. The highest speeds may be associated with the Columbia River discharge, and the low vector mean speeds in the southern portion of the study area with variable current directions.

The meridional velocity increases almost linearly out from the coast to a distance of 10 nautical miles as shown in Figure 11. This may indicate a frictional boundary layer, or it may arise from the low speed and southward flow found near the coast in the southern position of the study area.

The latitudinal variations of zonal velocity, as shown in Figure 9, indicates that the average zonal flow is onshore, except northward of 46°30'N. The westerly flow north of 46°30'N may be due to the Columbia River discharge (Marmer, 1926; Brunsen, 1972), or to the westward extension of the land north of this latitude.

The high onshore velocity indicated at 44°50'N, the latitude of Depoe Bay, may be an artifact related to the large number of bottles released along the Newport line (see Figure 1). Diffusion, or "random walk" of bottles, can introduce such an apparent onshore flow component. Consider a group of bottles released at some point in an ocean of zero mean velocity and horizontally isotropic turbulence. The bottles will be distributed within a more or less circular patch that increases in size with time. Bourret et al. (1960) have shown that for horizontal diffusion of the form described by Joseph and Sendner (1958), the mean distance from the centroid varies as

$$\frac{d\langle r\rangle}{dt} = 2p$$

where p is the Joseph and Sendner "diffusion velocity" and has a value of about 1.5 cm/sec in the open ocean (Okubo, 1969). If this ocean is bounded only by an infinite straight coast, bottles recovered directly shoreward of the release point will have an apparent average onshore velocity component 2p. Those bottles recovered at great distances along the coast from the release point will have an apparent onshore velocity near zero. As we assume the bottles spread out in uniform directions from the release point, the mean shoreward component is

$$\frac{2}{\pi}\int_0^{\pi/2} 2p\sin\theta\, d\theta = \frac{4}{\pi}\, p\,,$$

or about 2 cm/sec. Thus we can assume the mean zonal velocities calculated here may be biased by about 2 cm/sec (i.e. 0.04 knots). Since the linear density of recoveries would be greatest directly onshore of the release point, the bias would be greatest at the latitude of release. For an ocean with a mean northward velocity, the bias would be greatest northward of the release point. This appears to be the case shown in Figure 9, at least for those station lines having a large quantity of data: the peak onshore velocity at $44^{o}50'$N is north of the Newport line ($44^{o}39'$N), and the peak at $43^{o}35'$N is north of the Coos Bay line ($43^{o}20'$N). As the bias thus varies with latitude and is comparable to the values shown in Figure 9, the zonal averages of zonal velocity actually may not differ significantly from zero.

RECOMMENDATIONS FOR FURTHER STUDIES

Investigation of Temporal Variations

It has been tacitly assumed here that month to month variations of velocity within the fall-winter season are negligible and that year to year variations are also negligible. This assumption should be tested for all release stations. These tests may indicate data for some period should be excluded from the computations and they will provide a measure of confidence in the computed mean velocities.

Extension of Computational Method

The following extension of the computational method should provide a more accurate representation of the surface current field. The extension does this by weighting nearshore velocities most heavily with data from nearshore releases, and by compensating offshore releases for velocity variations between the release stations and the coast.

A mean current field is first computed as previously described. Using release-recovery data from stations nearest the coast, bottle velocities are then assigned to grid points lying along the tracks between these release stations and the coast (neglecting the previously computed mean velocities at these points). Grid points between the stations and the coast which do not lie along any track may retain the original mean values or be assigned new values through meridional interpolation.

Next, using the bottle recovery data from stations just offshore of the stations nearest the coast, and using the grid point velocities between the coast and the latter stations, compute for each bottle the location and the time at which it would be found at a distance from the coast equal to that of the nearest stations. These computed bottle locations and times are then used as "recovery" data for releases from the stations just offshore of the stations nearest the coast. The bottle velocities calculated from this release "recovery" data is assigned to those grid points lying along tracks between the release stations and "recovery" locations. Those grid points not assigned velocities by the above procedure and situated between the stations nearest to the coast and next-to-nearest to the coast may either retain the original mean values or be assigned new values through interpolation. The choice of retaining original values or using interpolated values might be made on the basis of the number of successive points not lying along tracks, or one could employ a weighted average of original and interpolated values.

Then, using recovery data from the third stations offshore and the velocities between the second stations offshore and the coast, times and locations of bottle "recoveries" at the offshore distance of the second stations are determined. Bottle velocities are then determined and assigned to those grid points lying along the directions of these velocities between the third offshore release stations and "recovery" locations situated at the distance of the second stations from the coast. Again the grid points between the release stations and "recovery" distances from the coast that do not lie along a track may either maintain the original values or be assigned new values through interpolation.

The procedure described above is continued out to the stations farthest from the coast. The mean velocity field calculated in this way should more closely resemble the actual field, especially if the actual field has strong spatial variations.

Investigation of Diffusion

Previous research using drift bottle data has apparently been confined to investigating mean surface advection; this information can be used to determine the most probable location of a drifting object, such as a life raft. It has been recommended that temporal (e. g. year to year) variations of velocity be investigated also. With this additional information the probability of locating a drifting object within some area can be estimated. Such an estimate is required for an efficient search for a drifting life raft whose position at some previous time is known. The following research on diffusion of drift bottles is recommended to provide information on the probability of floating objects being within some area if they were close together at an earlier time. This information is important during search and rescue operations when one life raft is located and other life rafts are to be found. While diffusion has been studied with drifting objects, drift bottle data have apparently not been used. Probably this is because drift bottle data includes no information between release and recovery. Tracking drifting objects, such as drogues, with a ship or a plane is expensive and data can be obtained in this manner only during low sea state conditions.

