AN ABSTRACT OF THE THESIS OF

ADRIANA HUYER for the MASTER OF SCIENCE
(Name) (Degree)

in OCEANOGRAPHY presented on March 18, 1971
(Major) (Date)

Title: A STUDY OF THE RELATIONSHIP BETWEEN LOCAL WINDS AND CURRENTS OVER THE CONTINENTAL SHELF OFF OREGON

Abstract approved: Redacted for privacy
June G. Pattullo

This thesis demonstrates that at low frequencies (periods longer than 2.5 days) local currents off the coast of Oregon are closely related to the wind. Wind and current observations made during August and September 1969 are described and compared to demonstrate that a relationship exists; the physics of the interaction is not understood.

The data are described as functions of both time and frequency. Spectral analysis shows that wind and current were related at frequencies less than 0.017 cycles per hour and at the diurnal frequency; at other frequencies they are apparently not related. The wind and current were then filtered to suppress frequencies higher than 0.017 cycles per hour; they are shown as functions of time. Comparison of the time series reveals certain features of the relationship between wind and current. The current can be considered to be the sum of

two parts: a "response" current, which is related directly to the wind, and a "residual" current which is also variable. The amplitude of the response depends on the amplitude of the wind and on the density profile of the water. The time lag between the wind and the response current was variable; on a few occasions the current led the wind. Both the response and the residual current were generally parallel to the bottom contours. The residual current seems to change during periods when the response current is interrupted, so that short current records are not indicative of the mean flow.

A Study of the Relationship Between Local Winds and Currents over the Continental Shelf Off Oregon

by

Adriana Huyer

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1971

APPROVED:

Redacted for privacy

Professor of Oceanography
in charge of major

Redacted for privacy

Head of Department of Oceanography

Redacted for privacy

Dean of Graduate School

Date thesis is presented March 18, 1971

Typed by Muriel Davis for Adriana Huyer

ACKNOWLEDGMENTS

My major professor, Dr. June Pattullo, suggested that I study the 1969 current meter data; this thesis is the result. Dr. Stephen Pond criticized the manuscript and suggested improvements. I would also like to thank Mr. Fred Barber whose enthusiasm for oceanography first sparked mine.

TABLE OF CONTENTS

LIST OF FIGURES

A STUDY OF THE RELATIONSHIP BETWEEN LOCAL WINDS AND CURRENTS OVER THE CONTINENTAL SHELF OFF OREGON

INTRODUCTION

This study describes wind and current data observed from an instrument array moored on the continental shelf off Oregon in August and September 1969. The purpose is to determine whether the wind and current are related, particularly at low frequencies, and to describe this relationship as much as possible. One current record and the wind are examined in detail. They are described and compared as functions of both time and frequency.

General Description of the Region

The oceanography of the Oregon coastal region is largely determined by the large scale wind pattern. The atmospheric circulation over the northeast Pacific Ocean changes seasonally (Smith, 1968). The North Pacific High causes northerly and northwesterly winds during summer; they are strongest off Oregon during July and August. In late fall and winter the high is weaker and farther south; winds near the Oregon coast are predominantly westerly or southwesterly.

The annual cycle in the wind causes seasonal changes in the current and density regimes. The southward winds in summer cause upwelling; the pycnocline is tilted upward toward the coast. When upwelling is most intense, during July and August, the pycnocline intersects the surface. Surface currents in summer are southward. Upwelling ceases during fall and winter when northward winds dominate (Smith, 1968). The southward California Current persists offshore but a northward surface current (the Davidson Inshore Current) is observed inshore.

Review of Earlier Studies

It has long been recognized that winds exert an influence on the circulation of the world ocean (Sverdrup, Johnson and Fleming, 1942). Many seasonal variations in currents are attributed to seasonal variations in the wind field. The effect of monsoon winds on currents in the Indian Ocean (Cox, 1970) is probably the most vivid example. Other examples are variations in the Benguela and Peru Currents (Schell, 1965; 1970). There are many theoretical studies of the wind-driven circulation of the ocean (Robinson, 1963). Recent theoretical studies include the effect of fluctuating winds on the large-scale circulation (Longuet-Higgins, 1965; Lighthill, 1969; Veronis, 1970).

The interaction between wind and currents at the inertial frequency has also been studied extensively. The most recent studies are by Pollard (1970) and Pollard and Millard (1970).

Studies of the relationship between wind and current at periods of the order of a few days are not plentiful. The most notable is by

Collins and Pattullo (1970) who describe observations from the Oregon coast. Murray (1970) describes current variations during passage of a hurricane. The influence of the wind on the sea at these frequencies has also been studied by Groves and Miyata (1967) and Groves and Hannan (1968).

Studies of the influence of the wind on currents off the Oregon coast began with Jones (1918). He indicated that the surface currents appeared to be caused by the prevailing weather. Marmer (1926) summarized current observations from lightships along the Pacific coast. He found that high currents were associated with high wind speeds, and that the direction of the current depends partly on the angle between wind direction and coastline. Drift bottle returns provided additional evidence for the northward Davidson Current in winter and southward flow in summer (Schwartzlose, 1962). Burt and Wyatt (1964) found that both normal and anomalous currents could be explained by the associated wind patterns. Current meters were moored over the continental shelf off Oregon each year from 1965 to 1969. The data are summarized in data reports (Collins, Creech and Pattullo, 1966; Mooers _et al._, 1968; Pillsbury, Smith and Pattullo, 1970). Collins _et al._ (1968) compared 1965 and 1966 current measurements by drogues and moored and suspended current meters. They found good agreement between the various methods. Collins (1968) and Collins and Pattullo (1970) used the data to study the relationship between wind and currents at periods long compared to the tides. They obtained a regression model of the longshore current on the longshore wind.

MEASUREMENTS

Taut wire instrument arrays were moored over the continental shelf off the Oregon coast during August and part of September 1969. Current meters and thermographs were installed at three locations and the surface wind was measured at one (Figure 1). The observations are described in a data report (Huyer et al., 1971). The current record from NH-3 was only 12 days long; the three other current records were each about 50 days long. In each of the longer records, low frequency variations appeared to be related to variations in the wind. The resemblance between wind and current was strongest at DB-7. At NH-15, there was a stronger density gradient than at DB-7. Such stratification apparently reduces or complicates the interaction between the wind and current; this effect can be seen later in this study. For these reasons, only the 40 m current data from DB-7 and the wind data from NH-15 are considered in this study. The Braincon current and wind meters recorded at 20 minute intervals. Wind measurements began at 2020 GMT, 30 July and ended at 0020 GMT, 20 September; current measurements began at 1920 GMT, 30 July and ended at 0820 GMT, 19 September.

