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14. Abstract/Notes

Direct measurements of local horizontal current flow within a cool surface plume were made with drogue floats during the March 17-19, 1977 period of JOINT II. Detailed use of the trajectory data provided an opportunity to estimate horizontal divergence within the upper 4m of the plume and on one occasion to 10 m depth. STD casts from a Lagrangian time series were used to estimate the thickness of the mixed layer depth and vertical stability within and adjacent to the plume. These determinations suggest that while limited to a thin surface layer, the upwelling velocity within the plume over 6-hour intervals may be considerable, although 24-hour values of $\underline{w}$ *may average* $2x10^{-2}$*cm* sec^{-1}*. Because of the isotherm changes observed in the near-daily sea surface temperature (SST) charts for the plume, calculations were made of the daily insolation and heat content in the upper water column within the plume and were compared to the horizontal and vertical motion in the plume. The apparent complex interrelations between the observed changes in SST and the horizontal circulation suggest that future studies of cool surface plumes of centers of upwelling be rigorously planned and completed in terms of sampling frequency, density and duration.*

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SHORT TERM VARIATIONS OBSERVED IN THE CIRCULATION HEAT CONTENT AND SURFACE MIXED LAYER OF AN UPWELLING PLUME OFF CABO NAZCA, PERU

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ABSTRACT

Direct measurements of local horizontal current flow within a cool surface plume were made with drogue floats during the March 17-29, 1977 period of JOINT II. Detailed use of the trajectory data provided an opportunity to estimate horizontal divergence within the upper 4 m of the plume and on one occasion to 10 m depth. STD casts from a Lagrangian time series were used to estimate the thickness of the mixed layer depth and vertical stability within and adjacent to the plume. These determinations suggest that while limited to a thin surface layer, the upwelling velocity within the plume over 6-hour intervals may be considerable, although 24-hour values of $\underline{w}$ may average 2×10^{-2} cm sec^{-1}. Because of the isotherm changes observed in the near-daily sea surface temperature (SST) charts for the plume, calculations were made of the daily insolation and heat content in the upper water column within the plume and were compared to the horizontal and vertical motion in the plume. The apparent complex interrelations between the observed changes in SST and the horizontal circulation suggest that future studies of cool surface plumes or centers of upwelling be rigorously planned and completed in terms of sampling frequency, density and duration.

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INTRODUCTION

As part of the multidisciplinary CUEA Program during JOINT II, drogue (Lagrangian drifter) experiments were conducted from the R/V CAYUSE in the vicinity of the C Line off the southern coast of Peru (Plates III and IV). STD profiles were also made from the R/V CAYUSE before, during and after tracking drogues to obtain information on the short-term three-dimensional distributions of temperature, salinity and density. Because of the interactive mechanisms considered to be operating between the sea surface termperature, local wind field and surface water currents, a comparative study was made of these measurements together with measurements of solar radiation incident on the JOINT II area.

Past studies by CUEA scientists and others have shown that the phenomena of coastal upwelling may exhibit a two-dimensional circulation as is the case of upwelling off northwest Africa, or perhaps the three-dimensional circulation described for the Oregon coast and off the west coast of Baja California. One manifestation of a three-dimensional coastal upwelling circulation is the presence or occurence of cool surface plume-like features, or centers of upwelled water manifest at the sea surface. The purpose of this report is to describe variations in the circulation of such a surface thermal feature and how this motion relates to variations in the wind stress, the surface mixed layer depth, vertical stability and heating effects due to the incident solar radiation.

METHODOLOGY

The first flight of the National Center for Atmospheric Research aircraft over the JOINT II area, corresponded to the March 20-21, 1977 drogue experiment. For this experiment four drogues were set for 4 m depth and launched along a line roughly normal to the dominant axis of the surface thermal plume of cool water (see Fig. 1, left panel). The purpose of this experiment was to observe the effects of lateral shear on the surface plume structure. Six drogues were launched, one at a time, at 6-hour intervals near C-3 station for the March 23-25 experiment. The purpose of this experiment was to observe variations in water motion down the axis of flow of the plume as evidenced from the displacement of the drifters. The trajectories for the first three drogues and the second three drogues are also seen in Fig. 1 (center and right panels). Three drogues were set for 4 m depth and launched in a triangular configuration for the March 27-29 experiment. Unfortunately, no aircraft maps were available for this experiment due in part to fog over the region. At each of the vertices of the triangle another drogue was set for 10 m depth and similarly launched. One objective of this experiment was to observe vertical shears in horizontal currents in the upper 10 m of water. A second objective was to obtain estimates of divergence based on time changes in areas encompassed by the drogue triads (Molinari and Kirwan, 1975) and from such measurements to calculate the vertical velocity in or around the cool plume water. Additional details of the drogue experiments may be found in Stevenson and Wagner (1978).

Observations used in the analyses in this report were collected during the March 10-30 period. Data coverage, however, was not uniform in the time nor space and a data subset containing more dense coverage for the intervals of

March 23-25 and March 27-29 was used for the several 24-hour time series analyses. STD profiles used in this report were principally obtained from Leg 1 data of the R/V CAYUSE (Stevenson and Wagner, 1978). STD profiles from 63 stations were made as a Lagrangian STD time series and were all located within an area of about 2 km by 2 km and extended over the period of March 23-29. Mixed Layer Depth (MLD) was calculated from the vertical temperature profiles of the Lagrangian STD series where MLD was defined as being that thickness of the surface layer in which $\Delta T/\Delta Z \leq 0.2C/10m$. Some additional STD/CTD data collected from the R/V COLUMBUS ISELIN (Johnson et al., 1979) and the R/V MELVILLE (Huyer et al., 1978) were also used in the preparation of maps of sea temperature and mixed layer depth.

Sea Surface Temperature (SST) maps were based on infrared measurements of the sea surface made during aircraft overflights centered over the C Line and covering a coastal area of 45 km offshore by 85 km alongshore. A Barnes Precision Radiation Thermometer (PRT-5) instrument aboard the aircraft produced a data record which was digitized at one minute intervals and whose data points were transcribed onto base charts prior to contouring of sea surface temperatures. Further details on the collection and processing of these remotely sensed temperature data are found in Stuart and Bates (1977).