It is recommended that drift bottle data be employed in the following manner to investigate diffusion. Each group of bottles released simultaneously at each station is to be treated separately. From the recovery data for bottles of each group, mean time until recovery, mean length of the straight line track and the angle between this track and the coastline can be determined. The longshore distances of individual recoveries within each group from the intersection of the mean track with the coastline can be computed. The spreading of these distances along the coast due to an acute angle (θ) between the mean track and the coastline can be removed by multiplying the distances by $\sin\theta$. Sets of these corrected distances can then be combined within similar classes of mean track length and similar classes of mean time between release and recovery. The standard deviations of corrected distances along the coast can be determined for all classes. Making the usual assumption that the two-dimensional distribution of a cluster of bottles at sea is Gaussian, these are the standard deviations of the two-dimensional distributions just before arriving at the coast. A plot of the standard deviation of a cluster versus mean track length class then may be viewed as the spreading with distance traveled of any group of drifting objects released together simultaneously. Similarly, a plot of the cluster standard deviation versus time between release and recovery can be interpreted as indicating the expected spreading with time of any group of floating objects released together simultaneously.

Autoplot of Current Chart

The hand plotting of arrows of the mean current chart (Figure 12) is tedious and time consuming. Automatic plotting of arrows by computer is not generally available. Even the plotting of streamlines by a computer requires sophisticated programming (Dartt, 1972). Computer plots of isolines of stream function may be readily obtained with a contouring program once the grid points are assigned stream function values. The problem here arises with determining the stream function field, for this field can only be defined in terms of the horizontally non-divergent part of the flow field. Progress has been made toward solving this program (Hawkins *et al.*, 1965), and should a satisfactory solution become available it is recommended that it be employed to represent the surface current field computed from drift bottle data.

SUMMARY AND CONCLUSION

The analytical method used in this study is a new approach to the determination of currents by use of drift bottle data. The method was applied to bottles released off Oregon. Selection of the data and study area were based on existing knowledge of the surface currents off Oregon and the distribution of bottle tracks. Speed and direction of each bottle were computed by the Mercator Sailing Method, and velocity components were assigned to numerical grid points lying along the straight line track between the release and recovery points. Grid points lying along two or more tracks were assigned average values. Grid points not assigned values by this procedure were assigned values through two-dimensional interpolation. Small scale irregularities in the velocity field were attenuated by smoothing. The smoothed mean velocity field was then used to form vorticity and divergence fields and compute zonal and meridional averages. Computer programs to perform the above calculation are included as Appendices I, II and III. The surface currents are represented in various charts (Figures 12, 13 and 14) showing the spatial distribution of currents off Oregon. It is believed that more of the information contained in drift bottle data has been extracted by the analytical method employed in this research than the methods that have been used in the past.

The mean currents based on the smoothed u, v fields for the fall-winter season have a predominantly northerly flow component with speeds increasing from the south to the north (from 0.01 knots to 0.35 knots). This probably is related to the increase in speed of southerly winds from south to north in the study area during the fall-winter period. The northerly flow of the Davidson Current in October during the years 1961-70, as compared with the dominant southerly flow during this month prior to 1935, shown in the Atlas of Surface Current of the Northeastern America (USNHO, 1947), may indicate a major change of Davidson-California System within the past forty years or so. The average zonal flow is apparently onshore, except northward of $46^{\circ}30'$N. Diffusion of bottles may introduce such an apparent onshore flow component, while the Columbia River discharge and the westward extension of the land north of $46^{\circ}30'$N may give rise to the westerly flow. The mean current charts appear to be useful in navigation, planning for waste disposal and other practices affected by the surface current field off Oregon.

Errors in the mean surface currents during the fall-winter season are introduced through the analytical method and the assumption of negligible temporal variations within this season and during the ten years of this season. Further studies are recommended to investigate both temporal variations and diffusion, and to improve the analytical method by compensating for spatial velocity variations and by employing computer autoplotting.

BIBLIOGRAPHY

Arthur, R. S. 1965. On the calculation of vertical motion in eastern boundary currents from determinations of horizontal motion. Journal of Geophysical Research 65(5):2799-2803.

Bowditch, N. 1962. American practical navigator. U.S. Navy Hydrographic Office, Pub. No. 9. 1524 pp.

Brunsen, B.A. 1973. Steric contributions to the seasonal oscillation in sea level off Oregon. M.S. thesis. Oregon State University, Corvallis. 75 pp.

Bourret, B. and S. Broida. 1960. Turbulent diffusion in the sea. Bulletin of Marine Science of the Gulf and Caribbean 10(3):354-364.

Bumpus, D. and L. Lauzier. 1965. Surface circulation on the continental shelf eastern Northern America between Newfoundland and Florida. American Geographic Society serial Atlas of Marine Environment, Folio 7.

Burt, W. and B. Wyatt. 1964. Drift bottle observations of the Davidson Current off Oregon. Studies on Oceanography, University of Tokyo Press. 156-165.

Collins, C.A. 1968. Descriptions of measurements of current velocity and temperature. Ph.D. Thesis, Oregon State University, Corvallis. 154 pp.

Dartt, D.G. 1972. Automated streamline analysis utilizing "optimum interpolation". Journal of Applied Meteorology 11(9):901-908.

Dingle, A.N. and C. Young. 1965. Computer applications in the atmospheric sciences. University of Michigan, Ann Arbor.

Duxbury, C.A., Betty-Ann Morse and N. McGary. 1965. The Columbia River effluent and its distribution at sea, 1961-1963. Technical Report No. 156. University of Washington, Seattle, Washington.

Huang, Joseph C.K. 1972. Recent decadal variation in the California Current system. Journal of Physical Oceanography 2(10):382-390.

Howkins, H. F. and S. L. Rosenthal. 1965. On the computation of stream functions from the wind field. Monthly Weather Review 93(4):245-252.

Joseph, J. and H. Sendner. 1962. On the spectrum of the mean diffusion velocities in the ocean. Journal of Geophysical Research 67(8):3201-3205.

