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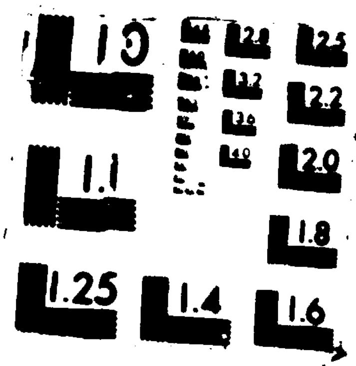
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FINAL TECHNICAL REPORT

To The Office Of Naval Research
Ocean Science and Technology Division
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800 North Quincy Street
Arlington, Va 22217

"SATELLITE AND SYNOPTIC STUDIES OF CHEMICAL FRONTS IN THE CALIFORNIA CURRENT AND COASTAL UPWELLING ZONE" (SFRC N00014-85-K-0054 A00001)

BY
DR. EUGENE D. TRAGANZA
31 May, 1987

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Project Director 5/31/87

IA. Summary

The major accomplishments of this ONR research are reported in a series of five publications on "chemical fronts" associated with upwelling systems, including "cyclonic upwelling systems" and "jets" which originate in the coastal zone off Pt. Sur California. Enclosed is a reprint of the final paper "Chemical flux, mixed layer entrainment and phytoplankton blooms at upwelling fronts in the California coastal zone" (Traganza et al., 1987). This research began as a result of one of the first satellite IR images of the California Current System. The image revealed a surface thermal pattern of cyclonic eddies nearshore which were similar to "nutrient cells" suggested by conventional data from the California Cooperative Fisheries Investigations (see satellite image in Traganza et al., 1980, "Satellite Observations of a Nutrient Upwelling Off the Coast of California"). Ultimately, from the close inverse correlation of nutrients and temperature discovered by this ONR project, satellite images were converted into nutrient maps. This was reported in three invited talks to the Gordon Research Conference on Chemical Oceanography in the U.S.A., the NATO Advanced Research Conference in Portugal, the International Union of Geodosy and Geophysics in West Germany and published in our paper "Nutrient Mapping ...etc., Traganza et al., (1983).

A number of at-sea experiments were conducted in this ONR project to investigate the significance of "chemical fronts" as sites of chemical exchange and primary production. We learned to use satellite IR images to detect upwelling systems and to predict the subsurface chemical structure of fronts from the surface thermal pattern. We discovered "surface jets" (giant plumes) and distinctively structured eddy-like features which we named "cyclonic upwelling systems" (see Traganza et al., 1981, "Satellite Observations of a Cyclonic Upwelling System and Giant Plume in the California Current"). A nomencleture and a sequence of evolution of upwelling frontal systems was developed (Traganza et al., 1985). A variety of upwelling systems were found to form sharp thermal/chemical gradients or "fronts" where phytoplankton were often found to concentrate and persist. This validated satellite ocean color imagery* (Traganza et al., 1983). Following our discovery of these frontal systems, three papers (Traganza et al., 1983, 1985 and 1987) quantitatively described these systems and offered a conceptual explanation of the frontal bloom phenomenon. In the last of this series of papers three-dimensional mapping was used to relate subsurface structure to satellite imagery, and an atmospheric forcing model was applied to analyze and predict the interaction of physical, chemical and biological processes at upwelling fronts. Since some of these systems extend for hundreds of kilometers into the California current and persist with prominent blooms, the process must be considered in the mass balance of the California current system.

* The British National Space Agency, London, has just released a publication on the commercial application of satellite ocean color imagery featuring our image from the 1983 paper.

IB. January 1987 publication in <u>Continental Shelf Research.</u>

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Chemical flux, mixed layer entrainment and phytoplankton blooms at upwelling fronts in the California coastal zone

EUGENE D. TRAGANZA,* DONALD G. REDALJE† and ROLAND W. GARWOOD‡

(*Received 22 December 1985; in revised form 23 April 1986; accepted 28 February 1986*)

Abstract—Atmospheric and *in situ* physical processes appear to generate a sustained chemical flux at the frontal boundaries of coastal upwelling systems. In this study off Pt. Sur, California, satellite images and three-dimensionally presented *in situ* data show the evolution of an upwelling system with a strong chemical front and a large phytoplankton bloom in a surface layer juxtaposed to the frontal boundary. Nutrient uptake from this layer by phytoplankton, ranging from 0.15 to 2.39 μM NO_3 d^{-1}, is indicated by primary production measurements in the bloom. Based on an atmospheric forcing model, wind stress drives the physical entrainment of nutrients from deeper layers into the "mixed layer" adjacent to the front at rates ranging from 0 to 0.76 μM NO_3 d^{-1}. From a dynamic balance of nutrient exchange processes, a lateral cross-front exchange from the upwelling system to the adjacent mixed layer is also indicated. These two mixing processes, sustained by atmospheric forcing may explain the chemostat-like persistence of phytoplankton pigments which appear along the boundaries of upwelling systems *in situ* and in remotely sensed ocean color images of the California coastal zone.

INTRODUCTION

EARLIER studies (TRAGANZA *et al.*, 1980, 1981, 1983) combining satellite and *in situ* data demonstrated that Pt. Sur, California is an active upwelling center which frequently generates "cyclonic upwelling systems" and occasionally surface "jets" which extend hundreds of kilometers into the California current system. It was also shown, but without explanation, that phytoplankton concentrate along frontal boundaries (sharp thermal and chemical gradients) of upwelling systems. Our objective is to better understand this phenomenon which appears to be very important to primary production in this coastal upwelling region and the California current (TRAGANZA *et al.*, 1983; SIMPSON, 1984).

Under conditions of sustained, strong, northwesterly winds, cold water outcrops at the sea surface off Pt. Sur with a strong frontal zone which is clearly visible in satellite i.r. imagery (Fig. 1). An oceanic surface layer on the seaward side of the front is relatively warm, stratified and low in biologically active elements, such as nitrogen and phosphorous. The shoreward side is cold, well mixed, and relatively rich in these elements (TRAGANZA *et al.*, 1980, 1981). The nutrient-rich water which is brought into the euphotic zone inshore of the upwelling front may mix horizontally across the surface density front

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into the shallow seaward surface layer. Alternately, local wind stress may deepen the surface layer adjacent to the front and entrain nutrients vertically across the pycnocline which slopes to the surface at the frontal boundary (GARWOOD, 1977; SHAY and GREGG, 1984; ADAMEC and GARWOOD, 1985). Both possibilities are supported by the observation that it is there, just seaward of upwelling fronts, that the highest levels of chlorophyll concentrations regularly occur (MOOERS et al., 1977; TRAGANZA et al., 1983).