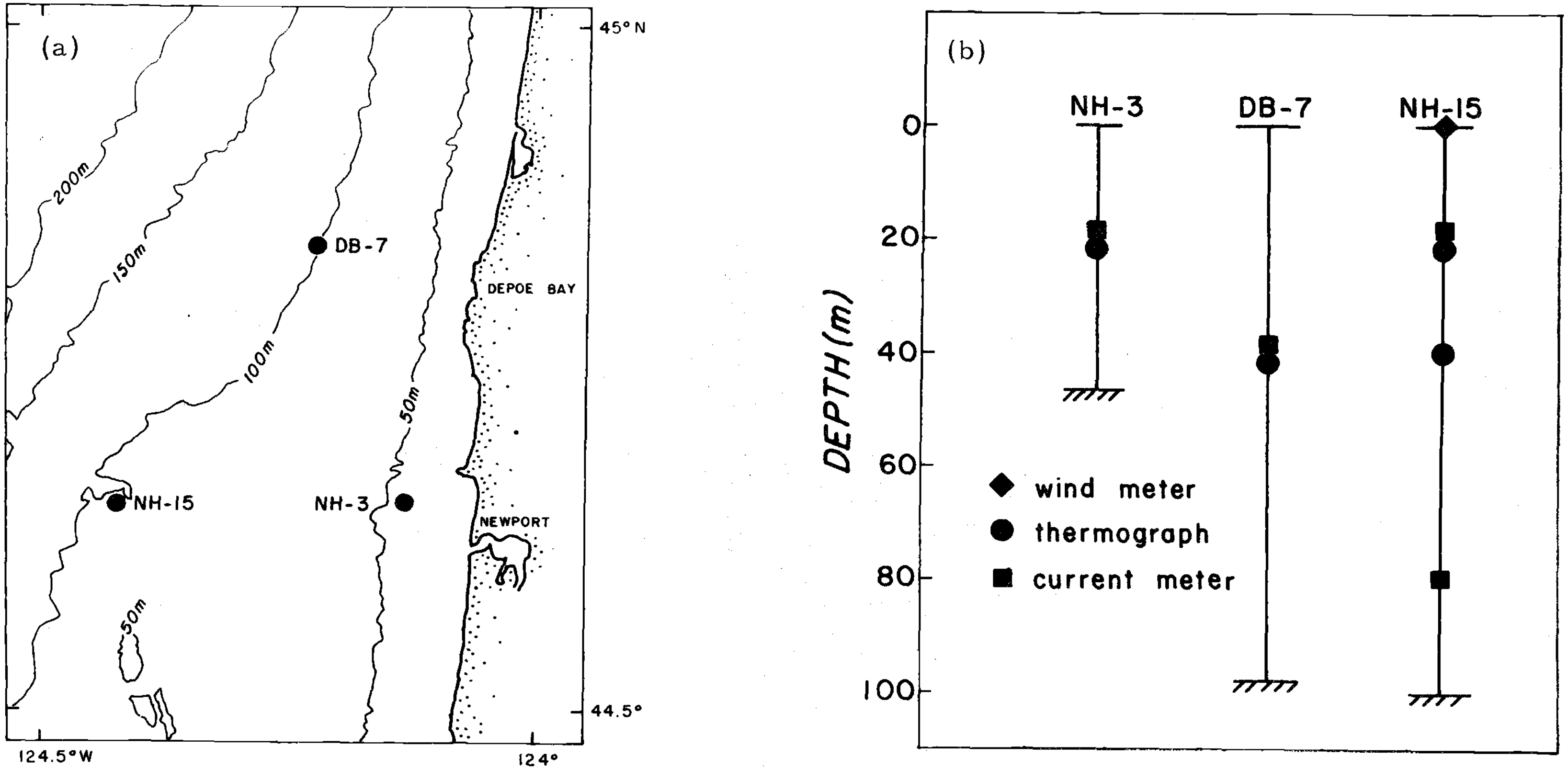

Figure 1. The locations (a) and depths (b) of the instruments moored during the period from 31 July to 21 September 1969.

DESCRIPTION AND ANALYSIS OF THE DATA

The wind and current are described and compared as functions of both time and frequency. The observations were filtered to yield "low pass" and "low low pass" time series. In the low pass series, signals with frequencies higher than 0.234 cycles per hour (periods shorter than 4.3 hours) are suppressed to less than 5% of their original amplitude, while signals with frequencies less than 0.114 cph (periods longer than 8.8 hours) are passed with more than 95% of the original amplitude. For the low low pass series, the corresponding frequencies (and periods) are 0.039 cph (26 hours) and 0.019 cph (2.2 days).

To describe the wind and current as functions of frequency, spectral functions were used. The <u>spectrum</u>, ϕ_α, of a fluctuating quantity α is defined as the contribution to the total variance from a band of frequencies Δf centered about f. Hence,

$$\int_0^\infty \phi_\alpha(f)\, df = \overline{\alpha^2}$$

where the bar denotes the time average. The <u>cross spectrum</u> gives the relationship between two fluctuating quantities, α and β. It is made up of two parts: the <u>cospectrum</u> and the <u>quadrature spectrum</u>. The cospectrum $\phi_{\alpha\beta}$ gives the contribution to the covariance as a function of frequency ($\int_0^\infty \phi_{\alpha\beta}(f)\, df = \overline{\alpha\beta}$) and is a measure of the part of one signal that is related to and in phase with the other. The quadrature spectrum is a measure of the part of one signal that is related to but 90° out of phase with the other. The co- and quadrature spectra are dimensional quantities. The relationship between the signals is more clearly demonstrated by the coherence squared and phase which may be obtained from the spectra and the cross spectrum. The coherence squared measures the fraction of $\phi_{\alpha}(f)$ that is related to $\phi_{\beta}(f)$, regardless of phase. The phase spectrum measures the amount by which one signal leads or lags behind the other. They are defined as follows:

$$\text{coherence squared} = \frac{(\text{cospectrum})^2 + (\text{quadrature spectrum})^2}{(\text{spectrum }(\alpha))\,(\text{spectrum }(\beta))}$$

$$\text{phase} = \tan^{-1}\left(-\frac{\text{quadrature spectrum}}{\text{cospectrum}}\right).$$

The coherence squared ranges between 0 and 1 and hence clearly demonstrates how well two signals are related as a function of frequency.

The spectral quantities were computed using subroutines of the ARAND system (Ochs, Baughman and Ballance, 1970) as follows:

> The low pass component series were used to calculate the spectra; the data interval was one hour, and 1190 points of each series were used. CCFFT was used to compute the auto- and cross-correlations with a fast Fourier transform algorithm. A weighting kernel was computed using WINDOW: the truncation point was 160 lags and a Parzen window was used. Smoothed spectral estimates

were obtained from the auto- and cross-correlation functions and the weighting kernel using TRANFRM. The resulting bandwidth of the spectral window was 0.008 cph. Spectral estimates were computed for 81 frequencies between 0 and 0.25 cph.

The Wind Observations

Eastward (u) and northwart (v) components of the low pass time series of the wind observations are shown in Figure 2. Long period (several days) variations of the wind were much stronger in the v component. Short term variations appeared in both u and v, but they are more obvious in the u component. Diurnal oscillations are apparent some of the time, e.g. 6-11 August and 4-8 September; shorter period oscillations are also present, e.g. during 26-28 August, 8-10 and 12-13 September. No wind speeds over 20 knots were observed. Southward velocities greater than 10 knots were observed frequently. Northward winds faster than 10 knots occurred only during 24-25 August, 27-28 August and 16-20 September.

Spectra and coherence squared and phase of the u and v components of the wind are shown for frequencies below 0.1 cph in Figures 3 and 4. The spectra show peaks at about 0.041 cph (24 hour period); the peak is larger for the u component. At very low frequencies (less than 0.02 cph) more of the energy is in the v component. Higher frequency variations occur mainly in u. There is high coherence between the components at the diurnal frequency; v leads

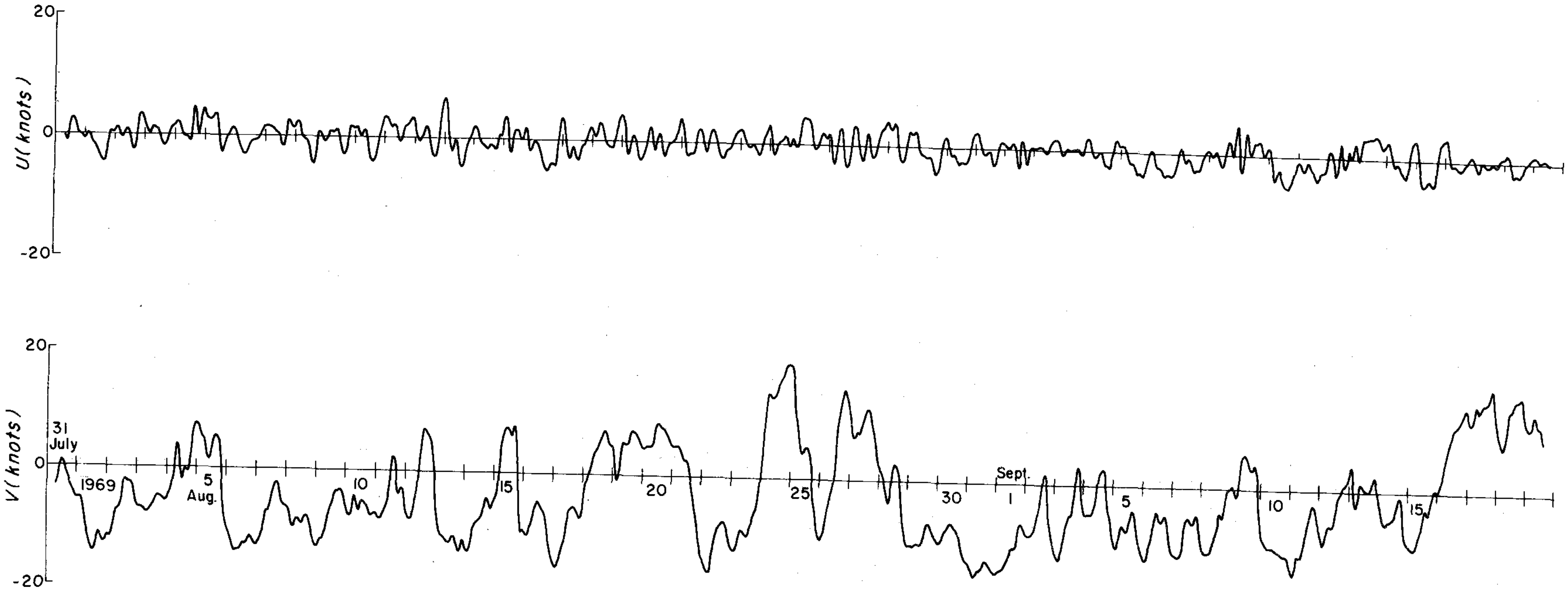

Figure 2. The eastward (u) and northward (v) components of the wind vs. time. The data were filtered to eliminate variations with periods less than 8 hours.