Lee, Kuo-heng. 1967. Geopotential anomaly and geostrophic flow off Newport, Oregon. M.S. thesis. Oregon State University, Corvallis. 40 pp.

Longuet-Higgins, M.S. 1969. On the transport of mass by the time-varying ocean currents. Deep-sea Research 16(5):431-447.

Marmer, H.A. 1926. Coastal currents along the Pacific coast of the United States. Washington. 91 pp. (U.S. Coast and Geodetic Survey. Special publication No. 121)

Namias, J. 1959. Recent seasonal interactions between north Pacific water and the overlying atmospheric circulation. Journal of Geophysical Research 64(6):631-646.

Okubo, A. 1962. A review of theoretical models for turbulent diffusion in the sea. Journal of the Oceanographical Society of Japan, 20th anniversary volume, 1962. 286-320.

Okubo, A. and D. W. Pritchard. 1969. Summary of our present knowledge of the physical processes of mixing in the ocean and coastal waters and a set of practical guidelines for the application of existing diffusion equations in the preparation of nuclear safety evaluations of the use of nuclear power sources in the sea. Technical Report NYO-3169-40. Chesapeake Bay Institute. The Johns Hopkins University.

Schwartzlose, R.A. 1964. Nearshore currents of western United States, Baja, California, as measured by drift bottles. CALCOFI Progress Rept. 1, July 1960-June 1962, California Dept. of Fish and Game, Sacramento, 15-22.

Stevenson, M.R., J.G. Pattullo and B. Wyatt. 1969. Subsurface currents off the Oregon coast as measured by parachute drogues. Deep-Sea Research 16(5):449-461.

Sverdrup, H. U., M. Johnson and R. H. Fleming. 1942. The oceans. New York, Prentice-Hall, 1087 pp.

United States Naval Hydrographic Office. 1957. Pilot Chart of the North Pacific. Washington, D. C.

United States Naval Hydrographic Office. 1947. Publication No. 570. Atlas of the Surface Currents of the Northeastern Pacific Ocean. Washington, D. C.

Wyatt, B., D. A. Barstow, W. E. Gilbert and J. L. Washburn. 1971. Drift bottle recoveries and releases off the Oregon coast, 1961 through 1970. Data Report 50. Oregon State University, Corvallis, Oregon.

Wyatt, B., W. V. Burt and J. G. Pattullo. 1972. Surface currents off Oregon as determined from drift bottle returns. Journal of Physical Oceanography 2(3):286-293.

APPENDICES

APPENDIX I

MAIN PROGRAM - UVFIELD

Notes on Program UVFIELD

This program reads drift bottle data and generates fields of average speed SP(I, J), direction DIR(I, J), and the u and v components U(I, J) and V(I, J). In the present study these fields have the dimension (30, 60) and are in COMMON. Also in COMMON is N(I, J), the number of tracks passing grid points (I, J). The fields are generated in a rectangular area (expressed in minutes) and are defined in statements following COMMON. Statement 22 reads the drift bottle data: release year (NR), month (MO), latitude (LATA in degrees, ALM in minutes), longitude (LONA in degrees, AGM in minutes); recovery latitude (LATB in degrees, BLM in minutes), longitude (LONB in degrees, BGM in minutes); and number of days between release and recovery (DAY). Bottle data are rejected according to the criteria described in the text by lines 22 through 33.

Lines 39 and 40 call Function FMP (Appendix Ib) which converts latitudes to meridional parts. Function FDIR (Appendix Ia) is called in lines 51 and 107 to convert course angles into directions with respect to true north.

The WRITE statement of line 52 lists on the line printer the data not rejected. It also lists: number of data selected (KONT), distance between release and recovery in nautical miles (DIS), speed in knots (S), direction to true north (CRS), and velocity components in knots (UU and VV).

A 5 minute X 5 minute mesh size is employed in the present study. For another mesh size lines 55 through 60 would have to be changed, as well as the dimension of variables and the boundary initialization.

The "data" fields U(I, J), V(I, J) and N(I, J) are written on tape by statement 46. These fields and the fields SP(I, J) and DIR(I, J) are written on the lineprinter by lines 113 through 128.

