Mesoscale Variability of Sea Surface Temperatures

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ABSTRACT

Results of an investigation of the nature of the mesoscale variability of sea surface temperature (SST) in the upwelling zone off the central coast of Oregon are presented. A knowledge of SST mesoscale variability is important toward understanding the mesoscale air-sea interaction process in an upwelling zone. Almost-daily sea surface temperature data gathered by remote sensing techniques provided the basis for this investigation. These data were gathered over a period of 60 days during the COHO Project in summer 1973. In order to study the influence of wind forcing on the mesoscale SST field, wind data were gathered from an anemometer located at Newport, Ore.

Some important results of this investigation are: 1) the daily SST fields respond rapidly to wind forcing; 2) the three-week mean SST’s tend to follow the large-scale bathymetry; and 3) identification of SST eddies from day to day on daily perturbation (from the three-week means) maps is made difficult because of the existence of strong horizontal flow and strong shear in the longshore current. Other important results are revealed by a two-dimensional spectral analysis of the daily horizontal sea surface temperature fields and the perturbation fields. This analysis indicates that a large amount of variance of the sea surface temperature is concentrated in the 16-40 km wavelength range, and over the range of scales from 4-20 km the isotropic part of the temperature variance spectrum obeys a $-3$ power law. These spectral results are important biologically and physically. An interesting feature of the mesoscale SST field, which is also important biologically and physically, is the existence of strong horizontal SST gradients called “oceanic fronts.”

1. Introduction

One of the intriguing characteristics of a coastal upwelling zone is the mesoscale variability of the observed sea surface temperature (SST). A knowledge of the mesoscale spatial scales of the SST is important toward understanding the mesoscale air-sea interaction process in an upwelling zone. Investigators (e.g., Smith, 1968) have long known that along the eastern boundaries of oceans low surface temperatures often occur due to upwelling of cooler subsurface water. In the Northern Hemisphere an equatorward wind stress along the eastern boundary of an ocean combined with the effect of the earth’s rotation produces a mass transport offshore in a surface Ekman layer. This divergence of surface waters away from the coast results in cold water being upwelled from the subsurface layers to replace this offshore flowing water mass.

In this paper some of the results of an investigation of the nature of this mesoscale variability of SST off the central coast of Oregon will be presented. Almost-

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northerly winds do not blow steadily during this whole period. Instead, CUE researchers observed "upwelling events" which occurred on the time scale of days or weeks. During these events winds are generally from the north and northwest. This variability in wind forcing seems responsible for rapid changes in the SST field. Data from the COHO Project reveal that nearshore SST's may drop as much as 6°C in three days during periods of intense northerly winds. CUE-I researchers found that during an upwelling event the warmest temperatures shoreward of the shelf edge may become cooler than the coldest temperatures in the region prior to the event, a result also shown by the COHO data (O'Brien, 1972b).

Another interesting feature observed during CUE-I and II in the upwelling region off the coast of Oregon is that on certain days the SST field may have embedded in it regions of strong horizontal temperature gradients called "oceanic fronts." SST's may change several degrees Celsius within several hundred meters to a kilometer within one of these frontal zones. These fronts are rather well-defined and their location usually changes from day to day. The length of the frontal zone may vary from several kilometers to several tens of kilometers. These oceanic fronts may also intersect the coastline at some location and then extend seaward in a SSW or SW direction. Because they concentrate phytoplankton and other buoyant materials, these fronts are quite important biologically.

An analysis of the three-week means from COHO Project data shows that the mean isotherms tend to follow the large-scale bathymetry of the upwelling region. Inspection of the daily perturbations from these means leads one to conclude that it is difficult to follow individual eddies from day to day. The reason for this is that horizontal flow in this area is strong (10-40 cm s⁻¹) and there is a strong shear in the longshore current.