RESULTS

The cold surface plume varied in both intensity (evidenced by an expanding/contracting area and cooler/warmer core temperature) and to a lesser extent in location. During Flight 1, the drogue motions contained strong shears in the alongshore and offshore directions. The changes in motion between the drogues can best be seen in Fig. 1 (left panel), where the more offshore drogues possess a strongly offshore component of motion. Because the mean direction of the inshore drogue was within about 8^0 of the geographic orientation of the coastline, the inshore drogue served as a local direction reference for the horizontal current shears tangent to the coast ($\partial v_t/\partial x_n$) and normal to the coast ($\partial v_n/\partial x_n$). Using the inshore and offshore drogue data we obtained 2.45×10^{-5} sec.$^{-1}$ and 6.28×10^{-6} sec.$^{-1}$ respectively for the shears tangent to the coast and normal to the coast. In addition to the strong shears present, however, horizontal divergence is present when the drifter's movements are plotted as polygons and this divergence accounts for the considerable increase in area of the polygons over the period of the experiment. During the March 23-25 period, the plume area increased in size and was acompanied by a lower core temperature as seen in the center and right panels of Fig. 1. Drogues nearer to the coast during this period moved directly outward from the plume and alongshore; those drogues further from the coast continued to move offshore and toward the south as they passed through the outer boundaries of the plume. During the March 23-25 experiment (Flights 4 and 7) the drogue polygons and local drogue motions shown in Fig. 2 suggested the presence of a convergence zone or front for a period of up to 36 hours before the front dissipated and the local parcel of water underwent progressively greater divergence. Although no overflight was available for the March 27-29 drogue experiment, the results of the drifter experiment are worth reporting. The drogue polygons are seen in Fig. 3 and indicate two items of particular interest: 1) the vertical current shear was strong ($\partial u/\partial z = -1.1 \times 10^{-2}$ sec.$^{-1}$, $\partial v/\partial z = 1.3 \times 10^{-2}$ sec.$^{-1}$) and indicated a current reversal between 4 m and 10 m depths and 2) changes in polygon areas at the two depths for the same time intervals were similar even though the polygon areas did not consistently expand during the experiment.

Fig. 4 (upper panel) is a time series of the vertical velocity estimates at a depth of 20 m and 2 km offshore along the C line, calculated using the variational method presented by O'Brien, Smith and Heburn (1980). Briefly, in this method, measurements of horizontal currents are objectively adjusted and vertical velocities calculated while satisfying some physical constraint. In this case, the physical constraint is simply three-dimensional mass continuity. The calculations use the low-low passed onshore velocity components measure at Oregon State University's (OSU) AGAVE and MILA V moorings, and Pacific Marine Environmental Laboratory's (PMEL) PS and PSS moorings. The alongshore divergence is estimated by using the alongshore components from OSU's PARODIA and MILA V moorings. Since the PARODIA data did not start until March 19, 1977, prior to March 19 the alongshore divergence is assumed to be zero, i.e., essentially two-dimensional continuity, for lack of a better estimate. The lack of high frequency fluctuations in the time series using the variational method is primarily due to the use of low-low passed current measurements where frequencies shorter than 24 hours are suppressed.

The changes in polygon divergence that gave rise to variations in vertical velocity are also seen in Fig. 4 (lower panel). The areal changes of the drogue polygons are evident in Figs. 2 and 3. Note that in addition to changes in polygon area (signifying divergence or convergence) the drogues may undergo marked changes in relative position to nearby drogues, due to significant deforming and stretching shears, and vertical vorticity. These shape and rotational changes, however, do not of themselves give rise to areal changes in the drogue triads. Vertical velocity was estimated from calculations of divergence made from drogue displacements taken on polygons of triangles at 6-hour intervals.

While a detailed discussion of measurement errors associated with drogue measurements may be found in the literature (e.g., Stevenson, 1974), estimates of divergence and vertical velocity errors are worth mentioning. For a typical 6-hour interval, mean current speeds were typically 5 cm sec^{-1} or more. Simple radar measurement errors for an equal period of time suggest an uncertainty of about ±0.1 cm sec^{-1}. Relating this value to divergence with a spatial scale of about 1 km would provide an uncertainty in divergence calculations of about $2x10^{-6}$ sec^{-1} and an uncertainty in w of about $1x10^{-3}$ cm $sec.^{-1}$, adequate for our present study where upwelling velocities often appear to exceed $1x10^{-2}$ cm $sec.^{-1}$. The drogue data therefore appear sufficient to make calculations of divergence over 6-hour intervals.

In addition to evaluating changes in local circulation, STD profiles were used to study diurnal changes in the upper 30 m of the water column. STD data from the 63 stations previously noted were time-folded into a 24-hour period and were used to construct the daily temperature curves for 0, 10, 20 and 30 m depth (Fig. 5). These curves show that diurnal changes in heating penetrate downward in the water column but occur primarily in the upper 20 m of the column. A decrease in the amplitude of the temperature curve is also apparent with depth. In addition there may be a phase shift in the curves with time but the phase relation appears to change between the upper 10 m and 20 m and 30 m curves. The diurnal heating curve for zero meters depth shown in Fig. 5 was used to correct or adjust surface temperature values obtained from ship measurements as shown in Fig. 6. Besides data from the R/V CAYUSE, additional data from the R/V COLUMBUS ISELIN and the R/V MELVILLE between Cabo Nazca and Punta Santa Ana on the aircraft maps of SST are not as readily seen in the surface temperature map of Fig. 6 produced from "bulk" STD temperature measurements. A cool plume or core feature is still evident, however, near the coast (Fig. 6).

Wind data for the 3-day study period were resolved into tangential and normal wind components and have been converted into stress units. The tangential (alongshore) wind stress is seen in Fig. 7 (upper panel). Even though the data were not smoothed the diurnal signal is quite apparent. The wind stress around local noontime is only 1/5 that observed during the nighttime (1900-2300 LST).

Because of the influence of solar heating on the water column, Mixed Layer Depth (MLD) data for the same 63 stations was used to construct a 24-hour curve and is seen in Fig. 7 (middle panel). The value of the MLD is seen to drop rapidly after 0700 LST and to remain at or near zero meters from 1100 LST through 1300 LST after which time the MLD increases steadily until midnight, after which time it remains steady until 0600 LST. The MLD curve was then inverted and used to adjust the MLD data used to construct the MLD map for March 24-25, seen in Fig. 8. Larger MLD values are seen in the cool core and around the perimeter of the plume with intermediate values between the two areas.