Interpolation is performed in lines 130 through 266. If N(I, J) is zero the point (I, J) is first assigned velocity component value U(I, J) and V(I, J) through meridional interpolation and N(I, J) is set to 9999. The u, v velocity component fields resulting from this interpolation are printed out in lines 176 through 185. Then zonal interpolation is performed for those points with N(I, J) = 9999, stored in the dummy variables SP(I, J) and DIR(I, J), and N(I, J) reassigned the value zero. The u, v velocity component fields resulting from only this zonal interpolation are printed by lines 249 through 258. The means of the meridionally and zonally interpolated velocity components are then computed, as well as the corresponding speeds and directions. These two-dimensionally interpolated fields, as well as the field N(I, J), is punched on cards by statement 66 and printed out by lines 273 through 292.

```
      PROGRAM UVFIELD
      COMMON U(30,60),V(30,60),SP(30,60),DIR(30,60),N(30,60)
C--FIELD BOUNDARIES: NJA=LAT 47 N=2820 MIN;NJB=LAT 42 N=2520 MIN;
C--NIA=LONG 126 30 W=7590 MIN:NIB=LONG 124 W=7440 MIN
        NJA=2820
        NJB=2520
        NIA=7590
        FNIA=NIA
        FNJA=NJA
        FNJB=NJB
      DO 11 I=1,30
      DO 11 J=1,60
      U(I,J)=V(I,J)=SP(I,J)=DIR(I,J)=0.0
      N(I,J)=0
11    CONTINUE
C--SORT FOR DATA OF DRIFT BOTTLES RELEASED BETWEEN OCT-FEB,1961-1970
      L=1
      KONT=0
      WRITE(5,109)
22    READ(2,101)NR,MO,LATA,ALM,LONA,AGM,LATB,BLM,LONB,BGM,DAY
      IF(EOF(2))GO TO 99
      IF(MO.LE.2.OR.MO.GE.10)GO TO 1
C--   IF(MO.LE.8.AND.MO.GE.5) GO TO 1
      GO TO 88
1     KK=MO+3
      IF(MO.GE.10)KK=MO-9
      F=180-(KK-1)*30
      IF(DAY.GT.F)GO TO 88
      ALAT=60.*FLOAT(LATA)+ ALM
      ALON=60.*FLOAT(LONA)+AGM
      IF(ALAT.LT.FNJB.OR.ALAT.GT.FNJA)GO TO 88
      IF(ALON.GT.FNIA)GO TO 88
      KONT=KONT+1
C--COMPUTE VELOCITY COMPONENTS
      BLAT=60.*FLOAT(LATB)+BLM
      BLON=60.*FLOAT(LONB)+BGM
      DLAT=ALAT-BLAT
        DLON=ALON-BLON
      AMP=FMP(ALAT)
      BMP=FMP(BLAT)
      DM=AMP-BMP
      ANG=DLON/DM
      C=ABS(ATAN(ANG))
      DIS=ABS(DLAT/COS(C))
      TH=24.0*DAY
      S=DIS/TH
      UU=ABS(S*SIN(C))
      VV=ABS(S*COS(C))
      IF(DLAT.GT.0.0)VV=-VV
      IF(DLON.LT.0.0)UU=-UU
      CRS=FDIR(UU,VV)
      WRITE(5,100)KONT,NR,MO,LATA,ALM,LONA,AGM,LATB,BLM,LONB
     1,BGM,DIS,DAY,S,CRS,UU,VV
C--GENERATE TRACK,FIND I,J CLOSEST TO TRACKS
C--I=1,30 REPRESENT LONG. 126 30 W TO 124 00 W
C--J=1,60 REPRESENT  LAT.  47 00 N TO  42 00 N
        IA=(FNIA-ALON)/5.0
        IB=(FNIA-BLON)/5.0
        JA=(FNJA-ALAT)/5.0
        JB=(FNJA-BLAT)/5.0
      IF(BLON.GT.ALON)GO TO 2
      SLOP=DLAT/DLON
      IF(SLOP.LT.-1.0)GO TO 2
      IF(SLOP.GT.1.0) GO TO 201
      DO 33 I=IA,30
      K=I-IA
        J=FLOAT(JA)+SLOP*FLOAT(K)
        IF(J.LT.1.OR.J.GT.60)GO TO 33
      U(I,J)=U(I,J)+UU
      V(I,J)=V(I,J)+VV
      N(I,J)=N(I,J)+1
33    CONTINUE
      GO TO 88
2     DO 44 J=JB,JA
      SLOP=DLON/DLAT
      K=J-JB
        I=FLOAT(IB)+SLOP*FLOAT(K)
      IF(I.LT.1.OR.I.GT.30)GO TO 44
      IF(J.LT.1.OR.J.GT.60)GO TO 44
      U(I,J)=U(I,J)+UU
      V(I,J)=V(I,J)+VV
      N(I,J)=N(I,J)+1
44    CONTINUE
```

```
      GO TO 88
201   DO 444 J=JA,JB
      SLOP=DLON/DLAT
      K=J-JA
      I=FLOAT(IA)+SLOP*FLOAT(K)
      IF(I.LT.1.OR.I.GT.30) GO TO 44
      IF(J.LT.1.OR.J.GT.60) GO TO 44
      U(I,J)=U(I,J)+UU
      V(I,J)=V(I,J)+VV