Finally, results from a two-dimensional spectral analysis indicate that over the range of scales from 4-20 km the isotropic portion of the temperature variance spectrum $E_r(k)$ is shown to obey a $-3$ law. Spectra were computed for daily SST's, three-week mean fields, and daily perturbations from these means. A plot of $kE_r(k)$ vs the logarithm of wavenumber $k$ reveals a spectral peak at wavelengths of 16-40 km.

2. Data acquisition and reduction

The purpose of this section is to provide a brief description of the acquisition and reduction of the SST data gathered during the COHO (Coho Salmon Prediction) Project. This project was undertaken in order to study the feasibility of applying remote sensing techniques to the gathering of mesoscale SST data off the central Oregon coast. The collection and analysis of these data was a necessary input for providing daily forecasts of environmental factors influencing the location of harvestable Coho Salmon in Oregon coastal waters. Coho Salmon have been observed to prefer a temperature range estimated to be between 11.0 and 13.0°C (Richey, 1971). One of the significant products of this project was 35 synoptically-analyzed SST maps made from 35 successful SST mapping flights. During the 62-day period of the project, flights could not be made on 27 days due to either an impenetrable ceiling along the coastal mountain range or inshore fog near the coast. Table 1 contains the COHO flight summary. This collection of analyzed data represents the largest accumulation of almost-daily SST data in a coastal upwelling region or other oceanic region to date. [For a more in-depth study of the COHO Project, see O'Brien (1974a, b, c).]

Flying at an average altitude of 150 m (500 ft) above the ocean, a high-winged, single-engine aircraft, equipped with a narrow-band, 10-12 μm (Barnes PRT-6) remote precision radiometer, made the daily SST mapping flights. This radiometer was chosen since it was the best radiometer available for use which could minimize effects of water vapor absorption in the air column between it and the sea surface. Our PRT-6 calibration procedure was designed to minimize the error caused by these effects and other errors which could arise during the data collection process. Before and after each flight field calibrations of the PRT-6 were made. An infight check which proved invaluable in providing a confidence level for the data was made through the use of a citizen's band (CB) radio. This radio permitted the aircraft data taker to make an almost instantaneous check between the temperature recorded by the strip chart recorder in the aircraft and the bucket temperature taken by a fishing boat almost directly under the radiometer. Two other infight methods for checking the effects of water vapor absorption were made by varying the air column length between the aircraft and the sea surface. Both were occasionally employed (Saunders, 1970; O'Brien, 1972a; Thompson, 1973). The air column length could be varied by banking the aircraft or by flying over the same water twice at different altitudes. Precision in measuring SST in this project was on the order of 0.25°C.

A typical flight plan is shown in Fig. 1 [for daily flight plans see O'Brien (1974b)]. The flight plan was developed to take advantage of the aircraft navigational aids in the central Oregon coastal area (Newport VOR). After the daily mapping flights were completed, the SST data were plotted on a map along the actual flight paths. These plotted values were then synoptically analyzed. Later the SST's from these daily maps were digitized and computer-contoured maps were produced. The SST's were digitized for every 1 km within the inshore 20 km and for every 2 km
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* Location codes: DB, Depoe Bay; LC, Lincoln City; NPT, Newport; YAC, Yachts.
** Measured at Newport.

offshore of 20 km. Bilinear interpolation reduced the offshore 2 km grid to a 1 km grid scale. The remainder of this paper deals with the scientific interpretation of this digitalized data. All SST maps in this paper are computer produced unless otherwise noted.

3. Features of the mesoscale sea surface temperature field

We investigate the response of the SST field to wind forcing, and describe horizontal SST gradients and their attendant oceanic fronts. Also presented is a case study of the daily temperature differences during an upwelling event.