Static Stability (E) for 0-10 m, 10-20 m and 20-30 m layers was also determined from the STD time series and the data time-folded into a 24-hour period as seen in Fig. 7 (bottom panel). Because of the large variations typically observed for Stability, a simple 3-point smoothing was performed on the time series. Note that while the mean Stability for the 0-10 m and 10-20 m layers is about the same, a strong diurnal signal is present in the surface layer. The Stability for the 0-10 m layer is considerably less during the period of 2100-0700 LST than at other times of the day. The wind stress fluctuations appear to be inversely related to both Stability and MLD curves. This reduced Stability occurs in the absence of solar heating and during times of increased wind strength. The local effects of momentum transfer from the wind field and vertical mixing appear to be limited to the upper 20 m of water. While a slight diurnal signal is present in the 20-30 m layer, the changes in the water column due to diurnal effects are greatly diminished in going from the 10-20 m layer to 20-30 m layer.

The amount of solar radiation available during the March 10-30 period is seen in Fig. 9. The level of daily insolation was surprisingly constant with a mean value of 479.8 Ly/day and a standard deviation of only ±30 Ly/day. The fluctuation represents an 8% change and of this amount 3-4% of the fluctuation was due to the seasonal progression of the sun's altitude. A detailed look at the daily solar traces for this period of time suggests that out of 20 daily solar traces only 5 contained significant levels of cloud contamination.

DISCUSSION AND SUMMARY

An evaluation of the SST maps based on aircraft data suggests that such temperature maps are capable of showing a considerable amount of detail, albeit of a thin layer of surface water. Other studies (Saunders, 1970) have shown that during relatively clear skies PRT data typically are within 0.5C of the bulk surface temperatures. During periods of low winds combined with high levels of insolation, the surface skin of the water may be considerably warmer than that found within the uppermost meter of water; both bulk temperatures and PRT values may possess diurnal signals on the order of 1-2C (Stevenson and Miller, 1972). Although the NCAR overflights were made during 1100-1500 LST, a time of relatively weak winds, the radiation bias appears to have been minimal (e.g., 0.5C) as evidenced from the calibration temperatures obtained during flights over the R/V CAYUSE.

A comparison of the drogue trajectories with aircraft SST charts suggests a strong association between nearsurface drogue trajectories and hypothetical water motion needed to support the observed isotherm patterns in and around the cool surface plumes. During the March 21-30 period, vertical velocities varied with both upwelling and downwelling present. Apparently the SST maps were sufficiently sensitive to indicate changes in the intensity of upwelling in the upper few meters of water on a time scale of 1-2 days, similar to the motions of nearsurface drogues.

While experiments involving a larger number of drogues would have been preferred, the experiments that were realized show the nearsurface water (i.e., 4 m depth) to be strongly coupled horizontally and vertically with the local wind field. Variations in the upper 30 m of the water column show a coupling with both the wind field and also the incident solar radiation. Although short term (e.g., 6-hour) time changes in vertical velocity result in unexpectedly large values of w, such data averaged over 24-hour periods produce values of w on the order of only $2\text{-}4 \times 10^{-2}$ cm sec^{-1}, which is of the same magnitude as the objective analysis model of upwelling based on current meter data (Fig. 4, upper panel). The vertical velocity time series of Fig. 4 suggests that both ensembles of suitably tracked drifters and data from areal arrays of current meters are capable of providing realistic estimates of w in a coastal upwelling zone.

Subsurface temperatures at 10 m and 20 m suggest that the coolest water lies along the coast around Cabo Nazca and extends southward toward Punta Santa Ana. This is different from the surface temerature maps which show surface water off Cabo Nazca to be warmer than, and outside, the cool water plume located north of Punta Santa Ana. If it is assumed that the coldest water represents the most recently upwelled water, then the most actively upwelled water begins its ascent in proximity to Cabo Nazca and flows poleward and alongshore. The water continues to rise as it moves into the vicinity of the surface plume at which time it finally breaks into the surface mixed layer. There the momentum from locally applied wind stress advects the cool water equatorward and offshore. Ekman suction in the vicinity of the cool plume assures continuance of subsurface water moving upward into the surface plume.

In the vicinity of the cool surface plume the daily insolation amounts to about 465 Ly/day if a 3% reflection factor is assumed for the large solar altitude (68-75°). Using a surface mixed layer of 6 m for the maximum mixing depth of the incident solar radiation, the influx of solar energy is sufficient to raise the temperature of the MLD by 0.81C/day. If we assume water at 4 m to flow out of the plume at 5-10 cm sec^{-1} then in one day, the water will be advected 4.3-8.6 km from the immediate area of the upwelling and the water will be advected outward from the cold core toward the plume perimeter in 1-2 days. From the separation of isotherms on the SST maps together with the advection rate in the surface layer, the horizontal gradient of the isotherms approximately equals the heating rate of the upper mixed layer and its advective rate out from the cool core area. Water ascending at $2x10^{-2}$ cm sec^{-1} would bring water from 6 m to the surface in about 8 hours. The effect of the cool ascending water is to reduce the net heat gain from solar insolation in the upper 6 m. Once the water parcel has moved away from the most intense upwelling area, i.e. the cool core, upwelling becomes less and the vertical velocity may in fact indicate subsidence. By this time the water has been advected to the perimeter of the plume where it may remain for another day or two all the time absorbing incident solar radiation. In summary then it appears that the warmer water immediately surrounding the cool core can be largely explained in terms of cumulative solar heating of the cool upwelled water as it moves away from the core of the plume.

Our analyses of local motions in the plume, mixed layer depth, heat content and vertical stability in a coastal upwelling plume would have been more complete had the original field work been planned and conducted somewhat differently. Our efforts suggest that plans for station spacing and sampling frequency for supportive hydrography in future studies be made with particular care. Further, while data from an array of current meters surrounding a plume can provide a sound basis for reference of local circulation, continuous measurements of a large number of some type of drifter are preferred. The Lagrangian drifter array can provide the necessary details of transient frontal features found within or adjacent to plumes and thereby provide improved insight into the dynamics of cool surface plumes or centers of upwelling.