      N(I,J)=N(I,J)+1
444   CONTINUE
88    L=L+1
      GO TO 22
C--COMPUTE MEAN U,V IN EVERY BLOCKS
99    DO 55 I=1,30
      DO 55 J=1,60
      IF(N(I,J).EQ.0)GO TO 45
      U(I,J)=U(I,J)/FLOAT(N(I,J))
        V(I,J)=V(I,J)/FLOAT(N(I,J))
      SS=(U(I,J)*U(I,J)+V(I,J)*V(I,J))
      SP(I,J)=SQRT(SS)
      UT=U(I,J)
      VT=V(I,J)
      DIR(I,J)=FDIR(UT,VT)
      GO TO 46
45    U(I,J)=V(I,J)=0.0
      SP(I,J)=DIR(I,J)=0.0
46    WRITE(3,107)U(I,J),V(I,J),N(I,J)
55    CONTINUE
      WRITE(5,108)
      WRITE(5,102)(I,I=1,30)
      WRITE(5,103)(J,(SP(I,J),I=1,30),J=1,60)
      WRITE(5,110)
      WRITE(5,102)(I,I=1,30)
      WRITE(5,105)(J,(DIR(I,J),I=1,30),J=1,60)
      WRITE(5,116)
      WRITE(5,117)(I,I=1,15)
      WRITE(5,118)(J,(U(I,J),I=1,15),J=1,60)
      WRITE(5,117)(I,I=16,30)
      WRITE(5,118)(J,(U(I,J),I=16,30),J=1,60)
      WRITE(5,119)
      WRITE(5,117)(I,I=1,15)
      WRITE(5,118)(J,(V(I,J),I=1,15),J=1,60)
      WRITE(5,117)(I,I=16,30)
      WRITE(5,118)(J,(V(I,J),I=16,30),J=1,60)
C--INTERPOLATE U,V FIELD VERTICALLY
        DO 4 I=1,30
        IP=0
        DO 3 J=1,60
        IF(J.LE.IP)GO TO 3
      IF(N(I,J).EQ.0.)GO TO 5
        GO TO3
5     IF(J.EQ.1) GO TO 7
        NN=0
        J1=J
        JM=J1-1
        DO 9 K=J1,60
      IF(N(I,K).GT.0)GO TO 10
        IF(K.EQ.60)GO TO 6
9       NN=NN+1
10      FN=NN+1
        JN=J1+NN
        DU=(U(I,JN)-U(I,JM))/FN
        DV=(V(I,JN)-V(I,JM))/FN
        DO 12 K=1,NN
        JJ=J1-1+K
        FK=K
        IP=J1+K
      N(I,JJ)=9999
        U(I,JJ)=U(I,JM)+FK*DU
12      V(I,JJ)=V(I,JM)+FK*DV
        GO TO3
6       NN=NN+1
        DO 13 K=1,NN
        JJ=J1-1+K
      N(I,JJ)=9999
        U(I,JJ)=U(I,JM)
13      V(I,JJ)=V(I,JM)
      GO TO 3
7     NK=0
      DO 8 L=1,60
      IF(N(I,L).GT.0) GO TO 14
      IF(L.EQ.60) GO TO 3
8     NK=NK+1
```

```
14     KK=L
       DO 15 K=1,NK
       U(I,K)=U(I,KK)
       V(I,K)=V(I,KK)
       N(I,K)=9999
15     CONTINUE
3        CONTINUE
4        CONTINUE
       WRITE(5,120)
       WRITE(5,117)(I,I=1,15)
       WRITE(5,118)(J,(U(I,J),I=1,15),J=1,60)
       WRITE(5,117)(I,I=16,30)
       WRITE(5,118)(J,(U(I,J),I=16,30),J=1,60)
       WRITE(5,121)
       WRITE(5,117)(I,I=1,15)
       WRITE(5,118)(J,(V(I,J),I=1,15),J=1,60)
       WRITE(5,117)(I,I=16,30)
       WRITE(5,118)(J,(V(I,J),I=16,30),J=1,60)
C--INTERPOLATE U,V FIELD HORIZONTALLY.
C--LET SP(I,J)BE DUMMY U(I,J);DIR(I,J) BE DUMMY V(I,J)
C--FOR HORIZONTALLY INTERP'D U(I,J) AND V(I,J)
       DO 37 I=1,30
       DO 37 J=1,60
       SP(I,J)=U(I,J)
       DIR(I,J)=V(I,J)
       IF(N(I,J).EQ.9999) GO TO 38
       GO TO 37
38     N(I,J)=0
       SP(I,J)=DIR(I,J)=0.0
37     CONTINUE
       DO 41 J=1,60
       JP=0
       DO 31 I=1,30
       IF(I.EQ.JP)GO TO 31
       IF(N(I,J).EQ.0)GO TO 51
       GO TO 31
51     IF(I.EQ.1) GO TO 32
       NH=0
       I1=I
       IM=I1-1
       DO 91 K=I1,30
       IF(N(K,J).GT.0)GO TO 71
       IF(K.EQ.30)GO TO 61
91     NH=NH+1
71     FH=NH+1
       IN=I1+NH
       DUH=(U(IN,J)-U(IM,J))/FH
       DVH=(V(IN,J)-V(IM,J))/FH
       DO 81 K=1,NH
       II=I1-1+K
       FHK=K
       JP=I1+K
       N(II,J)=9999
       SP(II,J)=U(IM,J)+FHK*DUH
81     DIR(II,J)=V(IM,J)+FHK*DVH
       GO TO 31
61     NH=NH+1
       DO 92 K=1,NH
       II=I1-1+K
       N(II,J)=9999
       SP(II,J)=U(IM,J)
92     DIR(II,J)=V(IM,J)
       GO TO 31
32     NHK=0
       DO 34 M=1,30
       IF(N(M,J).GT.0) GO TO 35
       IF(M.EQ.30) GO TO 31