Fig. 1 displays the pertinent bays, capes and towns which will be referred to later in this paper. Fig. 2 gives an indication of the response of the SST field to wind forcing. In order to analyze the effect of the wind field on the SST field, the wind data gathered from the anemometer located at the Newport south jetty were processed. Winds measured by this Bendix-Fries anemometer were recorded continuously on a strip chart. The values transcribed from the strip chart were 20 min averages centered at each hour. Since our SST data were gathered no more than once daily these hourly values were vector-averaged over a 24 h period to obtain the daily average which is referred to in this paper. Fig. 2a shows a time series of the daily averaged Newport winds and SST's at 3, 10 and 15 km off Cascade Head, Ore., during the period 13 June to 15 August. Newport winds are denoted by wind bars showing wind speed in knots. SST's normally increase in the offshore direction within 30 km of the coast. They are generally cooler when northerlies are blowing and warmer when southerlies are blowing. Values 5 km offshore of Cascade Head range from a low of 7.4°C on 14 July to a high of 15.2°C on 7 July. The most rapid cooling occurred during the days 9–12 July, a period of strong northerly winds. Winds were gusting to 19 m s⁻¹ from
the NNW on 12 July. During this period SST's 5 km offshore of Cascade Head dropped from 14.5°C to 8.5°C. Recall that the annual range is only 3°C (from monthly averages). An anomalous warming is shown during a period (4–7 August) when northerlies were blowing. An investigation of the horizontal SST maps for these days reveals that warm water was being advected through the flight region from the NW.

Fig. 2b shows a time series of the daily averaged Newport winds and SST's along the 40 m isobath offshore of selected points along the Oregon coast during the period 15 June to 15 August. The 40 m isobath is within 5 km of shore. Again we note that SST's are generally cooler when northerlies are blowing and warmer during periods of southerlies.

SST's from Newport to Cape Lookout may vary as much as 3.5°C and as little as 1.0°C along the 40 m isobath. As was true in the previous figure, the most rapid cooling along the 40 m isobath occurs during the period 9–12 July. We can note from Fig. 2 that during several periods the SST's reached about the same minimum value. In the summer of 1973 this minimum value corresponded to about the coldest water found on the bottom of the ocean on the continental shelf (Huyer, 1974).

An inspection of the daily horizontal SST maps reveals the large variability of the entire mesoscale temperature field from day to day. During a period of northerly winds the warmest temperature shoreward of the shelf edge may become cooler than the coldest temperature observed in this region prior to the period as shown by examining Fig. 3.

An investigation of the horizontal SST maps also reveals the existence of areas of strong horizontal SST gradients called “oceanic fronts.” These oceanic fronts represent a zero-order discontinuity in sea surface temperature. Surface convergence may exist in the vicinity of the oceanic front and may be found to be quite strong with long foam lines and color fronts tending to align themselves NE-SW along the coast. These frontal areas were often easily visible from the mapping aircraft.

Figs. 4b and 4c are horizontal SST maps which display regions of strong temperature gradients. These maps show horizontal SST’s for 15 and 16 July, respectively. Northerly winds had been blowing since 9 July. One of the oceanic fronts is located off Cape Lookout between the 100 and 150 m isobaths on 15 July. By 16 July the front has moved inshore of
figures really may exist on the scales of several hundred meters to 1 km instead of several kilometers as noted by the data-taker when he was gathering the SST data during the project. A study of Southern Hemispheric upwelling (Bang, 1973) showed a similar frontal structure and strong temperature gradients at the end of a period of Southern Hemispheric upwelling producing southerlies. In Thompson's (1974) model, which included thermodynamic effects, rapid lowering of the SST during wind forcing characteristic of upwelling events resulted in the formation of a strong horizontal temperature gradient or frontal region near shore.