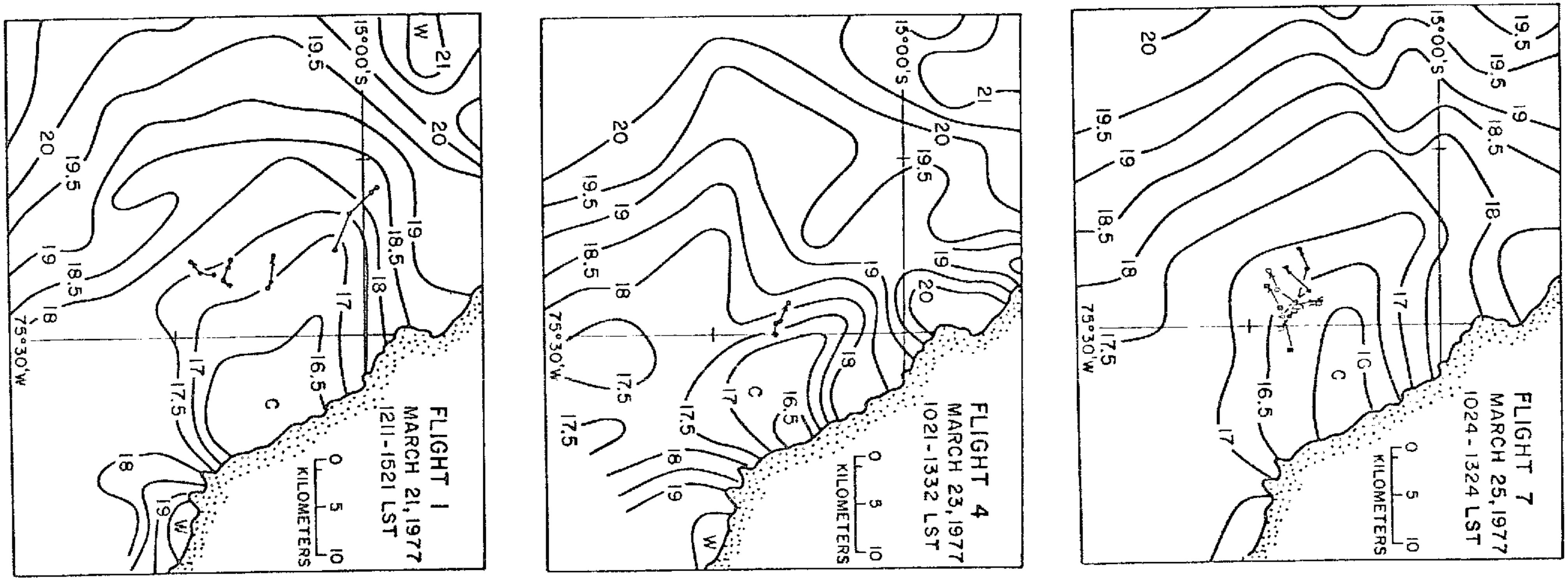

Fig.1 - Maps of SST as obtained via aircraft.
Left Panel - Flight 1, March 21, 1977.
Center Panel - Flight 4, March 23, 1977.
Right Panel - Flight 7, March 25, 1977.
Dots, squares, and triangles refer to 6-hour displacements of drifters for a 12-hour period centered around the flight time. Arrows indicate the sense of the drifter motion.

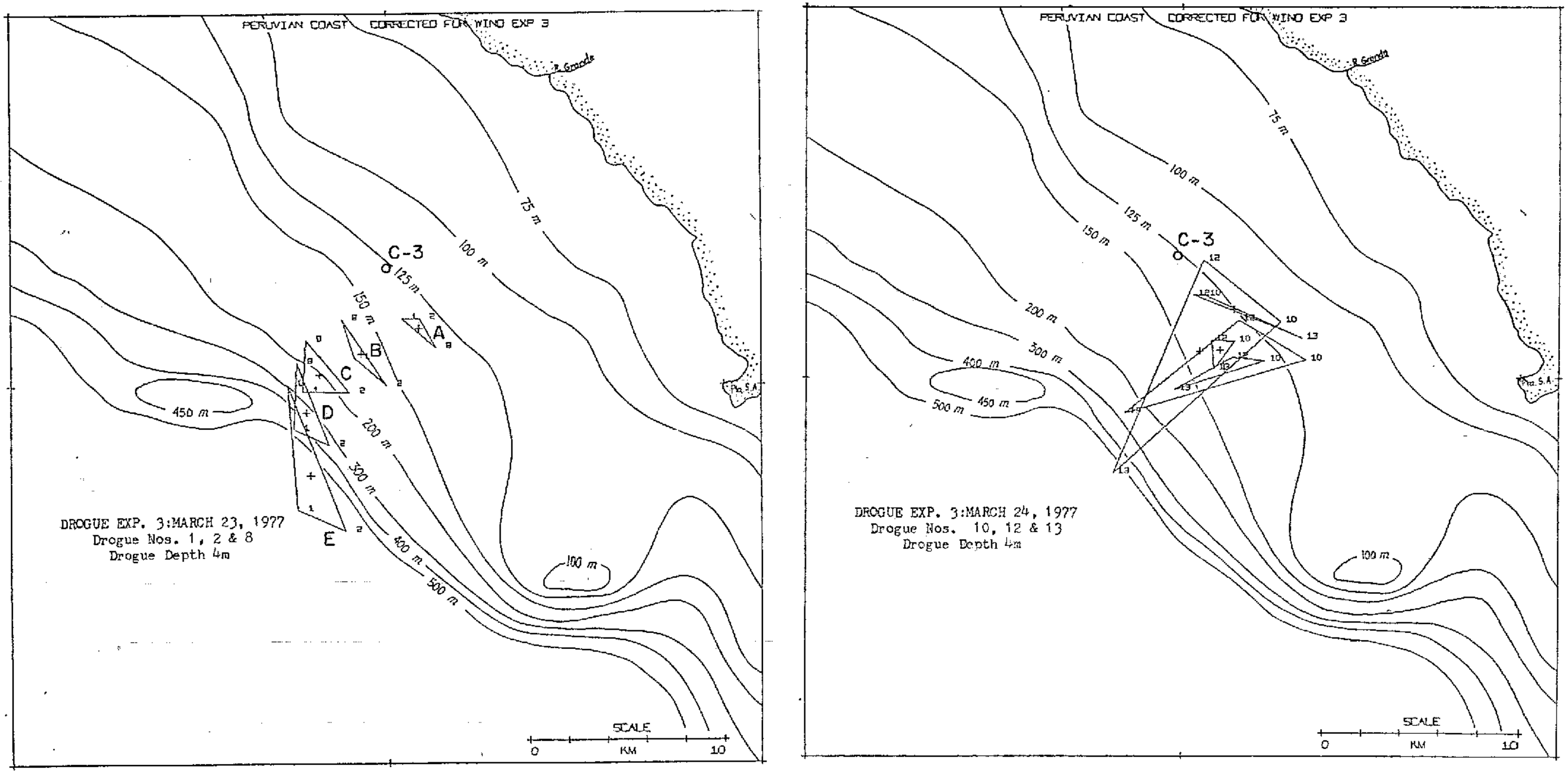

Fig. 2 - Drogue triangles plotted at 6-hours intervals. Left Panel - Progression of drifter ensemble shown after initial 36 hours of experiment. The drogues launched at Station C-3 (marked on Figure), drifted within the small triangle (A) for the first 36 hours, and during the following 24 hours moved successively through triangles B-E. Right Panel - Progression of drifter ensemble after initial 24 hours of experiment. Drogues in right panel were launched in sequence at Station C-3 following the three drogues in the left panel.