34     NHK=NHK+1
35     KH=M
       DO 36 K=1,NHK
       SP(K,J)=SP(KH,J)
       DIR(K,J)=DIR(KH,J)
       N(K,J)=9999
36     CONTINUE
31     CONTINUE
41     CONTINUE
       DO 93 I=1,30
       DO 93 J=1,60
       IF(SP(I,J).EQ.0.0)SP(I,J)=U(I,J)
       IF(DIR(I,J).EQ.0.0)DIR(I,J)=V(I,J)
93     CONTINUE
```

```
      WRITE(5,122)
      WRITE(5,117)(I,I=1,15)
      WRITE(5,118)(J,(SP(I,J),I=1,15),J=1,60)
      WRITE(5,117)(I,I=16,30)
      WRITE(5,118)(J,(SP(I,J),I=16,30),J=1,60)
      WRITE(5,123)
      WRITE(5,117)(I,I=1,15)
      WRITE(5,118)(J,(DIR(I,J),I=1,15),J=1,60)
      WRITE(5,117)(I,I=16,30)
      WRITE(5,118)(J,(DIR(I,J),I=16,30),J=1,60)
C--COMPUTE MEAN U(I,J) AND V(I,J) FROM VERT. ≤ HORIZ. INTERPOLATION
      DO 66 I=1,30
      DO 66 J=1,60
      IF(N(I,J).EQ.9999)N(I,J)=0
      IF(N(I,J).EQ.0)GO TO 25
      GO TO 62
25    U(I,J)=(U(I,J)+SP(I,J))/2.
      V(I,J)=(V(I,J)+DIR(I,J))/2.
62    SH=(U(I,J)*U(I,J)+V(I,J)*V(I,J))
      SP(I,J)=SQRT(SH)
      UH=U(I,J)
      VH=V(I,J)
      DIR(I,J)=FDIR(UH,VH)
66    WRITE(1,104)U(I,J),V(I,J),SP(I,J),DIR(I,J),N(I,J),
     3DIV(I,J),VOR(I,J)
      WRITE(5,113)
      WRITE(5,102)(I,I=1,30)
      WRITE(5,103)(J,(SP(I,J),I=1,30),J=1,60)
      WRITE(5,114)
        WRITE(5,102)(I,I=1,30)
      WRITE(5,105)(J,(DIR(I,J),I=1,30),J=1,60)
      WRITE(5,115)
        WRITE(5,102)(I,I=1,30)
        WRITE(5,106)(J,(N(I,J),I=1,30),J=1,60)
      WRITE(5,124)
      WRITE(5,117)(I,I=1,15)
      WRITE(5,118)(J,(U(I,J),I=1,15),J=1,60)
      WRITE(5,117)(I,I=16,30)
      WRITE(5,118)(J,(U(I,J),I=16,30),J=1,60)
      WRITE(5,125)
      WRITE(5,117)(I,I=1,15)
      WRITE(5,118)(J,(V(I,J),I=1,15),J=1,60)
      WRITE(5,117)(I,I=16,30)
      WRITE(5,118)(J,(V(I,J),I=16,30),J=1,60)
100   FORMAT(/2X,I5,3X,2I4,,4(I4,F5.1),F7.1
     2,F8.2,F8.3,F9.1,2F9.3)
101   FORMAT(5X,2I2,5X,4(I4,F5.1),7X,F8.2)
102   FORMAT(/4X,5HJ / I,1X,30I4)
103   FORMAT(//3X,I3,4X,30F4.1)
104   FORMAT(2X,3F10.6,F7.1,I5,2F10.6)
105     FORMAT(//3X,I3,4X,30F4.0)
106     FORMAT(//3X,I3,4X,30I4)
107   FORMAT(10X,2F10.6,I5)
108   FORMAT(20X,≠SORTED DATA WITH SPEED(KTS) AND DIRECTION≠
     3≠CALCULATED≠,//4X,≠NO.≠,5X,≠YR≠,2X,≠MO≠,2X,≠LAT OUT≠,
     52X,≠LON OUT≠,3X,≠LAT IN≠,2X,≠LON IN≠,4X,≠DIST≠,2X,
     5≠DAYOUT≠,4X,≠SPEED≠,3X,≠DIRECT≠,3X,≠U-COMP≠,3X,≠V-COMP≠)
109   FORMAT(1H1,/20X,≠ORIGINAL SPEED DISTRIBUTION≠)
110   FORMAT(1H1,/20X,≠ORIGINAL DIRECTION DISTRIBUTION≠)
C--111    FORMAT(1H1,/20X,≠SPEED DISTRIBUTION AFTER VERTICAL ≠
C--     5≠INTERPOLATION≠)
C--112    FORMAT(1H1,/20X,≠DIRECTION DISTRIBUTION AFTER VERT≠
C--     5≠ICAL INTERPOLATION≠)
113   FORMAT(1H1,/20X,≠MEAN SPEED FROM VERT. AND HORIZ. ≠
     7≠INTERPOLATION≠)
114   FORMAT(1H1,/20X,≠MEAN DIRECTION FROM VERT. AND ≠
     9≠HORIZ. INTERPOLATION≠)
115   FORMAT(1H1,/20X,≠NO. OF TRACKS PASSING EACH GRID ≠
     7≠POINT≠)
116   FORMAT(1H1,/20X,≠U-COMP OF ORIGIONAL FLOW FIELD≠)
117   FORMAT(/4X,5HJ / I,1X,15I5)
118   FORMAT(3X,I3,4X,15F8.3)
119   FORMAT(1H1,/20X,≠V-COMP OF ORIGIONAL FLOW FIELD≠)
120   FORMAT(1H1,/20X,≠U-COMP OF VERT. INTERPD. FLOW FIELD≠)
121   FORMAT(1H1,/20X,≠V-COMP OF VERT. INTERPD. FLOW FIELD≠)
122   FORMAT(1H1,/20X,≠U-COMP OF HORIZ. INTERPD. FLOW FIELD≠)
123   FORMAT(1H1,/20X,≠V-COMP OF HORIZ INTERPD FLOW FIELD≠)
124   FORMAT(1H1,/20X,≠U-COMP OF VERT ≤ HORIZ INTERPD FLOW FIELD≠)
125   FORMAT(1H1,/20X,≠V-COMP OF VERT ≤ HORIZ INTERPD ≠
     2≠FLOW FIELD≠)
      STOP
        END
```