According to KLEIN and COSTE (1984) it is usually assumed that nutrient gain by the surface layer of coastal upwelling areas is mainly controlled by vertical and horizontal advection. However, they also show that in relatively shallow layer regions, such as the Mediterranean, vertical transport is induced (on a time scale of days) by atmospheric forcing (wind stress). Hence, there is reason to consider the affects of atmospheric forcing on the surface layer adjacent to the upwelling front. It is often presumed that upwelling areas are too complicated to be represented by one-dimensional models used in these other studies. However, we have found that one-dimensional models are useful because the structural relationship of the upwelling front and adjacent mixed layer (Fig. 1) is very persistent, and local wind stress apparently will (vertically) erode the shallow thermocline at the surface density front.

Here, wind-induced mixed layer deepening and nutrient entrainment by the mixed layer were determined by an extension of GARWOOD's (1977) model. Models of this type have proven to be useful as shown by numerical predictions from field observations (KLEIN and COSTE, 1984). The model assumes horizontal homogeneity for the entrainment and turbulence processes, and is in that sense one-dimensional. However, the entrainment calculation is not dependent on temperature, density or velocity being horizontally homogeneous. Also, advection of non-homogeneous water is considered here in the balance of major processes which may affect nutrient exchange at an upwelling front, such that, the observed rate of change of mean nutrient concentration in the mixed layer, DN/Dt, is equal to the sum of mixed layer nutrient entrainment, biological uptake, advection and atmospheric exchange of nutrients.

KLEIN and COSTE (1984) suggest that nutrient entrainment which results from atmospheric forcing can be the main determinant for primary production. These authors did not obtain data to support this conclusion. Here, the Pt. Sur upwelling system was mapped to locate a phytoplankton bloom and describe the boundary region in which the upwelling front and oceanic mixed layer are juxtaposed. To investigate nutrient entrainment by the mixed layer, a time series of vertical profiles of nutrients and temperature were obtained in the bloom and adjacent to the front for initializing the model. Representative measurements of primary production in the frontal bloom were compared with nutrient entrainment by the mixed layer as calculated by the model. The results suggest there is a coupling between nutrient entrainment and primary production. But, from the balance of major nutrient exchange processes, additional fluxes are indicated to sustain the large phytoplankton blooms which are so prominent and persistent along boundaries of upwelling systems in the California coastal upwelling zone.

METHODS

Satellite i.r. images of the eastern north Pacific were obtained from the NOAA field station at Redwood City, California, to detect upwelling off Pt. Sur, California, and to localize the sampling area before beginning the cruise (Fig. 1). A squared spiral cruise