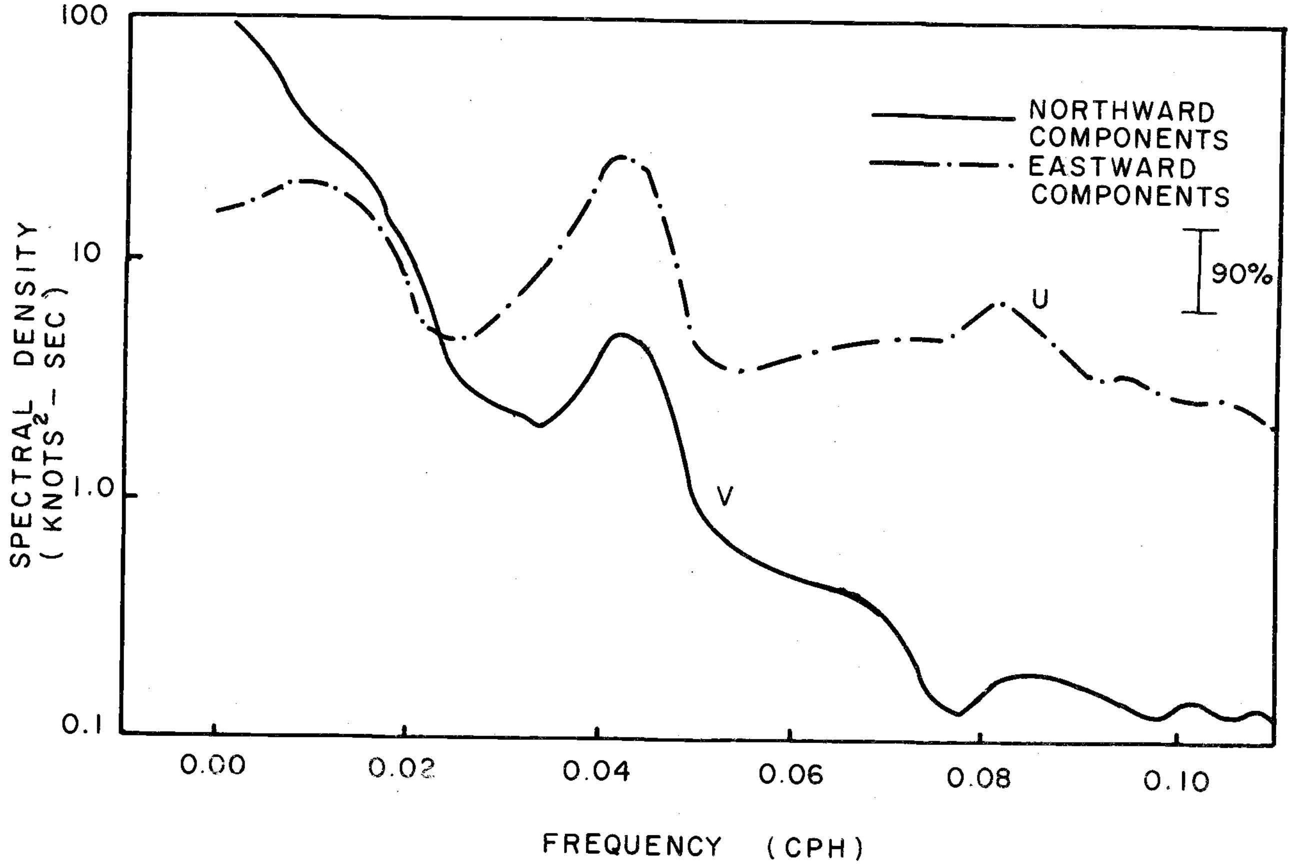

Figure 3. Spectra of the eastward (u) and northward (v) components of the wind. The spectra show the distribution of the total variance over frequency.

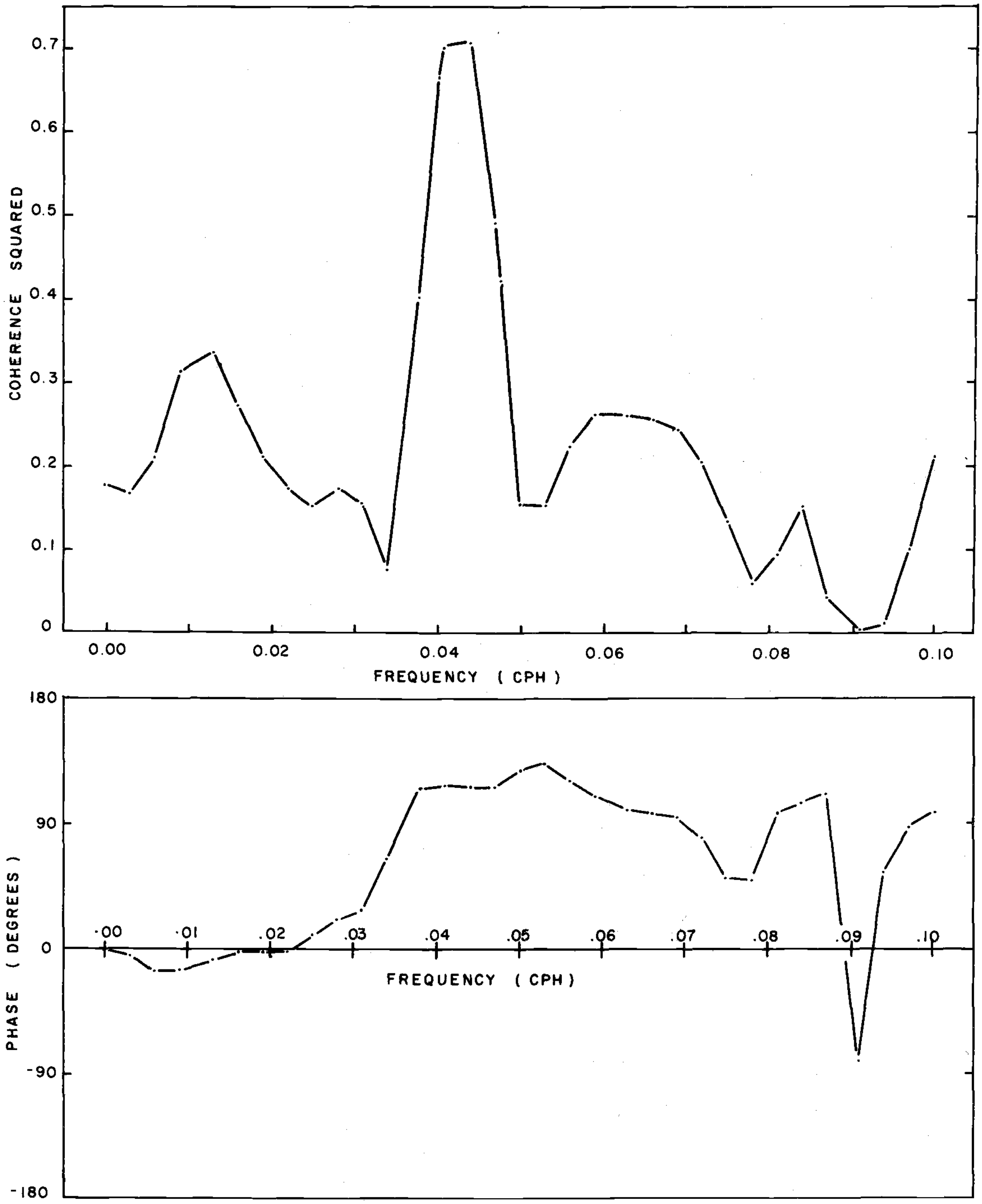

Figure 4. Coherence squared and phase between the eastward (u) and northward (v) components of the wind. The coherence squared measures the relationship between two components regardless of phase at each frequency. The phase shows how much v leads u at each frequency.

u by about eight hours (120^{o}). The coherence is also relatively high at 0.013 cph (three day period); the phase lag is 9^{o}, i.e. v lags by about two hours.

The Current Observations

The low pass series of the eastward (u) and northward (v) components of the current are shown in Figure 5. Intermediate frequency (tidal and inertial) oscillations are the most obvious features in the u component. The amplitude of these oscillations is variable. Damping seems to occur on 24-25 August. Longer term variations also occur: there was a net westward flow until about 20 August and again from 26 August until 7 or 8 September. A net eastward flow occurred from 16 September to the end of the observations on 19 September.

Short period oscillations were also important in the v component but the longer period variations have a larger amplitude. The current was northward on a few occasions; most of the time it was southward. The net current had a strong northward component (25 cm sec^{-1}) from 16 September to the end of the observations.