APPENDIX Ia

```
      FUNCTION FDIR(U,V)
        DD=ABS(U/V)
        DIR=ATAN(DD)
        DIR=DIR*57.29578
        IF(V)14,15,16
14      IF(U)17,17,18
15      IF(U)23,20,24
16      IF(U)19,21,21
17      DIR=180.0+DIR
        GO TO 21
18      DIR=180.0-DIR
        GO TO 21
19      DIR=360.0-DIR
        GO TO21
20      DIR=0.0
        GO TO 21
24      DIR=090.0
        GO TO 21
23      DIR=270.0
21    FDIR=DIR
      RETURN
      END
```

APPENDIX Ib

```
      FUNCTION FMF(XLAT)
      ALAT=XLAT*0.00029089
      A=3437.74677
      EP=0.08227185
      B=2.302585
      S=SIN(ALAT)
      OM=3.14159/4.0+ALAT/2.0
      EPSQ=EP*EP
      ESSQ=EPSQ*EPSQ
      SS=SIN(OM)
      CC=COS(OM)
      T=SS/CC
      TL=ALOG10(T)
      FMF=A*B*TL-A*(EPSQ*S+ESSQ*S*S*S/3.0)
      RETURN
      END
```

APPENDIX II

PROGRAM TO SMOOTH U(I, J), V(I, J) FIELDS - SMOOTH

Notes on Program SMOOTH

This program reads in the two-dimensionally interpolated U(I, J), V(I, J) fields that were punched on cards by statement 66 of the main program. Internal fields are smoothed MAXPAS times by the operation

$$X(I,J)^{k+1} = (X(I,J)^k + (X(I+1,J)^k + X(I-1,J)^k + X(I,J+1)^k + X(I,J-1)^k)/4)/2$$

where X(I, J) corresponds to either U(I, J) or V(I, J) and $k = 0, 1, 2, \cdots,$ MAXPAS. This operation is performed by first computing the change due to smoothing

$$R(I,J) = (-X(I,J) + (X(I+1,J) + X(I-1,J) + X(I,J+1) + X(I,J-1))/4)/2$$

where all the X correspond to the same k. Then the X at k+1 are computed by

$$X(I,J) = X(I,J) + R(I,J)$$

At boundaries special forms of the operator are employed. At k = MAXPAS the fields are punched on cards in DO LOOP 8.

```
      PROGRAM SMOOTH
C--APPLIES 5-POINTS SMOOTHER MAXPASS TIMES TO UV FIELDS
C--I=1IMAX AND J=1,JMAX.FILES SMOOTH FIELDS
C--
      COMMON U(30,60),V(30,60),RU(30,60),RV(30,60),N(30,60)
      IPASS=0
      IMAX=30
      JMAX=60
      IM1=IMAX-1
      JM1=JMAX-1
      MAXPAS=3
C--
C--READ IN U,V FIELDS
      DO 1 I=1,IMAX
      DO 1 J=1,JMAX
1     READ(2,101)U(I,J),V(I,J),N(I,J)
C--
C--NEW U(I,J)=OLD U(I,J)+RU(I,J);NEW V(I,J)=OLD V(I,J)+RV(I,J)
C--RU(I,J) AND RV(I,J) BE THE DIFFERENCES BETWEEN OLD AND NEW
C--FIND DIFERENCES ON UPPER AND LOWER BONDARIES.
10    DO 2 I=2,IM1
      RU(I,1)=(-U(I,1)+(U(I+1,1)+U(I-1,1))/2.)/2.
      RV(I,1)=(-V(I,1)+(V(I+1,1)+V(I-1,1))/2.)/2.
      RU(I,JMAX)=(-U(I,JMAX)+(U(I+1,JMAX)+U(I-1,JMAX))/2.)/2.
      RV(I,JMAX)=(-V(I,JMAX)+(V(I+1,JMAX)+V(I-1,JMAX))/2.)/2.
2     CONTINUE
C--
C--FIND DIFFERENCES ON LATERAL BONDARIES.
      DO 3 J=2,JM1
      RU(1,J)=(-U(1,J)+(U(1,J+1)+U(1,J-1))/2.)/2.
      RV(1,J)=(-V(1,J)+(V(1,J+1)+V(1,J-1))/2.)/2.
      RU(IMAX,J)=(-U(IMAX,J)+(U(IMAX,J+1)+U(IMAX,J-1))/2.)/2.
      RV(IMAX,J)=(-V(IMAX,J)+(V(IMAX,J+1)+V(IMAX,J-1))/2.)/2.
C--
C--FIND DIFFERENCES NOT ON BONDARIES.
      DO 4 I=2,IM1
      RU(I,J)=(-U(I,J)+(U(I+1,J)+U(I-1,J)+U(I,J+1)+U(I,J-1))/4.)/2.
      RV(I,J)=(-V(I,J)+(V(I+1,J)+V(I-1,J)+V(I,J+1)+V(I,J-1))/4.)/2.
4     CONTINUE
3     CONTINUE
C--
C--FIND DIFFERENCES FOR CORNERS
      RU(1,1)=(-U(1,1)+(U(2,1)+U(1,2))/2.)/2.
      RV(1,1)=(-V(1,1)+(V(2,1)+V(1,2))/2.)/2.
      RU(IMAX,1)=(-U(IMAX,1)+(U(IM1,1)+U(IMAX,2))/2.)/2.
      RV(IMAX,1)=(-V(IMAX,1)+(V(IM1,1)+V(IMAX,2))/2.)/2.
      RU(1,JMAX)=(-U(1,JMAX)+(U(1,JM1)+U(2,JMAX))/2.)/2.
      RV(1,JMAX)=(-V(1,JMAX)+(V(1,JM1)+V(2,JMAX))/2.)/2.
      RU(IMAX,JMAX)=(-U(IMAX,JMAX)+(U(IMAX,JM1)+U(IM1,JMAX))/2.)/2.
      RV(IMAX,JMAX)=(-V(IMAX,JMAX)+(V(IMAX,JM1)+V(IM1,JMAX))/2.)/2.
C--
C--DENOTE NEW U(I,J) AND V(I,J)   BY SAME ARRAY AND FILE.
      DO 5 I=1,IMAX
      DO 5 J=1,JMAX
      U(I,J)=U(I,J)+RU(I,J)
      V(I,J)=V(I,J)+RV(I,J)
5     CONTINUE
C--SMOOTH AGAIN UNTIL IPASS=MAXPAS; PRINT SMOOTHED FIELD
C--EVERY THREE PASSES.
      IPASS=IPASS+1
      IF(IPASS.EQ.3) GO TO 7
      IF(MAXPAS.GT.IPASS) GO TO 10
      REWIND 2
7     DO 8 I=1,IMAX
      DO 8 J=1,JMAX
      WRITE(1,102)U(I,J),V(I,J),N(I,J)
8     CONTINUE
101   FORMAT(2X,2F10.6,17X,I5)
102   FORMAT(2X,2F10.6,I5)
      STOP
      END
```