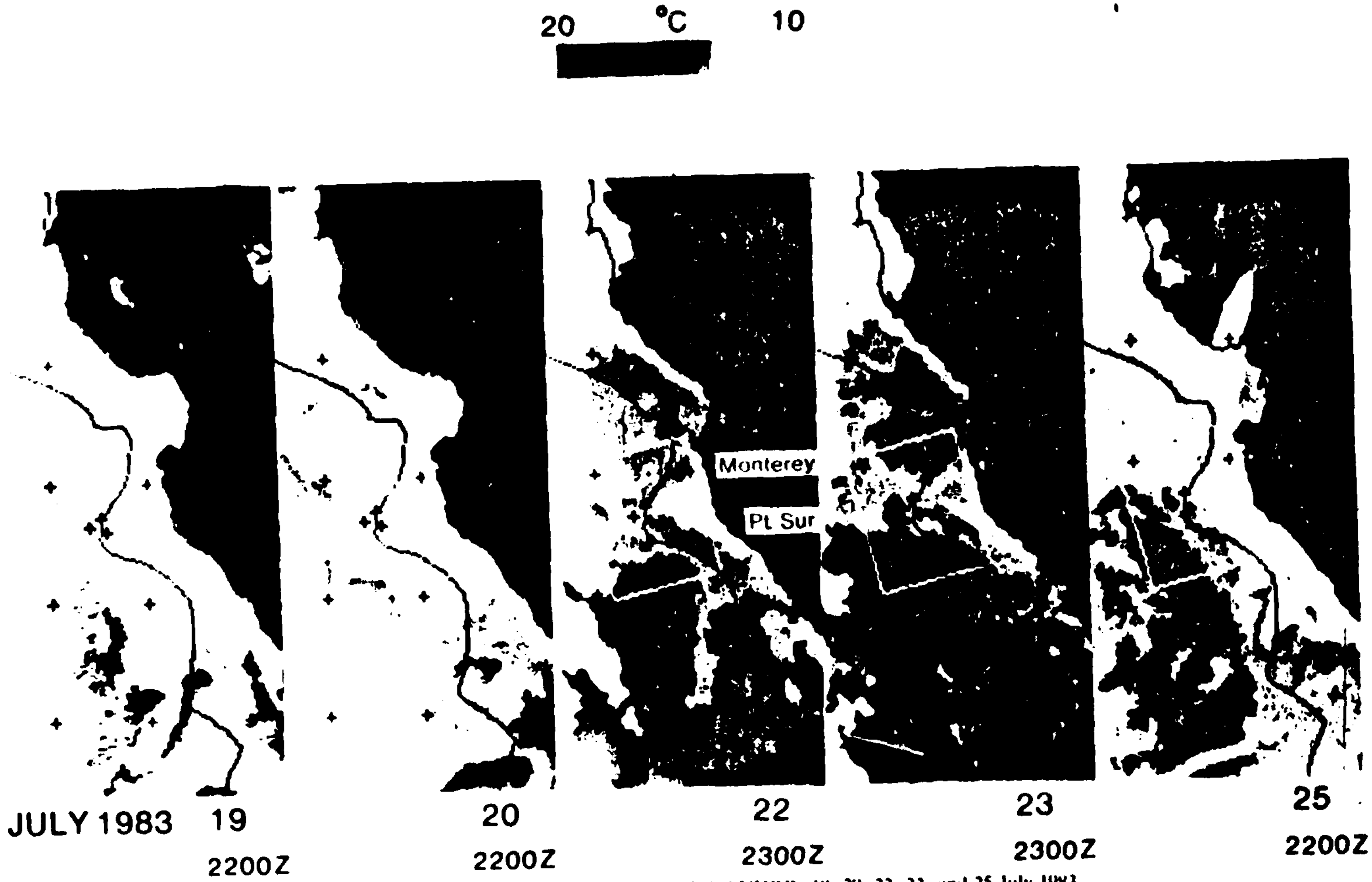

Fig. 1. Infrared images obtained by the NOAA-6 AVHRR, 19, 20, 22, 23, and 25 July 1983. Note newly forming upwelling system off Pt. Sur, California. Surface (3 m) temperature, nutrients, and chlorophyll and vertical temperature profiles were obtained underway in area delineated by rectangle, 22–23, 24–25 and 26–27 July. Three closely grouped crosses in center of rectangle locate average position of mixed layer stations adjacent to the front, 23, 26 and 27 July. All others are 30' latitude and longitude marks.

track (Fig. 2) was centered on the upwelling system. *In situ* temperature measurements were made continuously at 3 m while the ship transited the cruise track until a maximum area of 50 × 50 km was covered. This approach has proven to be the most effective way to search for and map the surface thermal signature of the Pt. Sur upwelling system (Traganza *et al.*, 1980, 1981, 1983). Underway measurements of temperature, nitrate and phosphate, and *in vivo* fluorescence were used to locate and map the distinctive thermal and chemical fronts and chlorophyll concentrations along the boundaries of the system. The system was mapped on 22–23, 24–25 and 26–27 July 1983. The first was the 50 × 50 km square. It was reduced by leaving off the northward 10 km leg and then reduced further by leaving off the seaward 10 km leg on the 2nd and 3rd mappings. Each mapping was followed by three vertical stations in the region of the phytoplankton bloom adjacent to the front—three each on days 23, 26, and 27 July 1983.

Infrared satellite imagery

Six satellite passes were processed (Fig. 1): five from NOAA-7 (19 July, 2200Z; 20 July, 2200Z; 22 July, 2300Z; 23 July, 2300Z; and 25 July, 2200Z) and one from NOAA-8 (20 July, 0200Z). Each pass was radiometrically calibrated for bands 4 and 5 (10.3–11.3 and 11.5–12.5 μm, respectively). Earth location was corrected so that the error was no more than 2 km. Each image was registered to a fixed grid with pixel dimensions of 1.1 km. Both the coast and the 1000 m bathymetric contour were registered to the same grid. Images were enhanced to cover the 12–16°C range of brightness temperature along the central California coast at temperature steps of 0.5°C so movement of temperature structure and thermal fronts can be seen relative to stations. An atmospherically corrected sea surface temperature was not derived because spatial smoothing effects from cloud screening and noise reduction would tend to attenuate the features of interest and corrected sea surface temperature estimates are not essential to this study.

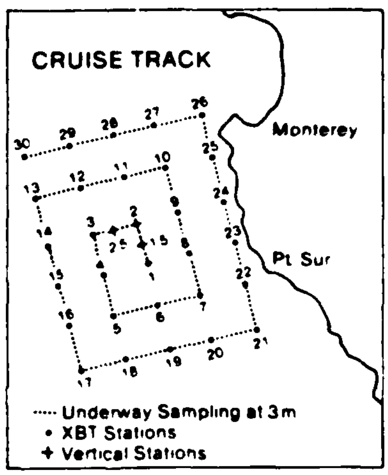

Fig. 2. Cruise track July 1983. XBT Stas 1–30, 1–25 and 1–20 were included during underway surveys of temperature, nutrients and chlorophyll at 3 m on 22–23, 24–25 and 26–27 July respectively. Vertical stations were occupied between surveys to obtain profiles of the same parameters and primary production.

Temperature

Expendable bathythermographs (XBTs) were dropped every 10 km along the track to obtain 30 vertical profiles of temperature on the full square and 25 and 20 on the two succeeding squares, respectively. XBT profiles were used to reconstruct the three-dimensional thermal structure of the upwelling system (Fig. 3). *In situ* water temperature was sensed continuously by a thermistor located at 3 m in the ships's seawater intake and recorded on a strip chart recorder. The equipment was calibrated against thermometer readings. A three-dimensional (3-D) presentation of the 3 m isopleth was constructed from seawater intake temperature along with chlorophyll and nutrient concentrations (Fig. 4).

Chlorophyll

In vivo fluorescence was measured continuously in the seawater after being pumped from the intake, through a debubbler, and into a Turner 111 fluorometer. All fluorescence values were recorded continuously on a strip-chart recorder. Fluorescence was calibrated against duplicate 100 ml samples of water which were taken every half-hour.