The final topic to be presented in this section is a case study of the daily horizontal SST differences during the period 7–16 July. Because mapping flights were not made on 8, 10 and 13 July, Figs. 5a, 5b and 6b represent SST differences for two days. This period of 10 days ended with 8 days of northerlies. Winds on 7 and 8 July were light southerlies. The strongest winds during the project blew from the north on 11 and 12 July. During the afternoon hours on 11 July winds blew steadily from the NNW at 8–10 m s⁻¹ with gusts to 15 m s⁻¹ while on 12 July winds blew steadily from the NNE at 14–16 m s⁻¹ with gusts to 20 m s⁻¹. Horizontal SST’s for 7 July are shown in Fig. 4a; values range from greater than 15°C along the coast northward from Depoe Bay to Cape Lookout to less than 13°C alongshore south of Depoe Bay to Newport. Fig. 4c shows horizontal SST’s for 16 July at the end of the case study period; values are less than 9°C all alongshore and are not greater than 13°C until we go offshore of the 150 m isobath in most of the region.

Fig. 5a shows the differences in SST between 7 and 9 July. Winds had only started to blow strongly from the NNW during the mapping flight on 9 July. Little cooling in the flight region is shown. With continued
northerly winds the SST's began to cool more rapidly as shown in Fig. 5b. The temperatures dropped from 1.5°C to greater than 2.0°C inshore of the 50 m isobath during the two-day period 9 to 11 July; the greatest cooling occurred between 11 and 12 July. Examination of Fig. 6a shows temperature decrease of as much as 3.0°C to 4.5°C in the offshore area between the 50 m and 100 m isobaths. In Thompson's (1974) model the water temperature cooled 5°C in less than one day very near the coast. Fig. 6b reveals that SST's changed very little over the region (0.5°C or less) except offshore from Cape Lookout. In a region 15–30 km offshore from Cape Lookout temperatures decreased by 0.5 to 1.5°C while northerlies were blowing. As was stated earlier in this section, the SST can only become as cold as the deep shelf water being upwelled. Values on 14 July were very cold as shown by Fig. 4d.

A glance at Fig. 7a shows that an intense warming happened offshore of the 100 m isobath in the Cape Lookout area between 14 and 15 July. SST's warmed as much as 5°C offshore of the 150 m isobath in this area, while values within 5 km of the coast warmed slightly (less than 1°C). Finally from Fig. 7b we note that warming has occurred 20–30 km offshore from Newport between 15 and 16 July. Warming has also occurred in the inshore 5 km south of Cape Lookout to Pacific City and also between the 100 and 150 m isobaths in this area and in a band approximately 5 km wide oriented SSW from Siletz Bay to Newport along the 50 m isobath.

4. Means and perturbations

In this section a discussion of two 3-week mean fields and daily perturbations from these means will be presented. Mean fields were computed for the periods 27 June to 16 July (20 days) and 22 July to 10 August (19 days). These two periods were chosen because there was different wind forcing during each period. During the first period two "upwelling events" occurred. Recall that during these events winds are generally from the N and NW. These events were separated by several days of southerly winds. Northerlies blew continuously throughout the second period. Since fog prevented mapping flights several times for several days in succession, the location of these gaps in the almost-daily array of SST maps dictated the choice of the averaging periods. Twenty-eight perturbation maps were computed. In order to compute these perturbation maps, the mean temperature at every point on the map was subtracted from the daily temperature at every point.

The mean temperatures in the mapping region during the first averaging period (27 June–16 July) ranged from less than 10°C near shore to 13°C off-
shore as shown in Fig. 8a. Fig. 8b shows that mean SST’s are less than 9°C in a small area near shore just south of Cascade Head and again just south of Depoe Bay during the second averaging period. From analyzing Fig. 8b we can see that mean SST’s in the COHO flight region are less during the second averaging period. This is probably due to the fact that the winds were consistently from the north during this period. Another aspect of the mean fields for these two periods is that the mean isotherms tend to follow the large-scale bathymetry.

If we glance through Figs. 9a, b, c, the perturbation maps for 14, 15, 16 July, we notice the large number of eddies which appear on these maps. There is a large variability in the transient SST field as shown by these maps. Also the existence and location of oceanic fronts may be determined. From investigation of all of the perturbation maps we found that daily perturbations of ±3°C from the 3-week mean were not uncommon inshore of the 100 m isobath.