APPENDIX III

PROGRAM TO COMPUTE VORTICITY, DIVERGENCE, AVERAGES AND STANDARD DEVIATIONS - DIVORSD

Notes on Program DIVORSD

This program reads in smoothed U(I, J) and V(I, J) fields output by program SMOOTH. The divergence and vorticity fields (DIV(I, J) and VOR(I, J)) are calculated for the interior grid (29 X 59). It should be noted that speeds are in knots and grid separations in nautical miles so that divergence and vorticity are in inverse hours. Zonal and meridional averages and standard deviations are computed for the fields U(I, J), V(I, J), DIV(I, J), and VOR(I, J).

```
      PROGRAM DIVORSD
      COMMON U(30,60),V(30,60),DIV(30,60),VOR(30,60),SX(60),
     1SX2(60),XAVE(60),STD(60),UPPER(60),FLOWER(60),
     2XVAR(60)
C--THIS PROGRAM IS TO COMPUTE MERID MEANS AND STD DEV
C--FOR SMOOTHED UV FIELDS
C--
C--
C-- READ IN SMOOTHED UV FIELDS
      DO 1 I=2,29
      DO 1 J=2,59
      READ(1,101)U(I,J),V(I,J)
      DIV(I,J)=VOR(I,J)=0.0
      SX(I)=SX2(I)=XVAR(I)=XAVE(I)=0.0
      STD(I)=UPPER(I)=FLOWER(I)=0.0
1     CONTINUE
C--
C--COMPUTE MERID MEANS AND STD DEV FOR VORTICITY FIELD
      WRITE(5,106)
      DO 2 I=2,29
      DO 2 J=2,59
      VOR(I,J)=(V(I+1,J)-V(I-1,J))/7.07+(U(I,J+1)-U(I,J-1))/10.
      XVOR=XVOR+VOR(I,J)
      SX(I)=SX(I)+VOR(I,J)
      SX2(I)=SX2(I)+VOR(I,J)*VOR(I,J)
2     CONTINUE
      DO 4 I=2,29
      XAVE(I)=SX(I)/58.
      XVAR(I)=(58.*SX2(I)-SX(I)*SX(I))/(58.*(58.-1.))
      STD(I)=SQRT(XVAR(I))
      UPPER(I)=XAVE(I)+STD(I)
      FLOWER(I)=XAVE(I)-STD(I)
      WRITE(5,103)I,XAVE(I),STD(I),XVAR(I),UPPER(I),
     2FLOWER(I)
4     CONTINUE
C--
C--COMPUTE ZONAL MEANS AND STD DEV FOR VORTICITY FIELD
      DO 5 I=2,29
      SX(I)=SX2(I)=XVAR(I)=XAVE(I)=0.0
      STD(I)=UPPER(I)=FLOWER(I)=0.0
5     CONTINUE
      WRITE(5,110)
      DO 6 I=2,29
      DO 6 J=2,59
      SX(J)=SX(J)+VOR(I,J)
      SX2(J)=SX2(J)+VOR(I,J)*VOR(I,J)
6     CONTINUE
      DO 7 J=2,59
      XAVE(J)=SX(J)/28.
      XVAR(J)=(28.*SX2(J)-SX(J)*SX(J))/(28.*(28.-1.0))
      STD(J)=SQRT(XVAR(J))
      UPPER(J)=XAVE(J)+STD(J)
      FLOWER(J)=XAVE(J)-STD(J)
      WRITE(5,103)I,XAVE(J),STD(J),XVAR(J),UPPER(J),
     3FLOWER(J)
7     CONTINUE
C--
C--COMPUTE MERID MEANS AND STD DEV FOR DIVERGENCE FIELD
      DO 8 J=2,59
      SX(J)=SX2(J)=XVAR(J)=XAVE(J)=0.0
      STD(J)=UPPER(J)=FLOWER(J)=0.0
8     CONTINUE
```

```
      WRITE(5,107)
      DO 9 I=2,29
      DO 9 J=2,59
      DIV(I,J)=(U(I+1,J)-U(I-1,J))/7.07-(V(I,J+1)-V(I,J-1))/10.
      XDIV=XDIV+DIV(I,J)
      SX(I)=SX(I)+DIV(I,J)
      SX2(I)=SX2(I)+DIV(I,J)*DIV(I,J)
9     CONTINUE
      DO 10 I=2,29
      XAVE(I)=SX(I)/58.
      XVAR(I)=(58.*SX2(I)-SX(I)*SX(I))/(58.*(58.-1.0))
      STD(I)=SQRT(XVAR(I))
      UPPER(I)=XAVE(I)+STD(I)
      FLOWER(I)=XAVE(I)-STD(I)
      WRITE(5,103)I,XAVE(I),STD(I),XVAR(I),UPPER(I),
     4FLOWER(I)
10    CONTINUE
C--
C--COMPUTE ZONAL MEANS AND STD DEV FOR DIVERGENCE FIELDS
      DO 11 I=2,29
      SX(I)=SX2(I)=XVAR(I)=XAVE(I)=0.0
      STD(I)=UPPER(I)=FLOWER(I)=0.0
11    CONTINUE
      WRITE(5,111)
      DO 12 I=2,29
      DO 12 J=2,59
      SX(J)=SX(J)+DIV(I,J)
      SX2(J)=SX2(J)+DIV(I,J)*DIV(I,J)
12    CONTINUE
      DO 13 J=2,59
      XAVE(J)=SX(J)/28.
      XVAR(J)=(28.*SX2(J)-SX(J)*SX(J))/(28.*(28.-1.))
      STD(J)=SQRT(XVAR(J))
      UPPER(J)=XAVE(J)+STD(J)
      FLOWER(J)=XAVE(J)-STD(J)
      WRITE(5,103)I,XAVE(J),STD(J),XVAR(J),
     5UPPER(J),FLOWER(J)
13    CONTINUE
C--
C--COMPUTE GRAND MEANS
      XVOR=XVOR/1624.
      XDIV=XDIV/1624.
      WRITE(5,109)XVOR,XDIV
101   FORMAT(2X,2F10.6)
103   FORMAT(13X,I3,5F14.8)
106   FORMAT(///20X,≠MERID MEANS AND STD DEV FOR VORTICITY≠)
107   FORMAT(///20X,≠MERID MEANS AND STD DEV FOR DIVERGENCE≠)
109   FORMAT(2F15.8)
110   FORMAT(///20X,≠ZONAL MEANS AND STD DEV FOR VORTICITY≠)
111   FORMAT(///20X,≠ZONAL MEANS AND STD DEV FOR DIVEGENCE≠)
      STOP
      END
```