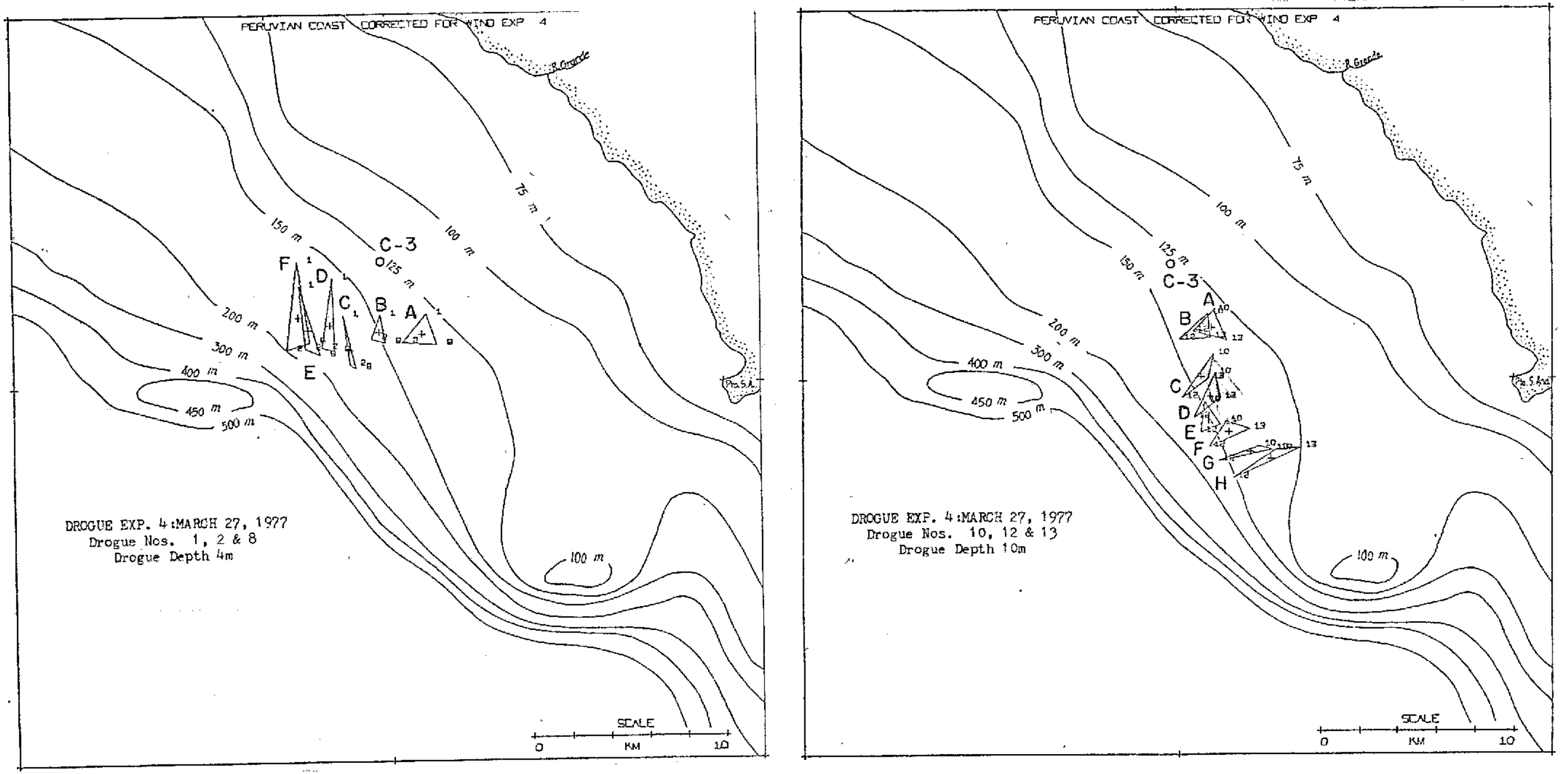

Fig. 3 - Drogue triangles plotted at 6-hour intervals. Left Panel - Drifter ensemble progressively moved across isobaths as shown by triangles A-F. Drogues set for 4 m depth. Right Panel - Drifter ensemble moved along isobath and poleward (triangles A-H). Drogues set for 10 m depth.