The tracing of individual eddies on these maps from day to day is made difficult because of the strong horizontal flow and the strong shear in the longshore current in the mapping region. During CUE-F surface drogues (Stevenson et al., 1974) were deployed to measure the strength and shear of the surface current under the northerly wind. From this experiment the above two characteristics of the flow were noted. The offshore drogues located about 15–20 km from the coast moved at an average speed of 35 cm s⁻¹ while the inshore drogues located about 7–10 km offshore moved at about 15 cm s⁻¹. This motion seems to be in accord with Ekman offshore/longshore transport that we would expect during periods of northerlies. Fig. 10 shows a 2-week average absolute geostrophic longshore flow off Depoe Bay, Oregon, in 1966. Note the strong equatorward surface jet (20 cm s⁻¹) and the strong average shear in the longshore current. Smith (1974) and Huyer (1974) document the validity of geostrophy for the longshore flow in this mesoscale upwelling region off Oregon.

The mean field (not shown) for the entire 62-day period of COHO operation was calculated from 35 daily SST maps. There are large (3–5 days) gaps in data at the beginning and end of the operational period. The coldest mean temperatures are located alongshore from Depoe Bay to Newport. This result is in agreement with the results of Hurlburt (1974) who modeled the effects of a mesoscale canyon-like feature off the Oregon Coast on the wind-driven eastern ocean circulation. He found that upwelling is less on the north side of the canyon and greater on the south side and near the coast on the axis of the depression.

5. Spectral analysis

The spectral study of this mesoscale SST data was undertaken to investigate the scales of eddies in the
horizontal temperature fields in an oceanic upwelling zone. Providing the motivation for this study were the results from a one-dimensional spectral analysis of mesoscale SST data presented by Saunders (1972). He computed spectra of SST's gathered from the Mediterranean Sea by an infrared radiation thermometer located in an aircraft. Over the range of scales 3–100 km, he found that the density of temperature variance seemed to obey a $k^{-3}$ power law where $k$ is the wavenumber and $\rho$ is approximately 2.2. As he states in his paper, however, this power law does not fit any proposed model of geophysical turbulence. Another study of SST's recorded from a remote-sensing infrared thermometer was presented by MacLeish (1970). The spectra computed from these temperatures have a maximum at the smallest wavenumber and then decrease rapidly as wavenumber increases; however, they do not decrease after a wavenumber greater than 2–5 cycle km$^{-1}$. Instead, in this high wavenumber range the spectral slope flattens with increasing wavenumber.

In the past several years much interest in the spectral distribution of intermediate- to large-scale atmospheric motions has been generated. Observational studies by Horn and Bryson (1963), Winn-Nielsen (1967) and Julian et al. (1970) indicated an approximate kinetic energy spectral slope of $-3$. These results, however, did not agree with Kolmogorov's (1941) $-5/3$ law which he predicted for the inertial subrange of three-dimensional isotropic turbulence. Atmospheric motions at mid-level had been considered approximately two-dimensional since Rossby et al. (1939), Kraichnan (1967) proposed a $k^{-3}$ behavior for the supposed approximately two-dimensional atmospheric motion. Charney (1971) proposed a theory which predicted a $-3$ dependence on wavenumber $k$ of the spectra both of atmospheric kinetic energy and atmospheric temperature variance when the flow is three-dimensional and quasi-geostrophic.

Lilly and Lester (1974) predicted that a horizontal spectrum of kinetic energy proportional to $k^{-3}$ implies potential temperature spectra proportional to $k^{-2}$. These studies are for much larger scales than those considered here.

Charney (1971) also reports that temperature spectra computed from an NCAR atmospheric prediction model made available to him by Wellick and Washington of NCAR revealed an approximate $k^{-3}$ behavior. In a spectral analysis of atmospheric temperature, Kao (1970) found that in the high-wavenumber range spectra generally decrease with increasing wavenumber and are proportional to $k^{-2}$. Lilly and Lester (1974) computed potential temperature spectra from stratospheric data gathered by an aircraft over Colorado in 1970. The spectral slopes in the 3–20 km range for potential temperature seemed to be approximately $-3$ in agreement with their theory. Charney also stated that his predicted $k^{-3}$ behavior for the kinetic energy spectrum and temperature variance might apply to oceanic fields in regions of strong baroclinic excitation. Upwelling regimes are areas of strong baroclinicity.