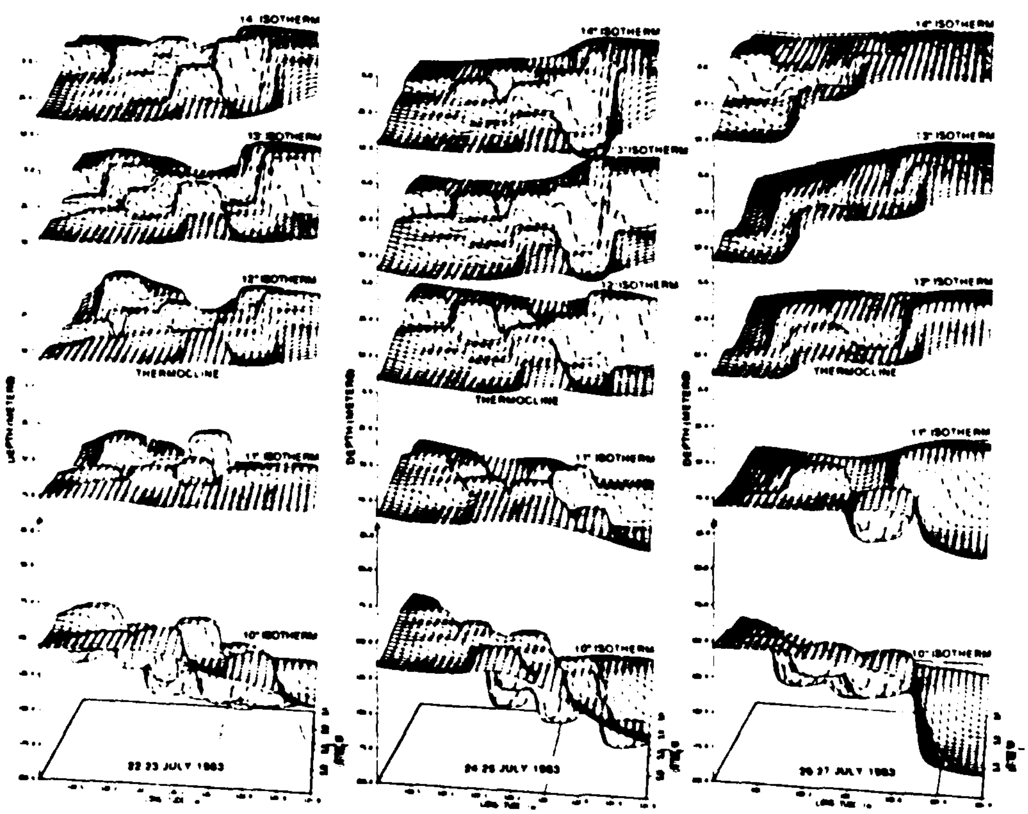

Fig. 3. Time series of three-dimensional thermal structure of a coastal upwelling system off Pt Sur, California, 22–23, 24–25, and 26–27 May 1983. Individual isotherm depth scales are offset by a constant interval of 75 m.

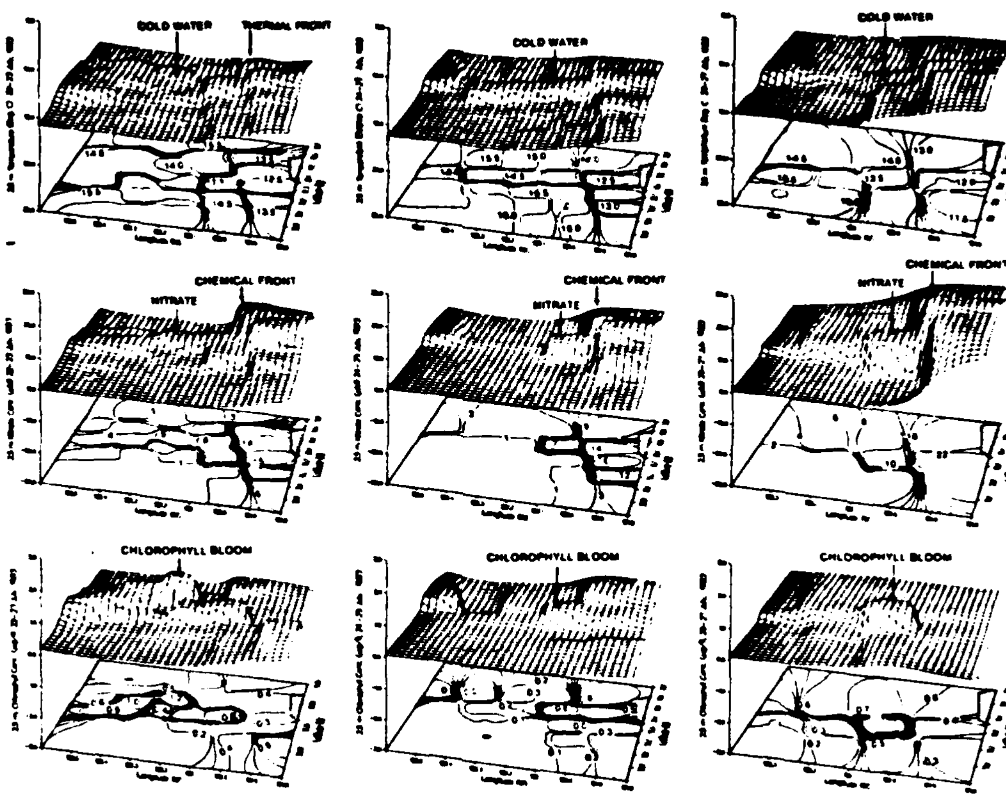

Fig. 4. Time series of temperature, nitrate, and chlorophyll at 3 m in the frontal transition zone of an upwelling system off Pt. Sur, California, 22–23, 24–25, and 26–27 July 1983.

prescreened (200 μm nitex), filtered (Whatman GF/F glass fiber filters), and analysed for chlorophyll.

Nutrients

Dissolved nitrate and phosphate were measured with a Technicon AutoAnalyzer every 2 min on the continuous flow of seawater which was pumped to the instrument from the ship's intake. All values of these samples and standards were recorded continuously on strip chart recorders [see Traganza *et al.* (1981) for details].

Primary production and biomass

Phytoplankton carbon specific growth rates and carbon biomass were determined using the "labeled chlorophyll *a*" technique of Redalje and Laws (1981). Primary production was calculated from these values. Nitrogen uptake rate was estimated using established relationships of phytoplankton carbon to nitrogen (Goldman, 1980).

Primary production was determined in samples taken from 50% I_0 (incident irradiance) and 10% I_0 light depths. These depths correspond to the general mean irradiance levels for the upper and lower parts of the shallow mixed layer. The water samples were inoculated with 250 μCi of $H^{14}CO_3^-$ and incubated for 24 h in 4-l polycarbonate bottles. The bottles had been wrapped with neutral density screens to properly regulate light penetration in a running seawater-cooled deck-top incubator. $H^{14}CO_3^-$ Stocks and incubation bottles were prepared using the clean techniques recommended by FITZWATER *et al.* (1982). Following incubation, the labeled particulate material was collected on Whatman GF/F glass fiber filters and treated as described by REDALJE (1983).