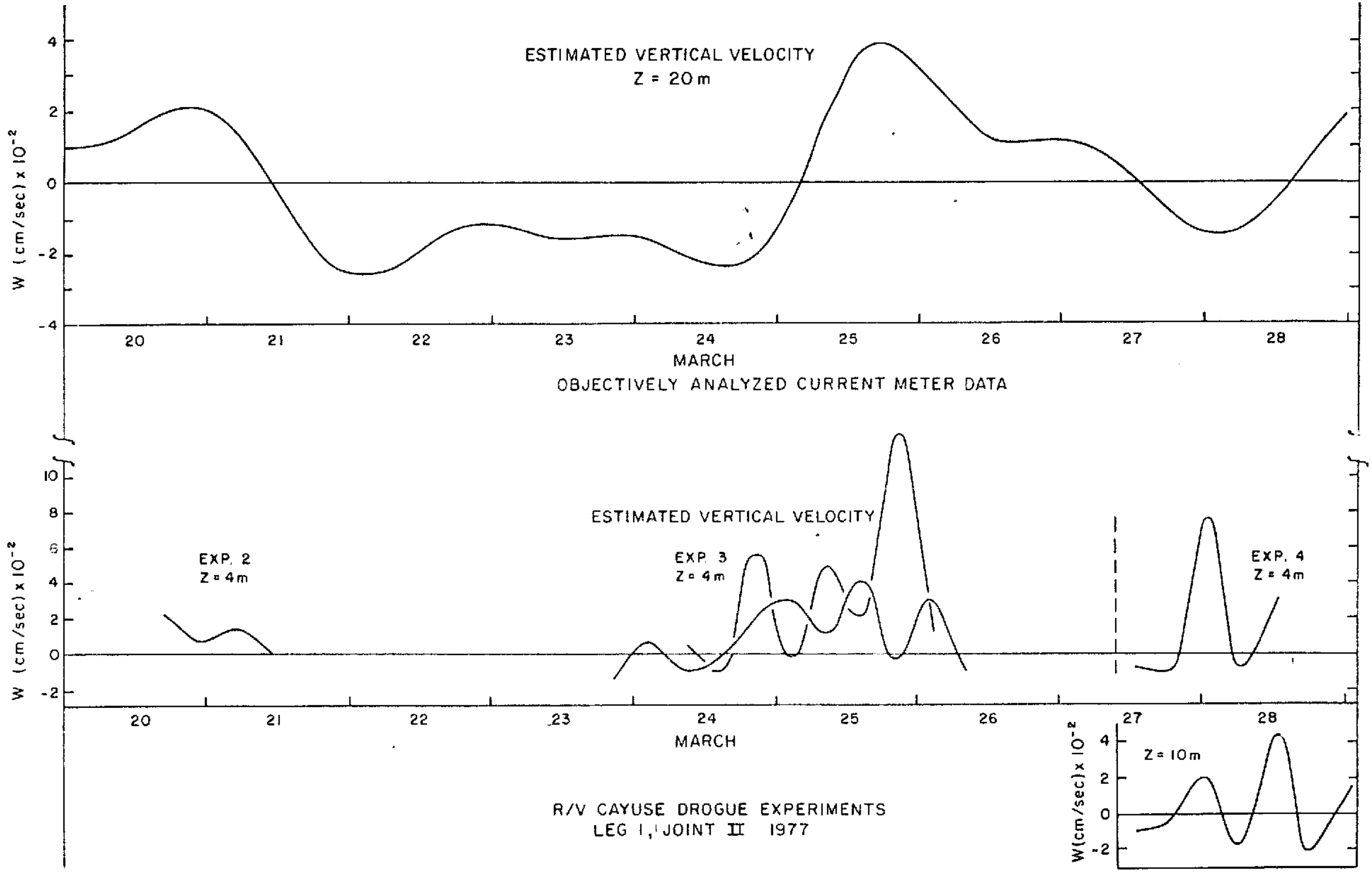

Fig. 4 - Vertical velocity estimated from: Upper Panel - Numerical model using objectively analyzed (low-low passed) current meter data. Lower panel - Changes in area (horizontal divergence) of drogue polygons over 6-hours intervals. Curves in lower panel for March 23-26; each curve represents 3 drogues separated by 6-8 km and adjacent to the cool plume. Differences in the lower two curves for March 23-26 suggest that significant variations in w occur in the vicinity of the cool plume.

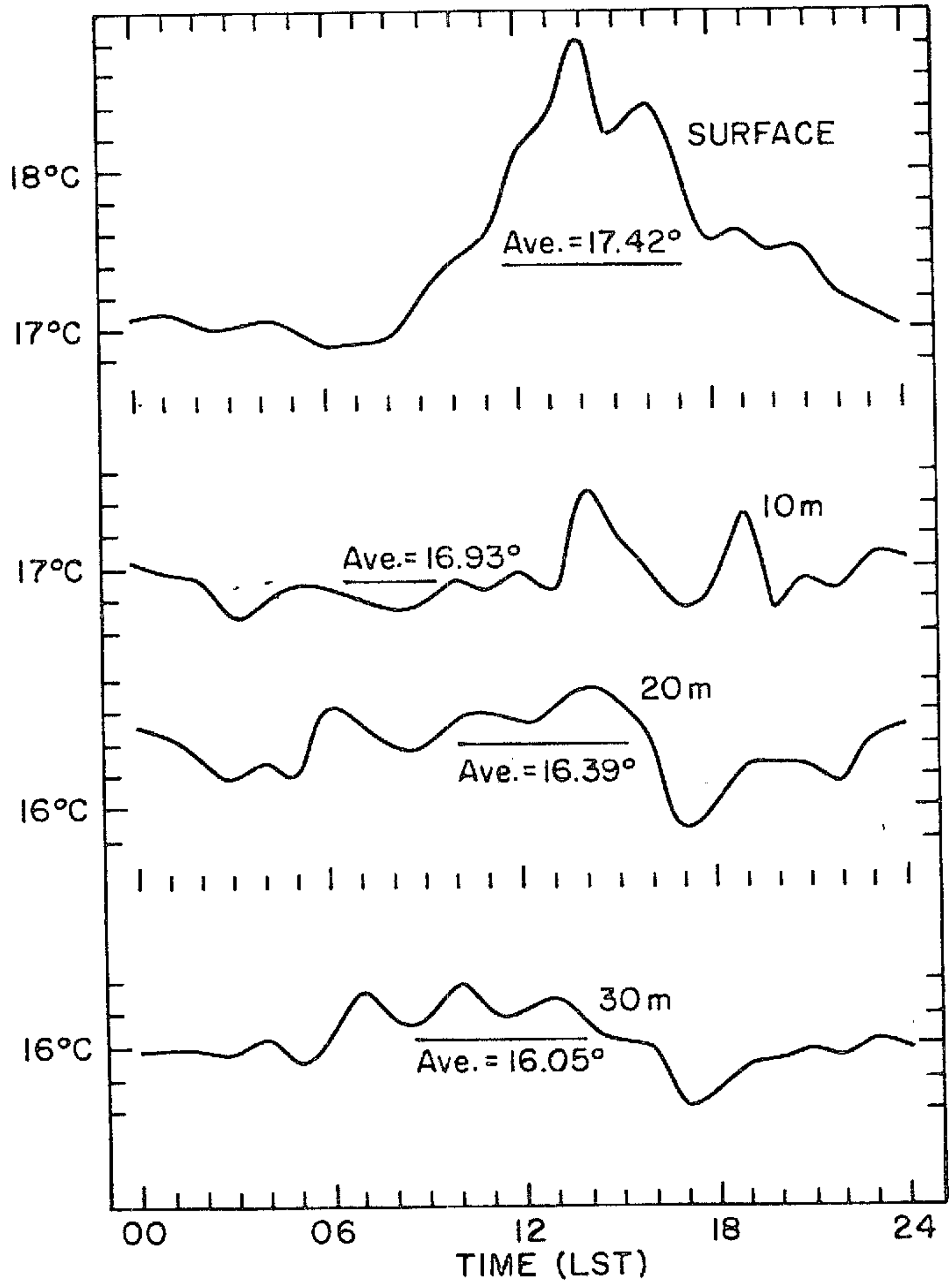

Fig. 5 - 24 hour temperature time series for 0, 10, 20 and 30 m depth. STD data used to construct temperature curve were from the period of March 23-25, 1977. Most of the diurnal signal appears to be confined to the upper 20 m of water.