In our spectral study we computed spectra from a rectangular grid of SST data. This grid contained 1600 data points equally spaced 1 km apart. Spectra were computed for daily SST, 3-week mean fields and daily perturbations from these means. This spectral analysis represents the largest undertaking of its kind in an oceanic region to date. Fig. 1 shows the rectangular grid which contained the SST values from which the spectra were computed. This figure shows that the $xy$ coordinates were rotated approximately 9° in the offshore direction. This was done so that the longshore sides of the rectangular grid of SST data points could be oriented parallel to the Oregon coastline in order to include as many of the nearshore points as possible while maximizing the size of the grid.

The sea surface temperature at each data point $x_iy_j$ can be written as a two-dimensional complex Fourier series expansion in the form

$$T(x,y) = \sum_{j_1} \sum_{l_1} A_{j_1 l_1} \exp\left(\frac{i2\pi j_1 x}{L_x}\right) \exp\left(\frac{i2\pi l_1 y}{L_y}\right),$$

(1)

$$T(x,y) = \sum_{j} \sum_{l} A_{j l} \exp\left(\frac{i2\pi j x}{L_x}\right) \exp\left(\frac{i2\pi l y}{L_y}\right);$$

(2)

where

$$k_{j_1} = \frac{j_1}{L_x}, \quad j_1 = 1(1) \frac{N_x}{2},$$

$$k_{l_1} = \frac{l_1}{L_y}, \quad l_1 = 1(1) \frac{N_y}{2},$$

The above expressions are composed of the double sum of complex harmonics where $A_{j_l}$ are complex Fourier coefficients. The length of the grid in the $x$
and is denoted by $L_x, L_y$, respectively, while the number of data points in the $x$ and $y$ directions is denoted by $N_x$ and $N_y$, respectively.

The sample temperature variance can be written as

$$
\sigma^2 = \frac{1}{N_x N_y} \sum_{x} \sum_{y} (T[x, y] - \bar{T})^2,
$$

(3)

where $\bar{T}$ is the sample mean. The sample mean is

$$
\bar{T} = \frac{1}{N_x N_y} \sum_{x} \sum_{y} T(x, y).
$$

(4)

More importantly, the sample temperature variance can be written as

$$
\sigma^2 = \sum_{j} \sum_{l} \frac{|A_{jl}|^2}{4}.
$$

(5)

In the above equation the temperature variance is expressed in terms of a sum of the squares of the complex amplitudes.

The SST variance spectrum is proportional to $|A_{jl}|^2$ and represents a partitioning of the temperature variance in wavenumber space. The symbol $E_T(\hat{k})$ will represent this partitioning and will be referred to as the two-dimensional temperature variance spectrum. The dimensions of $E_T(\hat{k})$ are LT$^2$ since $E_T(\hat{k})$ has units of variance of temperature (T$^2$) divided by wavenumber (L$^{-1}$).

The temperature wavenumber variance spectrum can always be defined as the separation into an isotropic part and an anisotropic part, i.e., as

$$
E_T(\hat{k}) = E_i(|\hat{k}|) + E_2(\hat{k}),
$$

(6)

where $E_i$ is the isotropic part, which does not depend on direction, and $E_2$ is the anisotropic part which does depend on direction. The wavenumber vector $\hat{k}$ is defined

$$
\hat{k} = k_x + ik_y.
$$

(7)

This complex variable can be written

$$
\hat{k} = |\hat{k}| e^{i\theta},
$$

(8)

which is a function of the wavenumber $|\hat{k}|$ and a phase angle $\theta$.