Data for mixed layer nutrient entrainment model

The effects of atmospheric forcing (wind stress and solar radiation) on mixed layer deepening and vertical nutrient entrainment by the mixed layer were estimated by an extension of GARWOOD's (1977) model. The model employs hourly observations of surface wind speed and direction, sea surface temperature, wet and dry bulb air temperature (dew point is calculated), and cloud cover. Profiles of nutrients and temperature in the water column were used to initialize the model at each station.

THE MODEL

Model for mixed layer entrainment of nutrients

The upward nutrient entrainment flux, $\overline{w'N'}(-h)$, into a mixed layer of depth h is dependent upon the turbulent entrainment velocity, w_e, and the discontinuity in nutrient concentration, $\Delta\bar{N}$, across the entrainment zone:

$$\overline{w'N'}(z = -h) = w_e \Delta\bar{N}.$$

Here z is positive upward, and $\Delta\bar{N}$ is positive if $\partial\bar{N}/\partial z$ is negative at $z = -h$, the base of an entraining mixed layer. Thus two factors are needed to predict the entrainment flux: the vertical profile of nutrient concentration, $\bar{N}(z)$, and the intensity of the turbulent mixing in the entrainment zone. The nutrient budget can be used to predict $\Delta\bar{N}$, or $\Delta\bar{N}$ may be specified from observations.

The rate of entrainment is a function of the state of the mixed layer turbulence, and as such requires a solution to the turbulent kinetic energy (TKE) equations [see reviews by ZILITINKEVICH *et al.* (1979) and GARWOOD (1979)]. For the problem at hand here, the entrainment velocity, w_e, is provided by the entrainment hypothesis of GARWOOD (1977):

$$w_e = (\overline{w'^2})^{1/2} E/(h\Delta B).$$

where $E = \overline{u'^2} + \overline{v'^2} + \overline{w'^2}$ is the total TKE, and ΔB is the buoyancy jump across the stable entrainment zone. This model has been tested extensively, including independent evaluations (MARTIN, 1985). The expression for w_e is derived from TKE budget in the entrainment zone, $-h > z > -h - \delta$. In this zone, the buoyancy flux is assumed to be balanced by the convergence of the vertical transport of TKE. This convergence term is modeled as a function of the TKE components and the vertical distance over which this energy must be transported.

The value of ΔB depends upon both temperature and salinity changes at the bottom of the mixed layer, $\Delta\bar{B} = \alpha g(\bar{T}(-h) - \bar{T}(-h - \delta)) - \beta g(\bar{S}(-h) - \bar{S}(-h - \delta))$, where δ is the thickness of the entrainment zone, and α and β are the thermal and haline expansion/contraction state coefficients, and g is gravity. The prognostic equations for the vertical component of the TKE, $\overline{w'^2}$, and the total TKE, E are determined by the vertically integrated TKE budget:

$$0 = mu^{*3} - \overline{B'w'}(-h)/(2Ri^*) - (\hat{E}^{1/2} + fh)\hat{E}$$

$$0 = (\overline{B'w'}(-h) - \overline{B'w'}(0))/2 + (\hat{E} - 3\overline{w'^2})E^{1/2} - (\hat{E}^{1/2} + fh)\hat{E}/3.$$

Here $u^* = (\tau/\rho)^{1/2}$ with τ the magnitude of the surface stress and ρ the water density, and $Ri^* = \Delta\hat{B}/(\Delta\hat{u}^2 + \Delta\hat{v}^2)$ is the bulk Richardson number. The quantities $\Delta\hat{B}$, $\Delta\hat{u}$ and $\Delta\hat{v}$ are the buoyancy and velocity jumps between the mixed layer (assumed well-mixed or nearly homogeneous) and the level immediately below the mixed layer, $z = -h - \delta$. These bulk TKE equations are solved algebraically.

The mixed layer depth is dependent upon both the entrainment velocity, w_e, and the mean vertical velocity at the base of the mixed layer, $\hat{W}(-h)$:

$$dh/dt = w_e - \hat{W}(z = -h).$$

Vertical advection does not directly influence the entrainment rate. However, over a period of time, $\hat{W}(-h)$ will change the mean profiles of buoyancy, velocity and nutrient concentration. For shorter periods of model integration, as in this case, $\hat{W}(-h)$ may be neglected. The permissible time period over which such advection can be reasonably neglected is a function of the magnitude of the vertical velocity and the depth of the mixed layer (MUELLER *et al.*, 1984).

The model requires specification of the time-dependent wind stress, τ, the effective surface buoyancy fluxes (due to net heat flux, but corrected for absorption of shortwave radiation below the surface), and the initial conditions. Initial conditions are required for the temperature, $\hat{T}(z)$, the salinity, $\hat{S}(z)$, and the nutrients, $\hat{N}(z)$. If available, initial velocity profiles are desirable. When $\hat{u}(z)$ and $\hat{v}(z)$ are unobserved, however, the assumption is made that the initial mixed layer current is determined by the steady state Ekman transport. This may be a source of inaccuracy in the computation of entrainment on a time scale shorter than a half-inertial period, but subsequent predictions are insensitive to the initial velocity conditions.

There are two basic modes of solutions to the above system of equations: an entraining mode and a non-entraining mode. In the entraining mode, the entrainment velocity, $w_e > 0$, and the mixed layer will deepen if $\hat{W}(-h)$ is neglected. In this case there will be an upward flux of nutrients provided the nutrient concentration below the layer is greater than the concentration in the mixed layer ($\Delta\hat{N} > 0$). Should there be a lower concentration of nutrients below the layer, then entrainment will result in an apparent negative or downward flux of nutrients out of the mixed layer.

In the non-entraining mode, the intensity of the vertical component of the TKE, $\overline{w'^2}$, is too small to support entrainment, and $w_e = 0$. In this case, the prognostic equation for dh/dt does not apply. Instead, a diagnostic value for a new shallower h is predicted by the solution of the two TKE equations above. In any case, with $w_e = 0$, there is no entrainment flux of nutrients into the mixed layer. This shallowing of the mixed layer in response to reduced wind mixing and increased surface heating therefore may cut off the source of nutrients for the mixed layer.