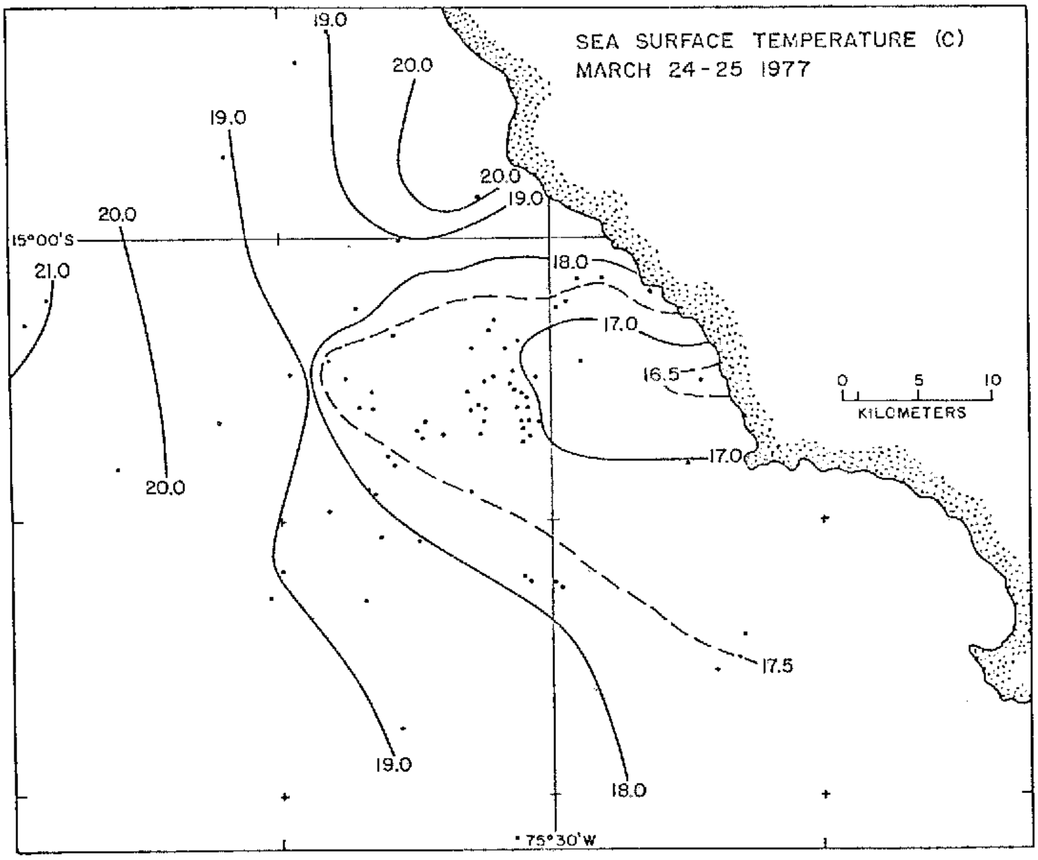

Fig. 6 - Sea surface temperature map composited for March 24-25, 1977. Data were corrected for diurnal changes in surface temperature using the surface temperature time series from Figure 5.

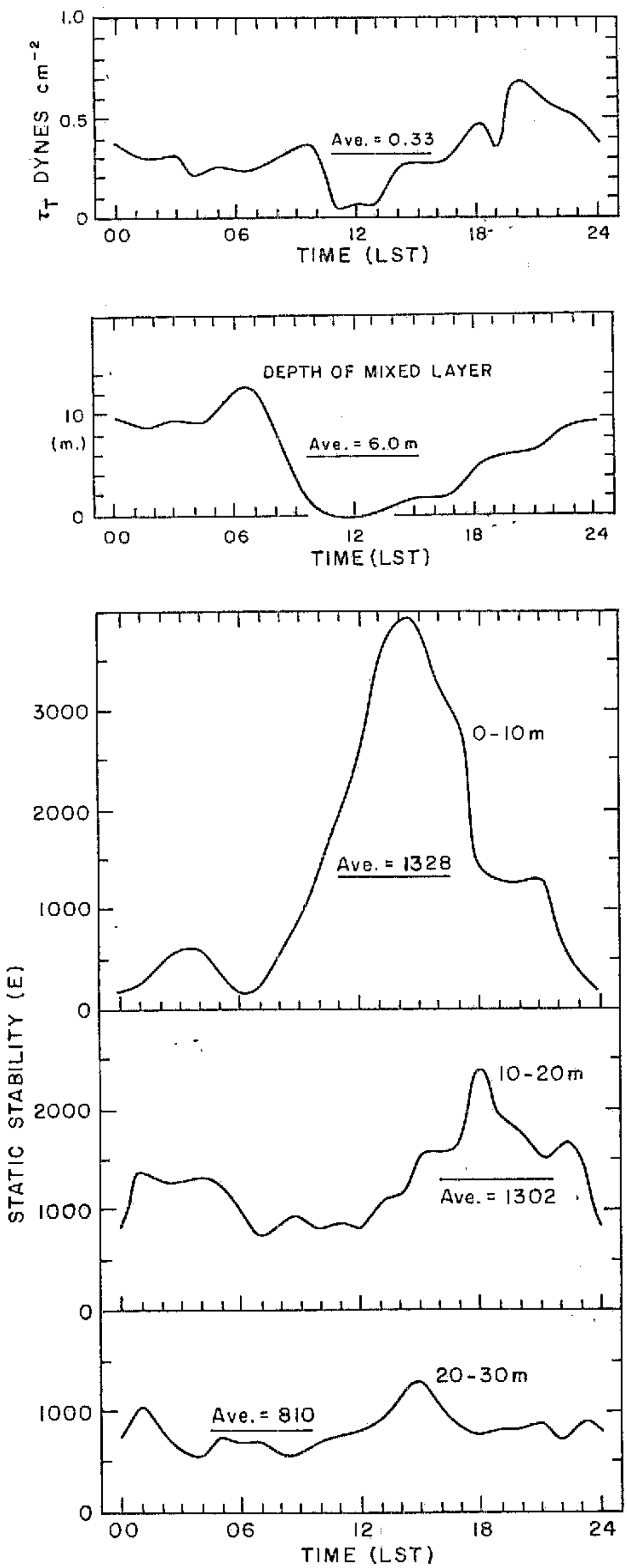

Fig. 7 - 24 hour time series for the period of March 23-25, 1977. Top Panel - Tangential wind stress based on hourly wind observations from the R/V CAYUSE. Middle Panel - Depth of Mixed Layer derived from three-day STD time series. Bottom Panel - Static Stability (E) obtained from the same STD time series for 0-10 m, 10-20 m and 20-30 m layers.