The spectra of the u and v components are shown in Figure 6. There is a lot of energy at very low frequencies in both components. At higher frequencies most of the energy is in the u component. Both spectra have peaks at 0.059 and 0.08 cph

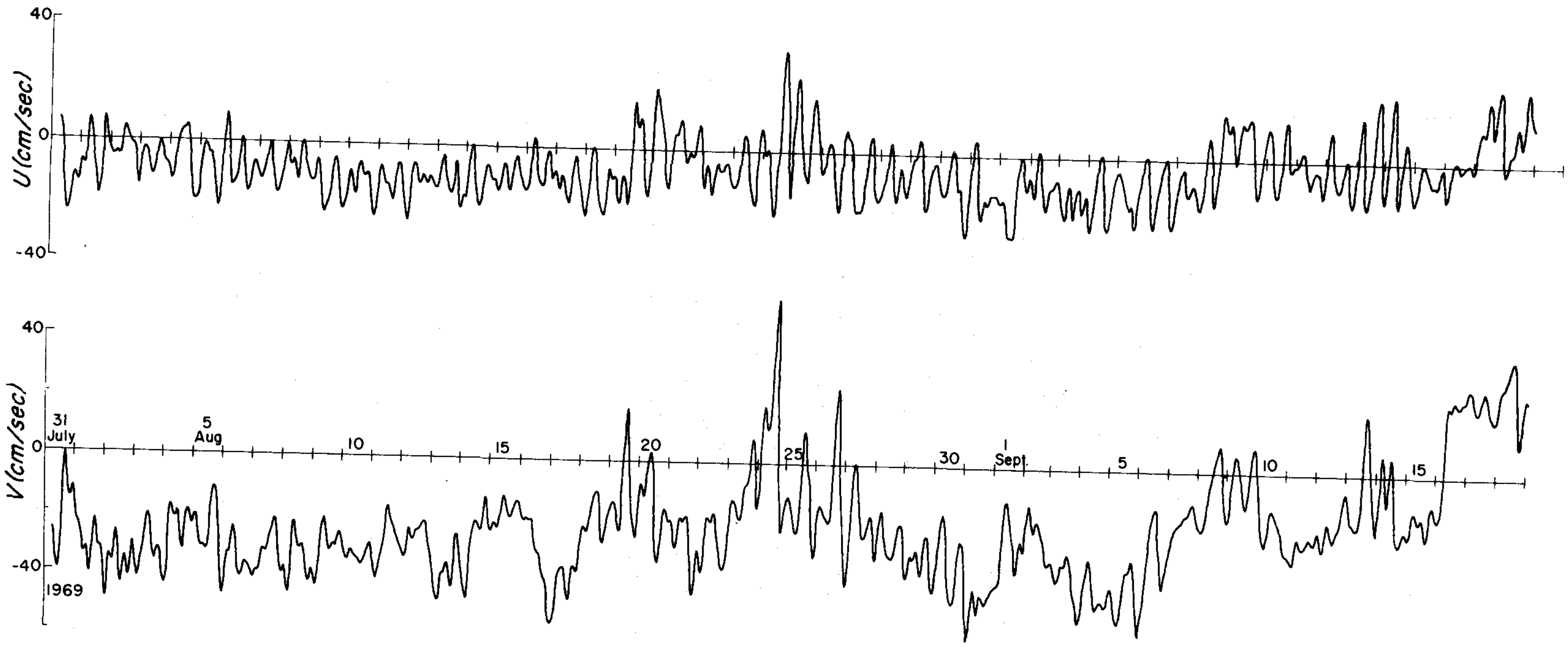

Figure 5. The eastward (u) and northward (v) components of the current vs. time. The data were filtered to eliminate variations with periods less than 8 hours.

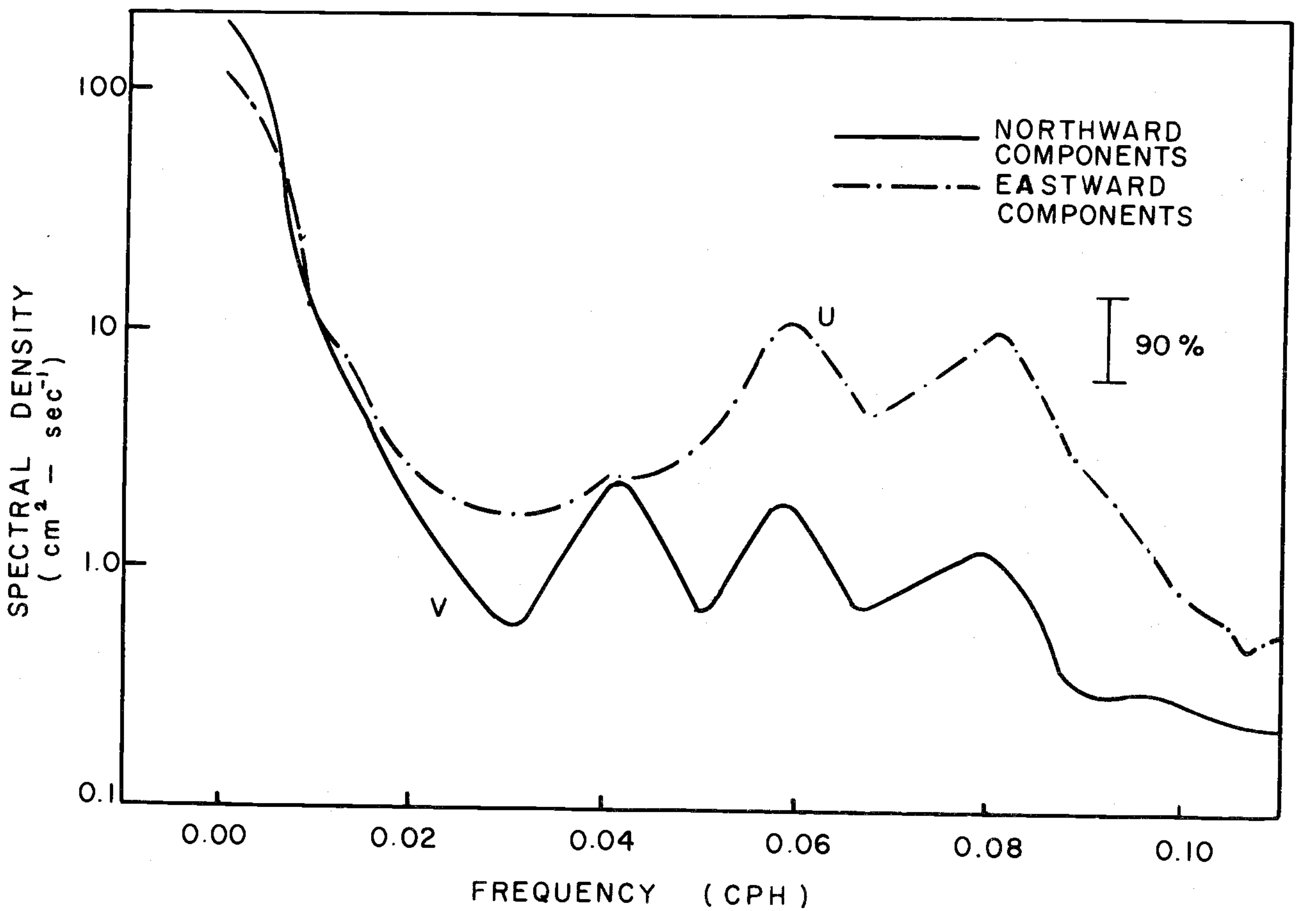

Figure 6. Spectra of the eastward (u) and northward (v) components of the current.

corresponding to the inertial period (16.9 hours) and to the semi-diurnal tide (12.4 hours) respectively. Most of the energy at both frequencies is in the u component. A diurnal oscillation (0.041 cph) exists in the v component; it is not apparent in the u component.

The coherence between u and v (Figure 7) is high at very low frequencies and in the band from 0.05 to 0.075 cph. It is low at both tidal frequencies but high at the inertial frequency. At the inertial period, the u component leads v by about three hours (about 65^{o}).

Comparison of Wind and Current

The wind and current are compared in terms of their principal axes components rather than the eastward and northward components. In these coordinates, one of the components is maximized and the other is minimized. If the second component is small enough, the comparison of the two vectors would be reduced to a comparison of the two major axis components. It will be seen later that the minor axis components of the wind and the current are both small.

By the definition of principal axes, the time average of the off-diagonal element of the Reynolds stress tensor is zero in these coordinates. The new components are:

$$u' = \cos\theta + v \sin\theta$$

$$v' = -u \sin\theta + v \cos\theta$$

where θ is the angle between the old reference frame and the

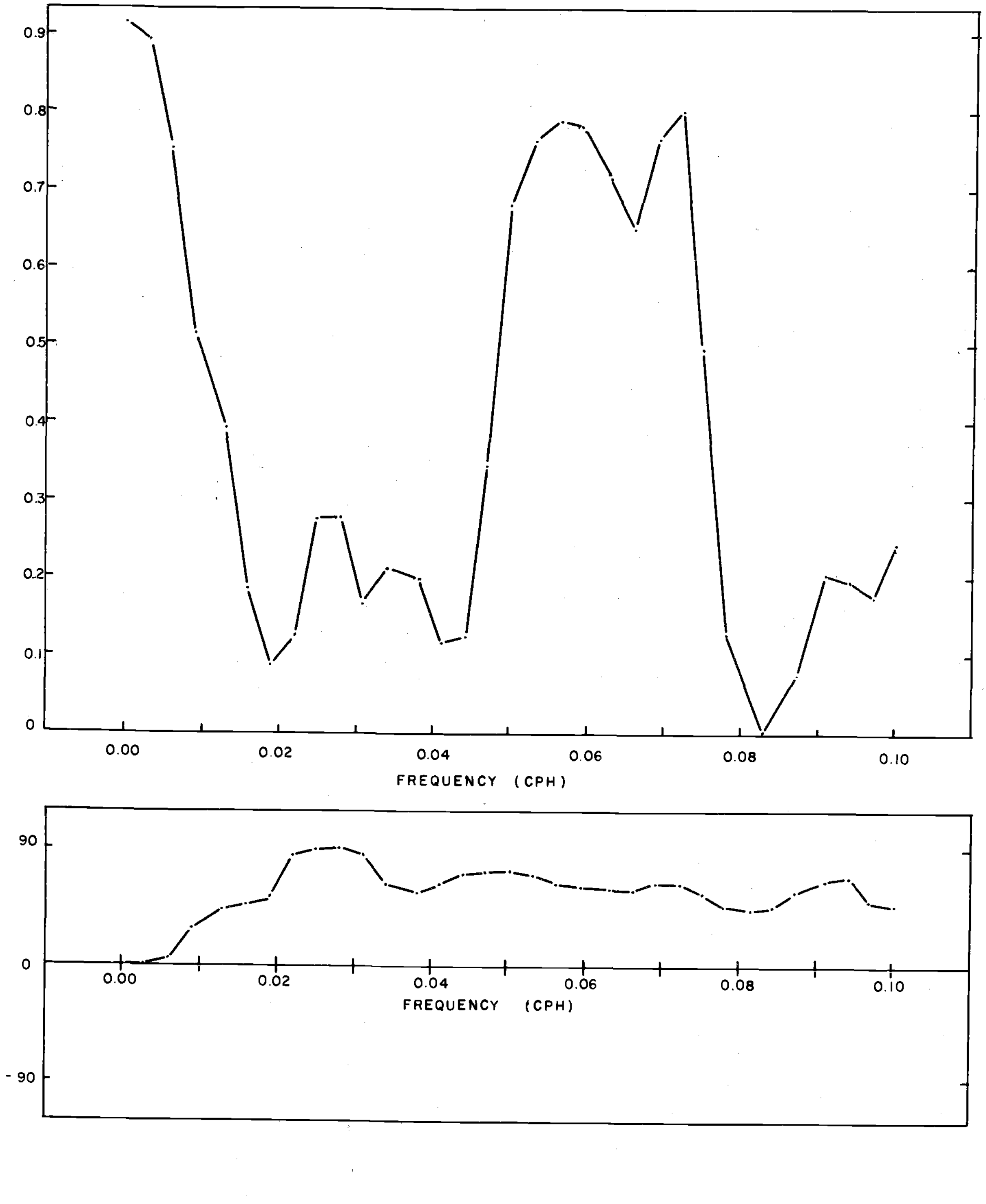

Figure 7. Coherence squared and phase between the eastward (u) and northward (v) components of the current.

principal axes. The off-diagonal element of the Reynolds stress is:

$$u'v' = uv \cos 2\theta + \frac{v^2 - u^2}{2} \sin 2\theta .$$

Its time average must be zero. Then

$$\theta = \frac{1}{2} \tan^{-1} \frac{2\overline{uv}}{\overline{u^2} - \overline{v^2}}$$

where the bars denote time averages. The low low pass time series were used to calculate θ for the wind and the current. Results were:

	θ
wind	$-4^{\circ}\ 2'$
current	$-17^{\circ}\ 27'$

The principal axes for the wind and current are shown in Figure 8. The principal axes of the wind are very nearly the same as the eastward and northward directions. It turns out that the major axes of both the wind and current are nearly parallel to the mean flow: the mean wind is toward 182° T and the mean current is toward 196°T (Huyer et al., 1971). The wind velocity components parallel to the minor and major axes of the wind are called u' and v' respectively: likewise the current velocity components parallel to the principal axes of the current are called u'' and v''.

Coherence Squared and Phase

The coherence squared and phase were computed for the four

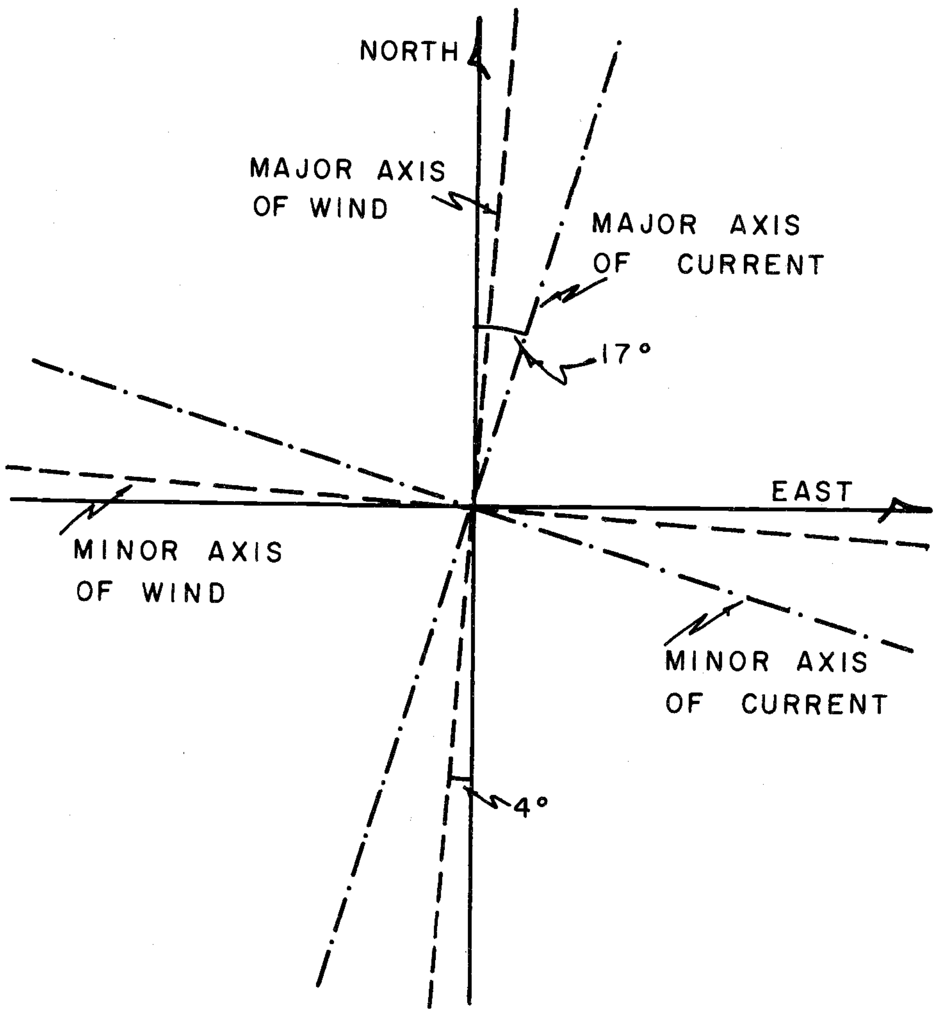

Figure 8. Orientation of the principal axes of wind and current. Principal axes are defined on p. 16.

pairs of wind and current components: minor axis components of the wind and current (u' vs. u''); major axis components of the wind and current (v' vs. v''); minor axis component of the wind vs. major axis component of the current (u' vs. v''); and major axis component of the wind vs. minor axis component of the current (v' vs. u''). Results are shown in Figure 9. The coherence between the minor axis component of the current and each of the wind components is low for all frequencies. Because of the low coherence, no significance can be attached to the phase spectra for these pairs of components. The coherence between the minor axis component of the wind and the major axis of the current is low except at the diurnal frequency (0.041 cph). The phase difference at this frequency is about 160°, i.e. the wind leads the current by about 11 hours. The coherence between the major axis components of the wind and current is high at low frequencies (0 to 0.017 cph) and at the diurnal frequency. At low frequencies the phase difference is essentially zero. At the diurnal frequency, the wind leads the current by about three hours.

At the diurnal frequency, the coherence between the wind and current may not reflect direct interaction between them. Rather, it is probably high because the rotation of the earth causes periodicity in both coastal winds and currents. Periodicity in the wind is the result of differential heating and cooling over land and water. The diurnal period is strong in both components of the wind (Figure 3).