RESULTS

Satellite and field observations

The value of satellite remote sensing is demonstrated in Fig. 1 which shows a newly forming upwelling system off Pt. Sur, California. The movement and form of small scale temperature structure is easily followed as the system develops in apparent conformity with bottom topography as indicated by the 1000 m isobath. Of importance here is the persistence of the upwelling front (mixed layer boundary) relative to the vertical stations (shown as 3 tic marks in the center of the image). Measurements were made at these stations to initialize the model and thus estimate the effects of atmospheric forcing on nutrient entrainment by the mixed layer. These stations are numbered 1.5, 2 and 2.5 (Fig. 2). The rectangle delineates the full area of underway analyses (22–23, 24–25, 26–27) for temperature, nutrients and chlorophyll at 3 m, and for (XBT) vertical profiles of temperature. XBTs were dropped every 10 km along the track (Fig. 2) at Stas 1–30 on the 50 × 50 km square, and at 1–25 and 1–20 on the succeeding two squares.

Figure 3 is a time series of isotherms reconstructed from the XBT data. The slopes of the isotherms reveal the vertical divergence at the coast with upwelling of 12–14° water and downwelling of 10–11° water. The 3-D presentation gives an excellent perspective of the thermal structure of a coastal upwelling system and a physical basis for interpreting processes of nutrient exchange at fronts. Additional obvious features are the thermal front and small scale structure (domes and depressions) in the isotherms. The position of the front and the structured region revealed in the isothermal field are also indicated in the satellite image (Fig. 1) and supported by the distribution of surface temperature and nutrients at 3 m (Fig. 4).

Figure 4 presents a striking view of a chemical front and adjacent phytoplankton bloom. The inverse correlation of nutrients with temperature imply that the 3-D field of isotherms could also represent nutrient isopleths, i.e. the nutrient field was, in fact, very similar to the 3-D thermal field. The location of the bloom is consistent with those of persistent plant pigment aggregations along frontal boundaries seen in earlier *in situ* studies and by comparisons of i.r. images with ocean color images (TRAGANZA *et al.*, 1981, 1983). Although only two Nimbus-7 CZCS visible images (from 19 and 25 July 1983) were available at this time, they support this observation.

Entrainment model data

The data from vertical stations 1.5, 2 and 2.5, on 23 and 26 July, are presented in Fig. 5. Data from 23 July were used to initialize the mixed layer entrainment model. Temperature profiles were used to determine initial mean temperature and approximate depth of the mixed layer (the shallower dashed line). Nitrate profiles were used to determine the initial mean concentration of the mixed layer and the difference between this nutrient concentration and that of the layer beneath. Subsequent profiles were computed as they *would* evolve due to atmospheric forcing (wind stress and solar radiation). The net effect of sustained wind stress (Fig. 6) and solar radiation at Sta. 2.5, for example, was expected to cause an increasing entrainment by the mixed layer (Fig. 7), a deepening of the mixed layer (the deeper dashed line in Fig. 5), decreasing mean temperature, and increasing mean nutrient concentration. Precisely this was borne out at Sta. 2.5 when it was revisited on 26 July to observe changes in these parameters. It is also interesting to see that there was an increase of chlorophyll—the maximum associated with the bottom of the mixed layer (Fig. 5). This increase in chlorophyll is consistent with the nutrient enrichment of the surface layer by fluid entrainment although a lateral cross-front exchange also may have played a role. Lastly, there is the possibility that the stations were not in the same water mass on 23 and 26 July. From Figs 1, 3 and 4, it appears that the front was in about the same location with respect to these stations. However, Fig. 5 (and calculations below) indicate some local advection of both warmer and colder waters.