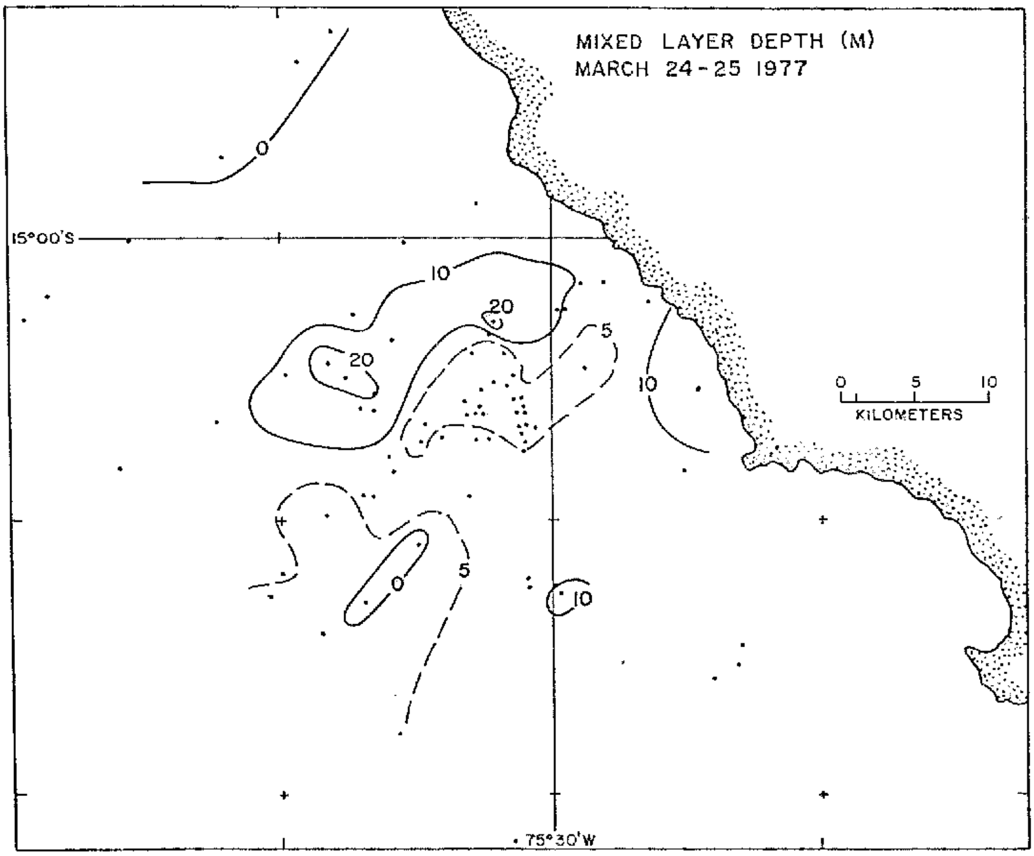

Fig. 8 - Mixed Layer Depth (MLD) map composited for March 24-25, 1977. Data were corrected for diurnal changes in MLD using the MLD time series from Figure 7 (Middle Panel).

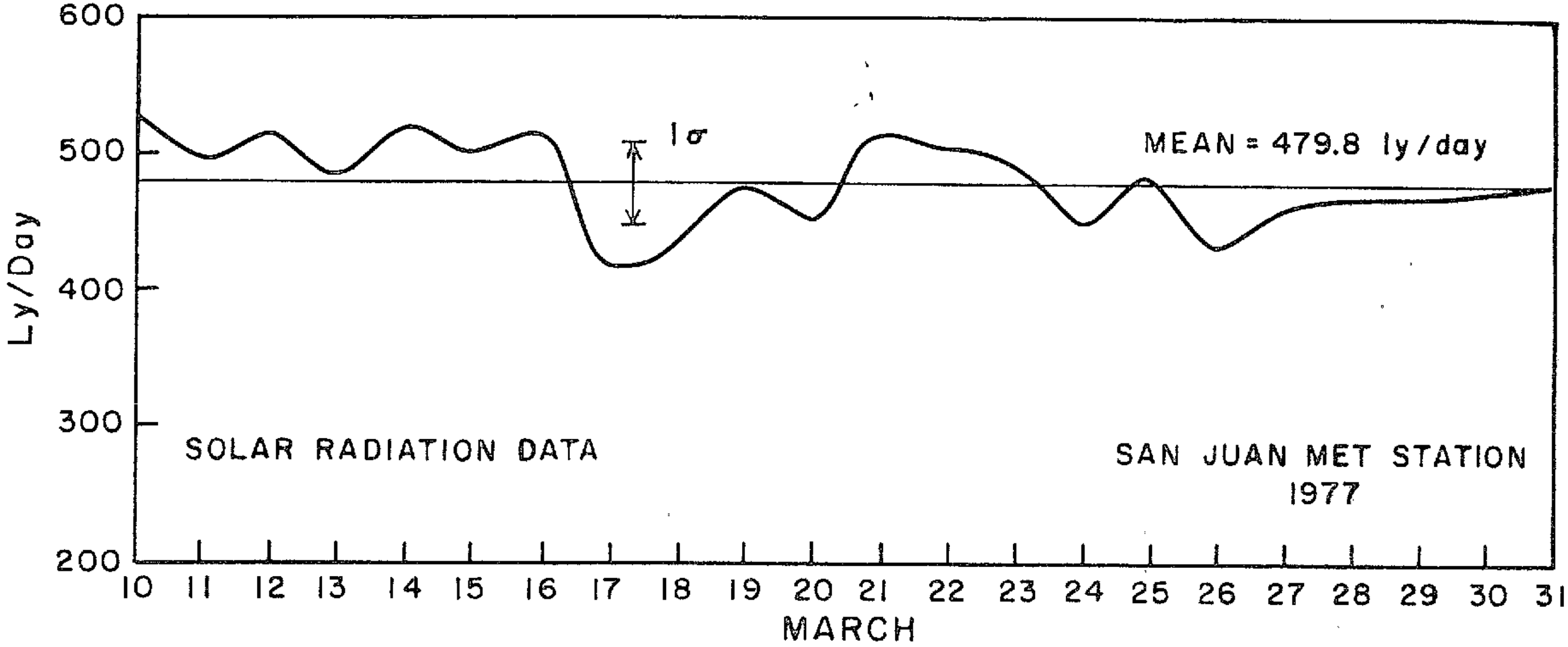

Fig. 9 - Daily solar radiation for March 10-30, 1977, based on integration of daily radiation traces. Note the 1 standard deviation of ± 30 Ly/day about the mean radiation line.

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