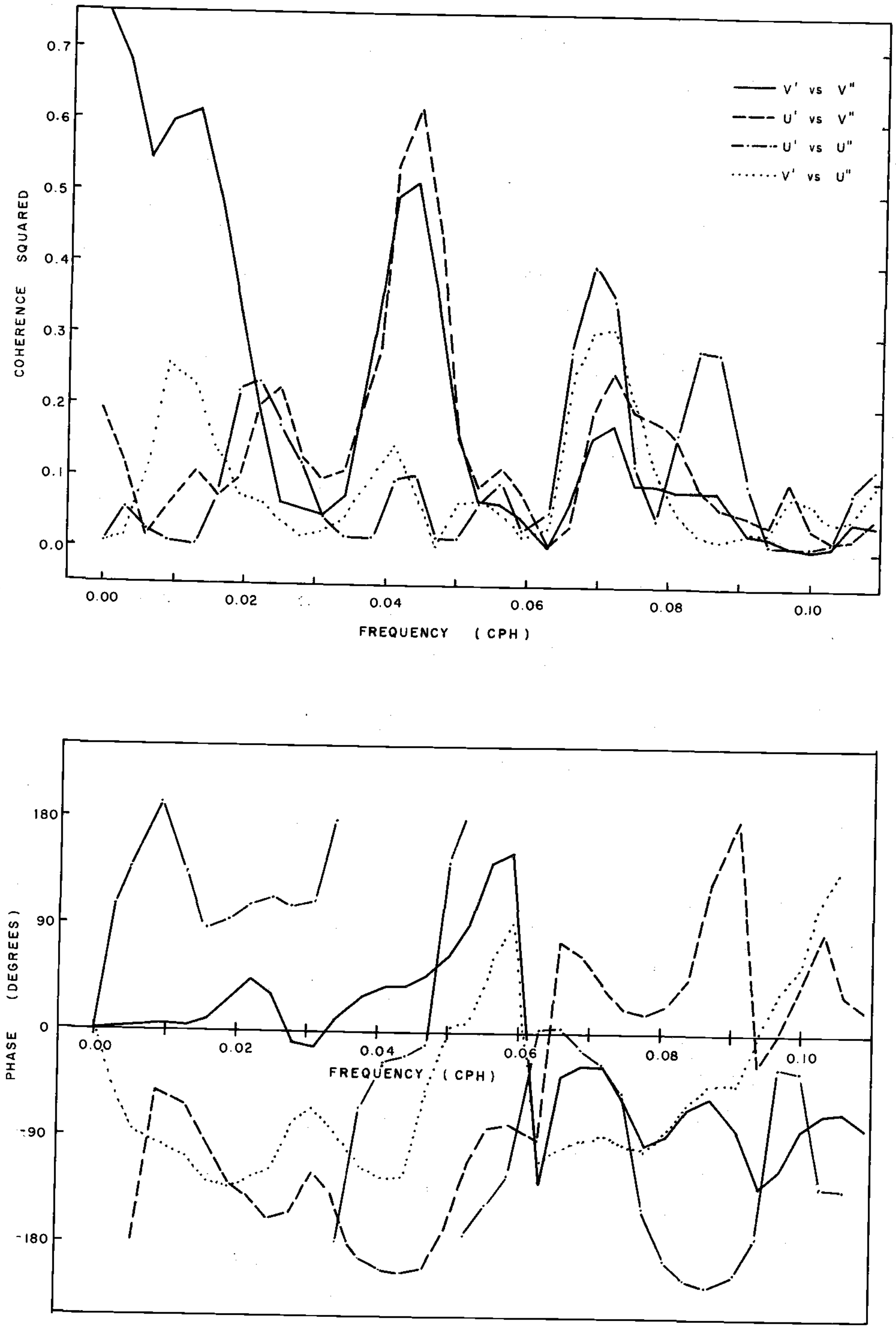

Figure 9. Coherence squared and phase between pairs of principal axis components of wind and current.

Diurnal tidal currents were concentrated in the north-south direction; they were much weaker in the east-west direction (Figure 6). Since the principal axes are not much different from u and v, the high coherence between the wind and the major axis of the current and the low coherence between the wind and the minor axis component of the current could have been predicted from Figures 3 and 6.

At low frequencies (0 to 0.017 cph), there is high coherence only between the major axis components of the wind and current. The coherence between the other pairs of components is very low at these low frequencies.

Comparison of the Time Series

To study further the relationship between wind and current at low frequencies, the observations were filtered to suppress diurnal and shorter periods; the half-power point of the filter is 0.025 cph. The low low pass time series of the principal axis components of the wind and current are shown in Figure 10. Wind and current are superimposed for easier comparison.

For both the wind and the current, the amplitude is much larger along the major axis than along the minor axis. Since v' and v'' are nearly parallel to the mean flow, there is no large cross-stream momentum transport at these low frequencies in either the wind or the current. Hence there is no large horizontal current shear

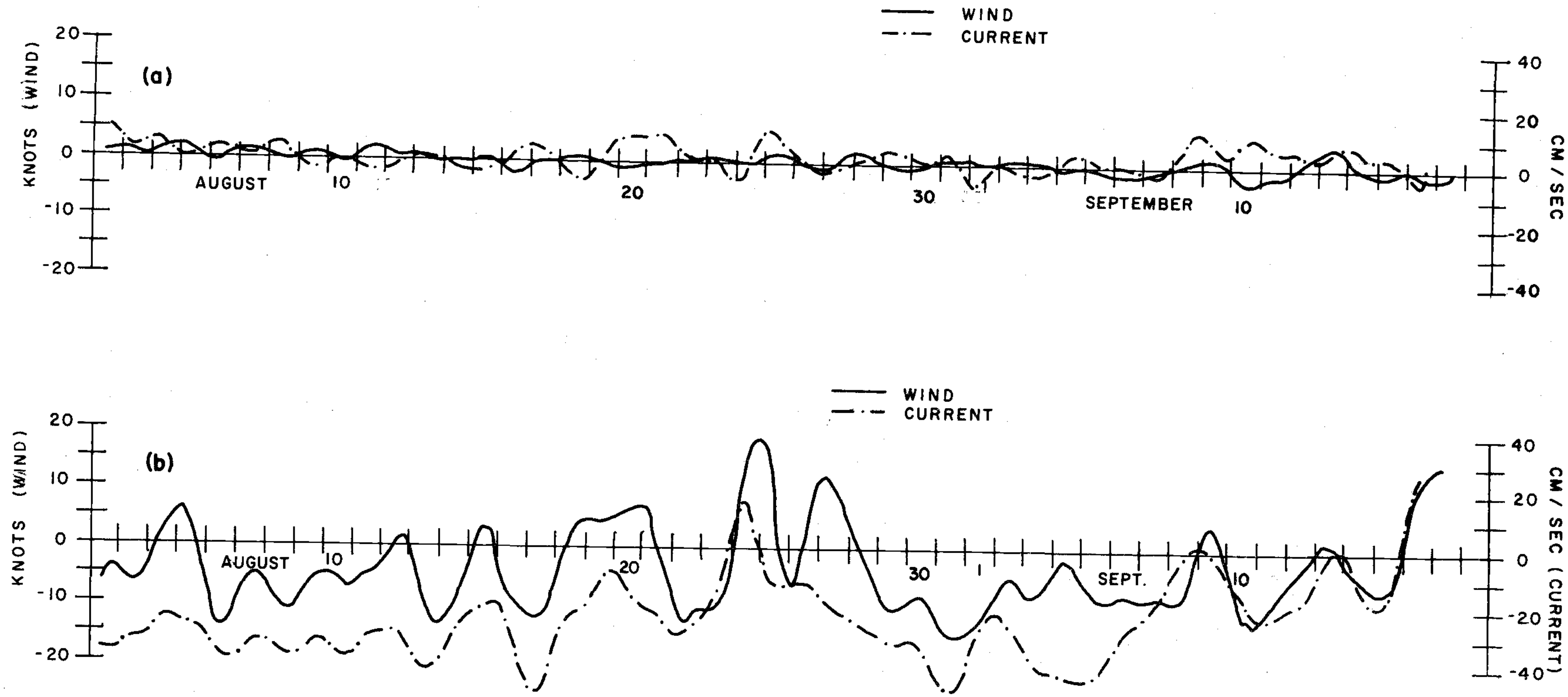

Figure 10. Principal axes components of wind and current vs. time: (a) minor axis components, (b) major axis components. The data were filtered to emphasize variations with frequencies less than 0.017 cycles per hour by suppressing higher frequency signals.

at this location.

The minor axis components of both wind and current are small. The wind and current can therefore be compared simply by comparing the major axis components. The high coherence obtained earlier between these components at low frequencies leads us to expect similarities between them.

Comparison of the major axis components of the wind and current (Figure 10) shows that:

1. Many variations in the current were similar to changes in the wind, particularly from 2-25 August and during 10-16 September.
2. Some variations in the wind are not reflected in the current data, e.g. during 26-29 August and 3-6 September.
3. The ratio of the amplitudes of associated current and wind variations is variable. The ratio is estimated to be 1.5% on 4-6 August; it seems to remain small during early August. The ratio is about 4% on 13-15 September.
4. The lag between wind and current variations is variable. The wind leads the current during 7-17 August. The wind lags behind the current during 23-25 August and the lag seems to continue until 10 September. The largest lag (on 24 August) seems to be about 16 hours. The wind's lead is largest (about 12 hours) on 13 September.

5. The wind-related current is superimposed on a time dependent "residual" current. It is directed along the negative v" axis, i.e. toward 197°T. Its speed was determined by subtracting the apparent wind response from the total current. The speed was variable: about 25 cm sec^{-1} until 25 August, 15 cm sec^{-1} during 29-31 August and about zero after 10 September. During the other time intervals, differences between the wind and current were too variable to estimate the residual current.

The current can be considered to the sum of two parts: a "response" to the wind and a "residual" current. This partition is somewhat arbitrary, but it is useful in comparing the wind and current observations. The "response" is that part of the current which tends to vary with the wind (1-4 above). The "residual" current is the remainder of the current (5 above); it too can be time dependent.

DISCUSSION

The Response of the Current to the Wind

The relationship between the local currents and wind is likely very complex. The currents may be driven directly by the wind stress; they may also be caused by changes in sea level, storm surges, curl of the wind stress or other indirect interactions with the weather. The phrase "the response of the current to the wind" is used to mean the part of the current that varies with the wind. There may be no real response of the current to the wind; both may be responding to a third phenomenon, or they may be responding to separate forces with the same period.