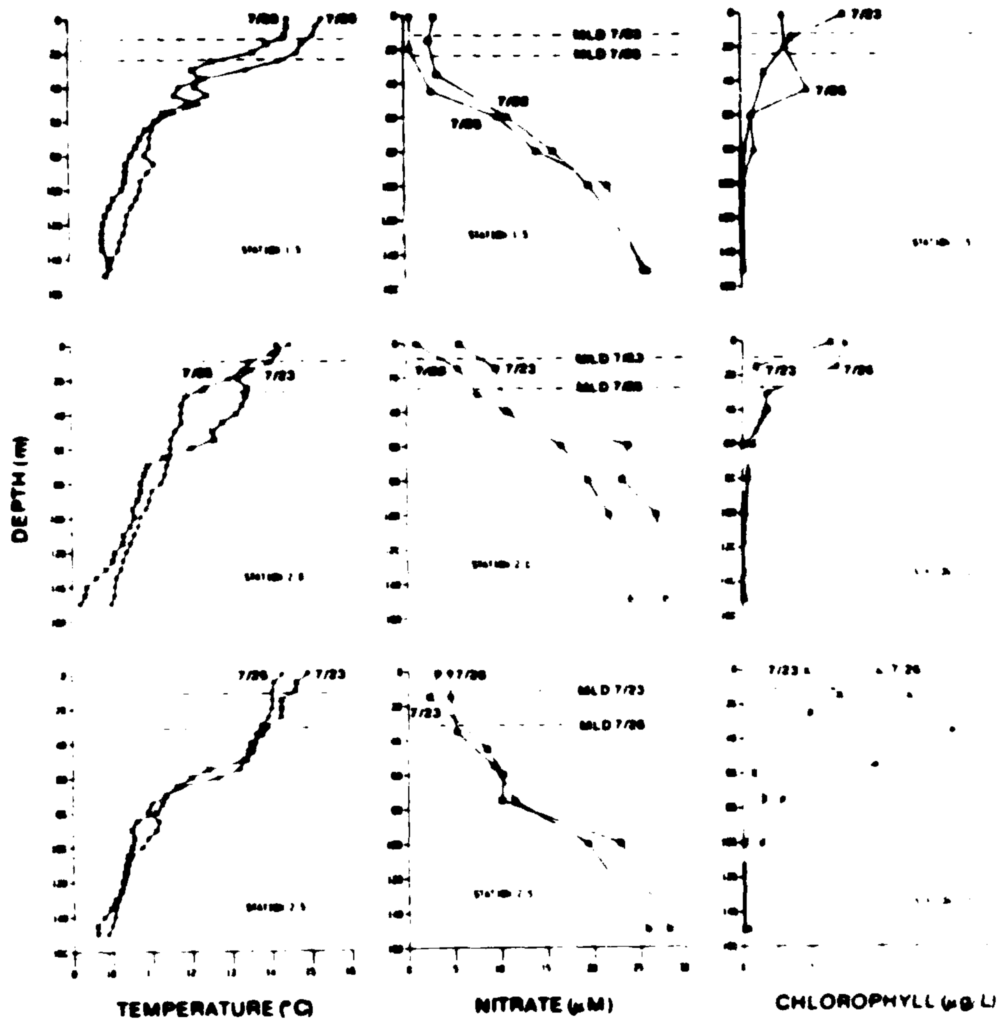

Fig. 5. Mixed layer profiles of temperature, nitrate and chlorophyll at 3 stations adjacent to an upwelling front off Pt. Sur, California, July 1983.

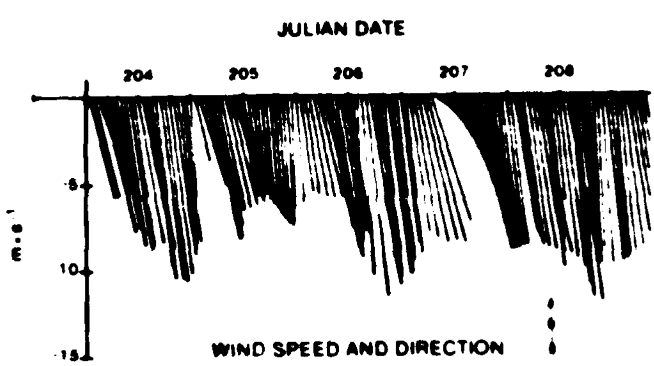

Fig. 6. Time series of surface wind vectors off Pt. Sur, California, July 1983.

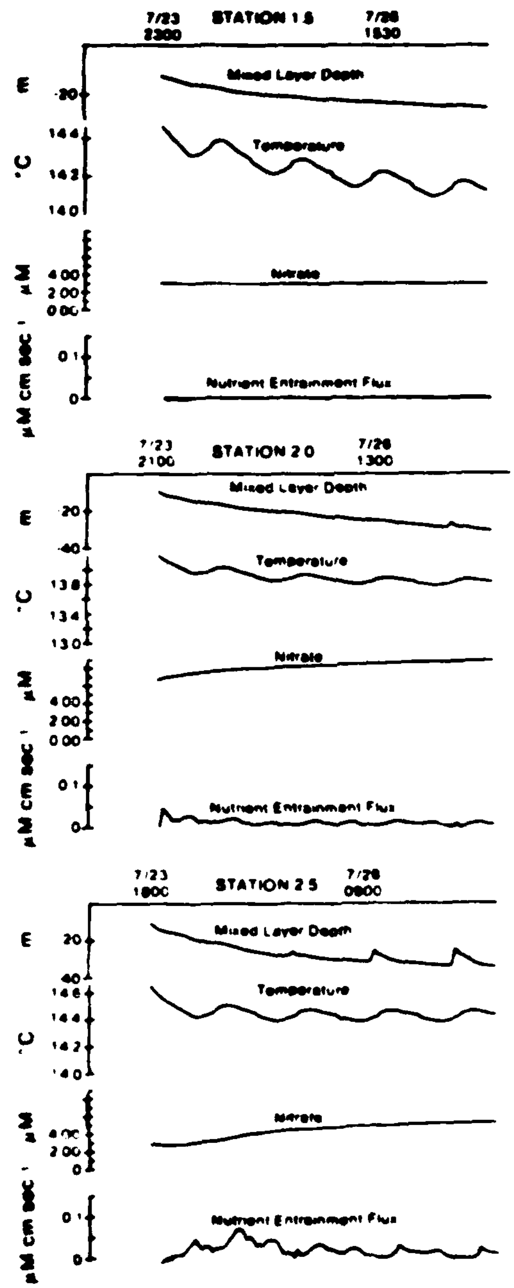

Fig. 7. Time-varying response and nutrient entrainment by the mixed layer due to atmospheric forcing (wind stress and solar radiation) off Pt. Sur, California, July 1983. Simulated by GARWOOD's (1977) model.

Nutrient exchange balance

The major processes which may have determined the dynamic balance of nutrient exchange are summed in an equation such that the observed rate of change of nutrient concentration in the mixed layer, $d\bar{N}/dT$, is the sum of:

nutrient entrainment + biological exchange + vertical and horizontal advection + atmospheric exchange.

The observed $d\bar{N}/dT$, for example, the observed rate of change of mean nutrient concentration of the mixed layer which deepened from 11 to 32 m at Sta. 2.5, is calculated from the vertical profiles in Fig. 5 as

$$dN/dT = (4.67 - 2.82\ \mu M\ NO_3^-)/(63.3\ h/24\ h\ d^{-1}) = 0.72\ \mu M\ NO_3^-\ d^{-1}.$$

Nutrient entrainment is calculated to show what would happen to nitrate levels if there were no biological exchange or advection and the atmospheric exchange was negligible. For example, if the mixed layer deepened from 11 to 32 m [as predicted at Sta. 2.5 (Fig. 7)] the change in the mean nitrate concentration of the mixed layer is computed as follows:

$$d\bar{N}/dt = (4.75–2.75\ \mu M\ NO_3^-)/(63.3\ h/24\ h\ d^{-1}) = 0.76\ \mu M\ NO_3^-\ d^{-1}.$$

Biological exchange is assumed to be nutrient uptake by marine phytoplankton which constitute the high chlorophyll concentrations observed in the bloom. Nitrogen uptake rate is estimated by applying established relationships between growth rates measured by carbon-14 uptake and the ratio of phytoplankton carbon to nitrogen (GOLDMAN, 1980). The estimate of this nonconservative term is computed from the expression for primary production, using data from 24 h carbon-14 uptake experiments conducted on 24 July 1983 (Table 1), where Cp is phytoplankton biomass in μg C l^{-1}; μ is specific growth rate