If we integrate the two-dimensional temperature variance spectrum over all phase angles, we have

$$
\frac{1}{2\pi} \int_{-\pi}^{\pi} E_T(|\hat{k}| e^{i\theta}) d\theta = E_i(|\hat{k}|).
$$

(9)

Recall that $E_i(|\hat{k}|)$ is the isotropic part of the temperature variance spectrum. Because this is true, we can go back to (6) and see that

$$
\int_{-\pi}^{\pi} E_2(|\hat{k}|) d\theta = 0.
$$

(10)

In our spectral study we are not dealing with a continuous field; instead, we are dealing with discrete points. For the case of a field of discrete points, a discrete sum must be employed in expressing the isotropic part of the temperature variance spectrum. This discrete sum can be written as

$$
\frac{1}{N} \sum_{j} \sum_{l} E_T(|\hat{k}| e^{i\theta}) = E_i(|\hat{k}|),
$$

(11)

where $j$ and $l$ are chosen such that $|k_x + l k_y| \leq |\hat{k}|$. Fig. 11 shows graphically the summing method that was employed. In this figure values of $k_x$ and $k_y$ range from 0 to $\frac{1}{2}$ km$^{-1}$. If a contribution, $E_T(|\hat{k}|)$, to the isotropic part of the temperature variance spectrum falls within a certain wavenumber range $|\hat{k}| \pm \delta |\hat{k}|$, it is summed in with all other contributions which fall within this range. The sum of all of the contributions to the isotropic part of the temperature variance spectrum is then divided by $N$, the number of contributions. The fact that we are computing the isotropic part of the temperature variance spectrum by this method is important as we shall see later.

Fig. 12a shows a graph of one of the computed spectra. This graph refers to a spectrum computed from the horizontal SST field on 14 July. The solid line in the graph refers to a plot of wavenumber times the isotropic temperature variance spectrum vs the log of wavenumber. This plot has the advantage that area under the curve represents the sample variance. From this plot we can see that there is a large contribution to the variance in the range of wavelengths from 16 to 20 km. The dotted line represents a plot of log of the isotropic temperature variance spectrum vs log of wavenumber. In this log-log plot we note a steep slope toward high wavenumbers.

Fig. 11. Schematic diagram of summation method for finding isotropic temperature variance spectrum.
The plots of $kE_\tau(k)$ vs the logarithm of wavenumber $k$ consistently revealed a spectral peak in the wavelength range 16–40 km. A peak at 16–20 km is significant and not an artifact of the limited observational region. A peak at 40 km is suspect due to the limited size. The consistency of the $-3$ slope for spectra computed from the daily horizontal SST fields can also be seen in the log-log plots of Fig. 14. Fig. 14 is a scatter diagram which represents a composite of 16 days of computed spectra from 16 days of SST data. Each day's spectrum was computed and then normalized by that day's variance and then a composite of the log-log plots was constructed. An approximate $-3$ slope in the range of wavenumber $1/20$ to $1/4$ km$^{-1}$ is easily seen. From this graph we conclude that the isotropic sea surface temperature variance spectrum follows a power law of $-3$.

We also did some calculations of the one-dimensional temperature spectra from our SST data. The results from these calculations indicated a $k^{-3}$ dependence of the spectra which was comparable to that found by Saunders (1972). While isotropy is assumed in the computation of the one-dimensional spectra, our computed spectra from the two-dimensional SST field only considered the isotropic part of the temperature variance spectrum. Saunders (personal communication) comments that the steep $-3$ spectrum is a result of unsampled variance between the aircraft tracks. In addition, J. J. Stephens (personal communication) comments that the synoptic analyst who produced the charts may have introduced a selective bias which would lead to a steep temperature spectrum. These

![Figure 12](image1)

**Fig. 12.** Graphic results of the spectral analysis of the horizontal sea surface temperature fields for (a) 14 July 1973 and (b) 15 July 1973: solid lines, $kE_\tau(k)$ vs log $k$; dashed lines, log $E_\tau(k)$ vs log $k$. Solid line labelled $-3$ represents $-3$ slope.