Response as a Function of Frequency

The coherence spectra suggest that the wind and current are related at low and diurnal frequencies (0 to 0.017 and 0.041 cph). As noted earlier, there is probably little direct interaction between wind and current at the diurnal frequency. Apparently the wind and current are related only at frequencies less than 0.017 cph (periods longer than 2.5 days).

For periods longer than 2.5 days, wind variations seem to be reflected in the current (Figure 10). When variations in the wind have somewhat shorter periods, the current does not seem as closely related to the wind. Examples of this apparently occurred on 22 and 26 August and 3-6 September. The most rapid changes in the wind occurred during 23-26 August. The current was oscillating strongly at intermediate (tidal and inertial) frequencies during this time (Figure 5). The oscillations in the eastward component appeared to be amplified early on 24 August, damped until early 26 August and amplified again. The increases in amplitude seem to be due to sudden increases in the speed of the northward wind component. Apparently these oscillations absorb some of the energy of the wind so that the net current does not follow the wind. The wind generation of inertial oscillations is discussed in detail by Pollard (1970); he states that features in the wind field with time scales less than the inertial period have the most effect on inertial oscillations. Pillsbury (personal communication) found currents of tidal period were also amplified by sudden changes in the wind.

The Amplitude of the Response

Changes in the density stratification may be the cause of the observed changes in the amplitude of the response. Figure 11 shows the observed distributions of sigma-t in a section west of Newport on 9 August and 9 September 1969. The stratification is more intense in early August; the near-shore water is almost homogeneous on 9

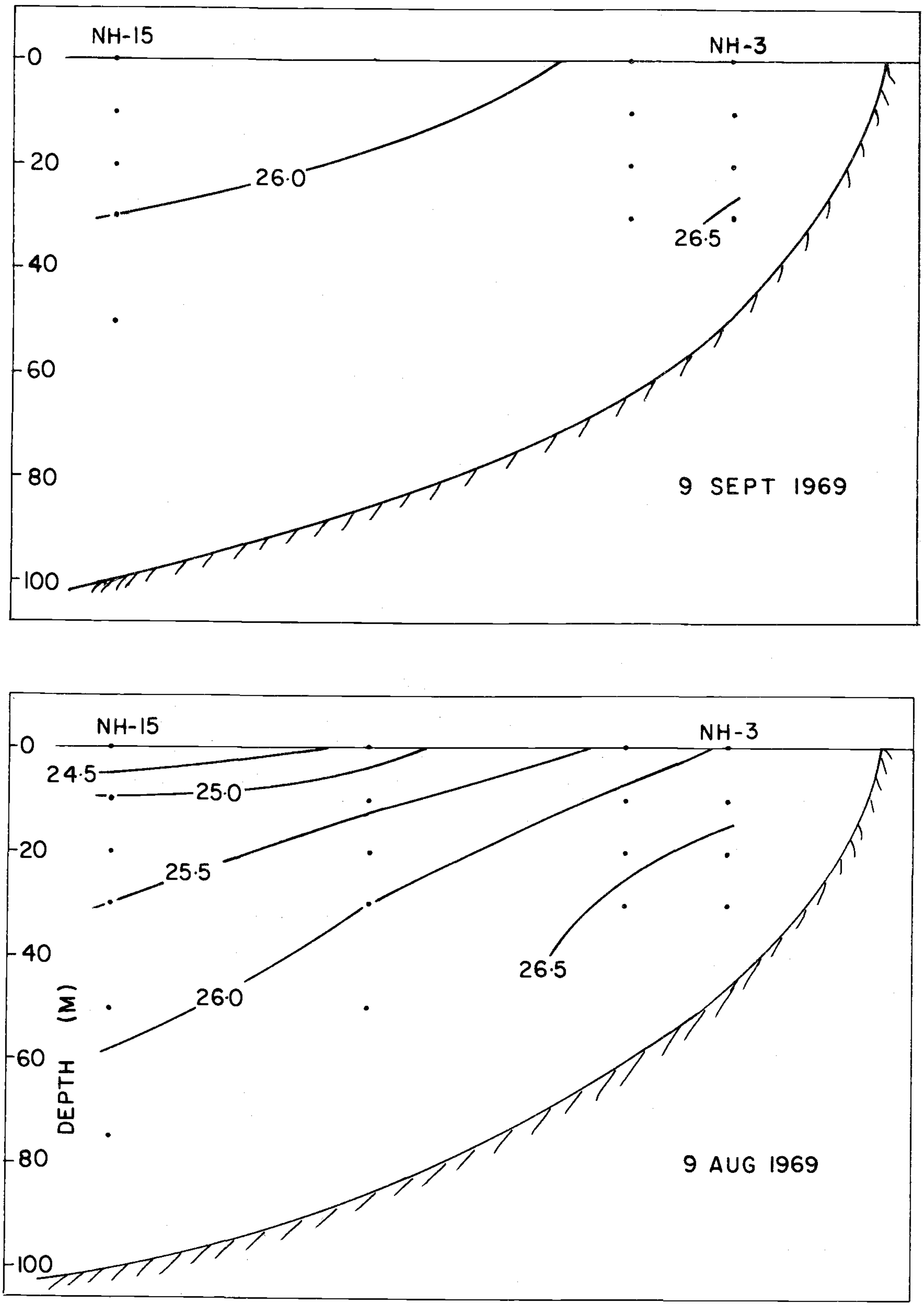

Figure 11. Distribution of sigma-t in a section west of Newport on 9 August and 9 September 1969. The data are from Wyatt et al. (1970).

September. Density observations were not available for DB-7 but the profiles would be similar. It appears that the low response amplitude (1.5%) was associated with a large vertical density gradient and that a larger response (4%) occurred when the water was more homogenous.

Collins and Pattullo (1970) used a regression model with data observed off Oregon in July, September and October 1965 and February 1966. Their regression coefficients between the longshore wind and current ranged between 0.7 and 2.5%. The present 1.5 to 4% result is not inconsistent.

Orientation of the Response

The response current is not parallel to the wind; the minor axis component of the current shows little if any coherence with the wind. The response current is parallel to the major axis of the current, which is very nearly parallel to both the mean flow and the bottom contours at DB-7 (see Figures 1 and 8). This result suggests that the bottom influences the orientation of both the mean and response current.

The Time Lag of the Response

It was expected that the response current would always lag the wind. Collins and Pattullo (1970) found that the currents lagged the winds by intervals between 0 and 0.7 days. Spectral analysis of the present data showed that the current generally lagged behind the wind at low frequencies. However, the comparison in the time domain showed that on some occasions the response current led the wind. There is a possibility that the observed lag is not real; the timing mechanism of one of the meters may not have worked properly. However, experience with the Braincon meters indicates that this is not very likely (Pillsbury, personal communication). If the current depends on the rate of change of the wind, then the current would lead the wind by 90°. If the current depends directly on the wind, the current would be in phase with the wind or lag somewhat behind it. The lag of the current behind the wind varied between +12 and -16 hours. This variability suggests that the current's response to the wind is complex.

The Residual Current

The residual current was not steady; it seemed to depend on the history of the current response to the wind. Apparently the residual does not change when the total current closely resembles the wind.

A very simple model is used to simulate the behavior of the residual current (Figure 12). For simplicity the wind and the reponse current are sinusoidal and have constant amplitudes. The response is interrupted at arbitrary intervals. At first, the total