![Figure 13](image2)

**Fig. 13.** As in Fig. 12 except for the 14 July 1973 perturbation field.

![Figure 14](image3)

**Fig. 14.** Scatter diagram representing a composite of sixteen log-log plots of the normalized isotropic temperature variance spectrum vs wavenumber. Each of the sixteen plots is a graphic representation of a daily spectrum. These spectra were computed during the period 27 June to 16 July 1973. The solid lines represent $-3$ slopes.
critiques are serious but cannot be tested with the present data base and must be left to future SST mapping programs.

Charney (1971) indicated in his paper that his predicted $k^{-3}$ behavior for the temperature variance might apply to oceanic fields in regions of strong baroclinicity. His prediction assumes isotropy. At that time no observations were available for comparison with his theory. An interesting note is that Lilly and Lester (1974) found an approximate $-3$ slope in a mesoscale wavelength (3–20 km) for spectra computed from atmospheric temperature data. We conclude this section by stating that we have found a $k^{-3}$ behavior of the isotropic sea surface temperature variance spectrum in the mesoscale wavelength range of 4–20 km. We do not, however, imply that the geostrophic turbulence theory is therefore applicable.

6. Summary and conclusions

From the extensive amount of SST data gathered during the 2-month COHO Project in 1973, we have presented some results of an investigation of the nature of the mesoscale variability of SST's off the central coast of Oregon. Basically, we found that the mesoscale SST field off the coast of Oregon is highly variable from day to day and point to point.

We investigated the response of the SST field to wind forcing. We found that SST's are generally cooler when northerlies are blowing and warmer when southerlies are blowing. Temperatures may vary rapidly within several days during periods of moderate to strong northerly winds. Upwelling caused by these northerly winds accounts for the lower SST's during these periods. This is, of course, to be expected.

In the present study we only considered the influence of the wind field on the SST field. The wind field does seem to dominate the SST field. Future research studies of large amounts of mesoscale SST data gathered by remote sensing techniques could investigate the effects of solar heating, precipitation, cloud cover, and differences in temperature between land and sea. Also not considered in this study were relations between the daily surface current and the mesoscale SST field. In addition, a strong feedback may exist between changes in the SST field and the sea breeze (Johnson and O'Brien, 1973).

An investigation of the daily horizontal SST maps revealed the location of areas of strong horizontal SST gradients called oceanic fronts. By examining perturbation maps, the location of these fronts is easily determined. A study of the 3-week mean SST fields indicated that the mean isotherms tended to follow the large-scale bathymetry.

From maps of the perturbations from the 3-week means, we observed large numbers of eddies in the mesoscale SST field. Individual eddies are not easily traced from day to day because of the strong horizontal flow and strong shear in the longshore current. In order to quantitatively determine the scales of the eddies in the horizontal temperature field in the upwelling zone, a spectral study of the SST data was undertaken. The results from this two-dimensional spectral analysis indicated that a large amount of the SST variance was concentrated in the 16–40 km wavelength range, i.e., in mesoscale eddies which are being advected through the upwelling region. This result also means that passive, neutrally-buoyant particulate matter would be expected to exhibit patchiness on the scale of 16–40 km. Therefore, in addition to SST's, phytoplankton and other buoyant material are expected to be concentrated in advected mesoscale eddies of 16–40 km in horizontal extent on the continental shelf.

From our spectral analysis, we also found that over the range of scales from 4–20 km the isotropic part of the temperature variance spectrum obeyed a $-3$ power law. Charney's (1971) theory is a candidate to explain this power law physically. Several other investigators have found approximate $-3$ spectral slopes from observed temperatures in the atmosphere.

It is hoped that the results of this analysis have provided an insight into the understanding of the nature of the mesoscale SST field in an upwelling zone and will provide the basis for additional research.

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