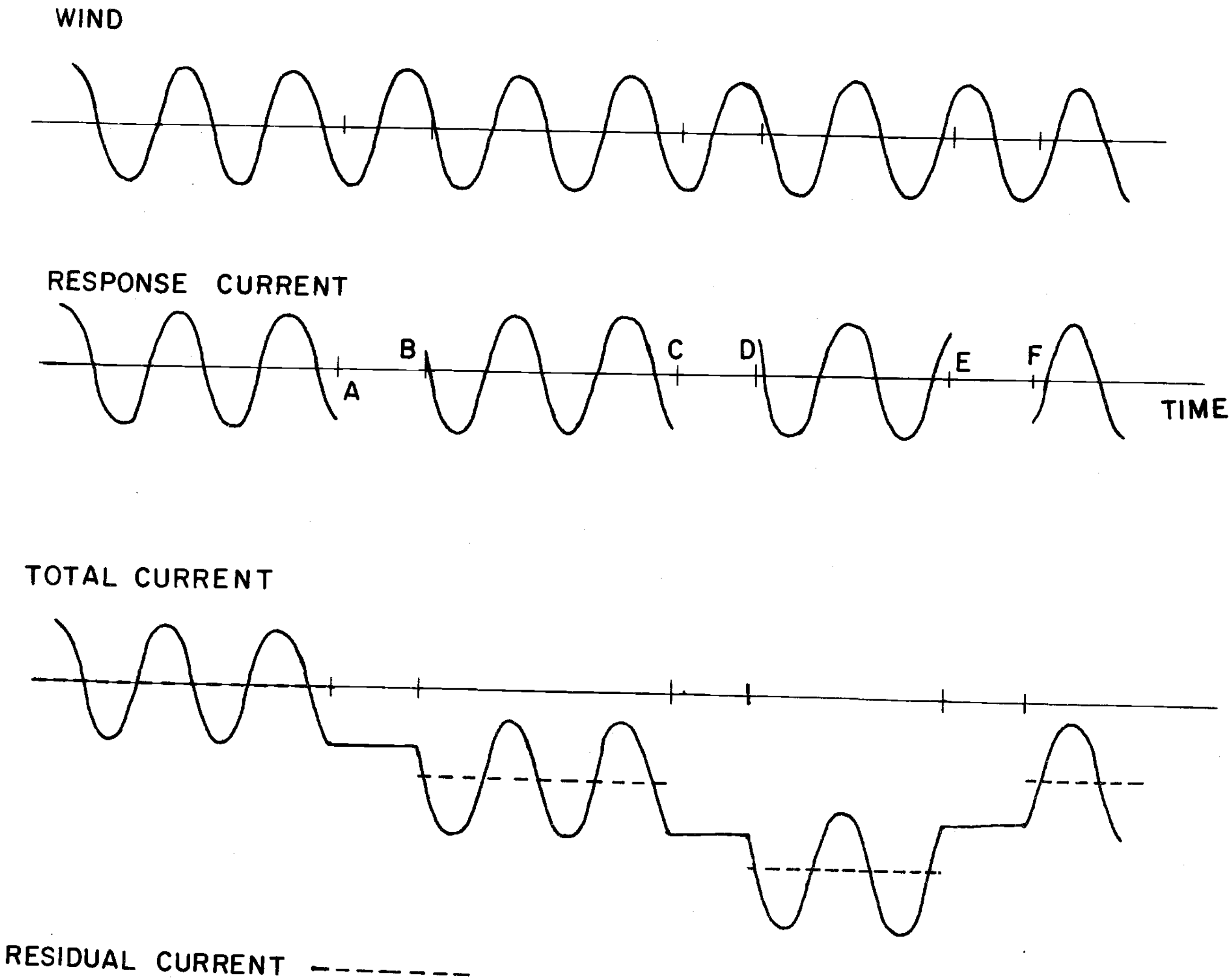

Figure 12. A model of the relationship between wind and current.

current is the sum of an initial residual and the response. When the response is interrupted at A, the total current remains constant until the response resumes at B. Then the response is simply superimposed on the existing total current, so the residual has a new value. The response is again interrupted between C and D, and E and F, and again new values of the residual current result. The change in the residual current depends on differences in the phase of the response at the times of interruption and resumption. If these interruptions are random in nature, so is the residual current.

The model is, of course, much simpler than the situation off the Oregon coast. However, a response current to the wind does exist. And interruptions in it seem to occur when the wind changes too rapidly. The model offers a simple explanation for the observed changes in the residual current.

Collins and Pattullo (1970) found both northward and southward residual currents. It seems that the residual current is quite variable, and that these variations are unpredictable. Therefore current records of a few days or weeks duration may not be representative of the mean flow regime.

SUMMARY AND CONCLUSIONS

The comparison of the current and wind observed off the Oregon coast during the summer of 1969 shows that, at low frequencies, the current is closely related to the wind. The current observations were from 40 m seven miles off Depoe Bay; the surface wind was observed 15 west of Newport.

Slow changes in the wind are related to similar changes in the current. It was suggested that rapid changes in the wind amplify intermediate frequency (tidal and/or inertial) oscillations in the current. The magnitude of low frequency current variations depends on the density profile of the water as well as on the magnitude of the changes in the wind. The response to the wind is largest when the density gradient is smallest. Both the response current and the mean current seem to be parallel to the bottom contours. Usually the wind leads the current, but sometimes the current leads the wind. The variable lag indicates that the relationship between the wind and the current is not simple.

The current can be thought of as the sum of a response current, which follows the variations in the wind, and a residual current. The simple response current can be interrupted or modified when the wind changes too rapidly. When this occurs, the residual current can change unpredictably. Thus there appear to be random changes in the current. Short current records are therefore of limited usefulness in studying the mean flow regime.

The nature of the relationship between the current and the wind is not understood. It has been demonstrated here that there can be a close relationship between the local winds and currents off the coast of Oregon.

REFERENCES

Burt, Wayne V. and Bruce Wyatt. 1964. Drift bottle observations of the Davidson Current off Oregon. In: Studies on Oceanography, pp. 156-165. Editor K. Yoshida. University of Washington Press, Seattle, 560 pp.

Collins, C. A. 1968. Description of measurements of current velocity and temperature over the Oregon continental shelf, July 1965-February 1966. Ph.D. thesis. Dept. of Oceanography. Oregon State University. 153 pp.

Collins, C. A., H. Clayton Creech and June G. Pattullo. 1966. A compilation of observations from moored current meters and thermographs. Vol. I: Oregon continental shelf July 1965-February 1966. Dept. of Oceanography. Oregon State University. Data Report 23. Ref. 66-11. 39 pp.

Collins, C. A., C. N. K. Mooers, M. R. Stevenson, R. L. Smith, and J. G. Pattullo. 1968. Direct current measurements in the frontal zone of a coastal upwelling region. Journal of the Oceanographical Society of Japan. 24 (6): 295-306.

Collins, C. A., and June G. Pattullo. 1970. Ocean currents above the continental shelf off Oregon as measured with a single array of current meters. J. M. R. 28: 51-68.

Cox, Michael D. 1970. A mathematical model of the Indian Ocean. Deep-Sea Res. 17(1): 47-76.

Groves, Gordon W. and Motoyasu Miyata. 1967. On weather-induced long waves in the Equatorial Pacific. J. M. R. 25(2): 115-128.

Groves, Gordon W. and E. J. Hannan. 1968. Time series regression of sea level on weather. Rev. Geophys. 6(2):129-174.

Huyer, A., J. Bottero, J. G. Pattullo and R. L. Smith. 1971. A compilation of observations from moored current meters and thermographs. Vol. V. Oregon continental shelf, 31 July-21 September 1969. Dept. of Oceanography. Oregon State University. Data Report 46. Ref. 71-1.

Jones, E. Lester. 1918. The neglected waters of the Pacific Coast. U.S. Coast and Geodetic Survey. Spec. Publ. 8. 21 pp.

Lighthill, M. J. 1969. Unsteady wind-driven ocean currents. Roy. Met. Soc. Q. J. 95: 675-688.

Longuet-Higgins, M. S. 1965. The response of a stratified ocean to stationary or moving wind systems. Deep-Sea Research 12: 923-973.

Marmer, H. A. 1926. Coastal currents along the Pacific Coast of the United States. U. S. Coast and Geodetic Survey. Spec. Publ. 121. 91 pp.

Mooers, C. N. K., L. M. Bogert, R. L. Smith and J. G. Pattullo. 1968. A compilation of observations from moored current meters and thermographs (and of complementary oceanographic and atmospheric data). Vol. II: Oregon continental shelf, August-September 1966. Dept. of Oceanography. Oregon State University. Data Report 30. Ref. 68-5. 98 pp.

Murray, Stephen P. 1970. Bottom currents near the coast during Hurrican Camille. J. G. R. 75(24):4579-4582.

Ochs, Lyle, Jo Ann Baughman and Jeff Ballance. 1970. OS-3 ARAND system: documentation and examples. Vol. I. Computer Center. Oregon State University. CCR-70-4. 158 pp.

Pillsbury, R. D., R. L. Smith and J. G. Pattullo. 1970. A compilation of observations from moored current meters and thermographs. Vol. III: Oregon continental shelf, May-June 1967, April-September 1968. Dept. of Oceanography. Oregon State University. Data Report 40. Ref. 70-3. 102 pp.

Pollard, R. T. 1970. On the generation by winds of inertial waves in the ocean. Deep-Sea Res. 17: 795-812.

Pollard, R. T. and R. C. Millard, Jr. 1970. Comparison between observed and simulated wind-generated inertial oscillations. Deep-Sea Rs. 17: 813-821.

Robinson, A. R. Editor. 1963. Wind-driven ocean circulation. A collection of theoretical studies. Blaisdell. New York. 161 pp.

Schell, I. I. 1965. On the origin and possible prediction of the fluctuations in the Peru Current and upwelling. J. G. R. 70(22): 5529-5540.

Schell, I. I. 1970. Variability and persistence in the Benguela current and upwelling off Southwest Africa. J. G. R. 75(27): 5225-5241.

Schwartzlose, Richard A. 1962. Nearshore currents of the western United States and Baja California as measured by drift bottles. California Cooperative Fisheries Investigations. Report 1, July 1969 to June 1962: 15-22.

Smith, R. L. 1968. Upwelling. Oceanogr. Mar. Biol. Ann. Rev. 6: 11-46.

Sverdrup, H. U., M. W. Johnson and R. H. Fleming. 1942. The oceans: their physics, chemistry and general biology. Prentice-Hall. Englewood Cliffs, N. J. 1087 pp.

Veronis, George. 1970. Effects of fluctuating winds on ocean circulation. Deep-Sea Res. 17(3): 421-434.

Wyatt, Bruce, William Gilbert, Louis Gordon, and Dennis Barstow. 1970. Hydrographic data from Oregon waters, 1969. Dept. of Oceanography. Oregon State University. Data Report. 42. Ref. 70-12. 155 pp.