Table 1. Phytoplankton specific growth rates, carbon biomass and carbon-14 production at an upwelling front off Pt Sur, California, 24 July 1983

	Station No	μ (d^{-1})	Cp (μg l^{-1})	μCp (μg l^{-1} d^{-1})	^{14}C Productivity (μg l^{-1} D^{-1})	Z (m)
50% light level	1.5	0.12	106	12.7	13.2	6
	2.0	0.67	127	85.1	65.0	1
	2.5	0.46	304	140	115	1
10% light level	1.5	0.08	254	20.3	20.6	19
	2.0	0.43	168	72.1	61.4	9
	2.5	0.58	346	201	158	9

μ, Specific growth rate. Cp, carbon biomass. ^{14}C productivity, primary production. Z, sample depth

Table 2. Estimated nutrient flux balance adjacent to an upwelling front off Pt. Sur, California, July 1983

	Station No.	$d\dot{N}/dT$ observed	=	nutrient entrainment	+	biological exchange	+	advection
		($\mu M\ NO_3\ d^{-1}$)						
50% light level	1.5	−0.82		0		−0.15		−0.67
	2.0	−0.63		+0.66		−1.02		−0.27
	2.5	+0.72		+0.76		−1.66		+1.64
10% light level	1.5	−0.82		0		−0.24		−0.58
	2.0	−0.63=		+0.66		−0.86		−0.43
	2.5	0.72=		+0.76		−2.39		+2.35

dN/dT is the rate of change based on the observed difference in mixed layer mean nitrate concentration between 23 an 26 July; entrainment by the mixed layer is based on initializing an atmospheric forcing model from data collected on 23 July; biological exchange is a representative uptake rate by phytoplankton based on 24-h carbon-14 primary production measurements and a C:N ratio of 7; advection is obtained by the algebraic sum, but it may include the effect of minor processes not exclusively considered, e.g. sinking, grazing and bacterially mediated recycling.

in d^{-1}; $dCp/dt = \mu Cp$ = primary production; and nitrogen flux, $dN/dT = [(\mu)(Cp)/12]/(C/N)$. For example, at Sta. 2.5 (at the 50% light level) on 24 July 1983, $d\dot{N}/dT$ = (0.46/day)(303.5 μg C l^{-1})(1 μM C/12 μg C)(1 μM N/7 μM C) = 1.66 μM N d^{-1}, and (at the 10% light level) $d\dot{N}/dT$ = (0.58/day)(346.5 μg C l^{-1})(1 μM C/12 μg C)(1 μM N/7 μM C) = 2.39 μM N d^{-1}; average = 2.0 μM N d^{-1}. Advection was obtained by the algebraic sum (assuming atmospheric exchange was negligible).

The dynamic balance of nutrient exchange processes at Stas 1.5, 2, and 2.5 are summarized in Table 2.

DISCUSSION

Atmospheric forcing and mixed layer–upwelling system interaction

Time series satellite and *in situ* observations (Figs 1, 3 and 4) clearly show that a thermal discontinuity or front can be maintained between an upwelling system and an adjacent oceanic mixed layer on a time scale of days. The *in situ* data also show a frequently observed association between phytoplankton and the sharp thermal and chemical gradients of upwelling fronts (TRAGANZA *et al.*, 1981, 1983).

To explain this frontal bloom phenomenon and the impact of upwelling circulation as it appears in satellite imagery (e.g. TRAGANZA *et al.*, 1980, 1981, 1983; TRAGANZA, 1984) one cannot assume that nutrient input into the surface layers is by upwelling alone. Local wind stress (Fig. 6) was sufficient to sustain the upwelling, but also to entrain elements from beneath the very shallow mixed layer which slopes to the surface along the seaward side of the frontal boundary. The presence of a frontal mixed layer (Fig. 3) and dynamic atmospheric forces (wind and solar radiation) which control processes of fluid entrainment by the mixed layer strongly suggest that nutrients are entrained by this mechanism in the area adjacent to the seaward side of the front. Upwelling and downwelling of the thermocline adds weight to this possibility in that they suggest convective turbulent mixing by the surface layer adjacent to the front. Internal waves could produce an apparent up- and downwelling structure because the sampling time interval is not synoptic. However, the persistence of specific upwelling and downwelling structure (domes and depressions) and the slope of individual isotherms over the 1 week time interval of the three surveys argues that the structure is real.

Chemical flux and primary production

From the satellite i.r. time series (Fig. 1), the same water mass appears to surround Sta. 2.5 between 23 and 25 July. The front appears to have maintained a relatively constant distance from Sta. 2.5 during this time, suggesting minimum advection of the water mass relative to the station. Thus, this location should have been ideal for measuring processes which may be involved in the dynamic balance of nutrient fluxes at the upwelling front.

When profiles from Sta. 2.5 on 23 and 26 July are compared (Fig. 5), they show temporal changes in nutrients and temperature of the mixed layer. The mean nutrient concentration of the surface layer increased while the mean temperature decreased and the mixed layer deepened. These observations suggest that mixing in the surface layer reached below the thermocline to entrain colder more nutrient-rich water. Strong winds (Fig. 6) provided atmospheric forcing during the same time interval. (In contrast, at Sta. 1.5 no nutrient increase was predicted by the model because there was an insufficient source of nutrients to entrain, see Figs 5 and 7). At Sta. 2.5 a biological response was observed; the chlorophyll maximum increased sharply and deepened, presumably because of utilization of entrained nutrients at the base of the mixed layer and resistance to sinking at this interface.

At Sta. 2.5 biological uptake was faster than the supply by entrainment (Table 2), but there appears to have been advection of more nutrient-rich water into the area. This may include cross-front exchange as well as a change of water mass.

At Stas 1.5 and 2 biological nitrogen uptake was faster than the supply by entrainment (which ranged from zero to positive) but advection was negative. Advection of less nutrient-rich water relative to these two stations is a possible (and likely) explanation, i.e. those stations occupied on 26 July were not in the same water occupied on 23 July.

Both nutrient entrainment and biological uptake are independent measurements based on conditions in the initial state of the water mass on 23 July 1983 and therefore can stand alone for direct comparison. The increase of nitrogen uptake (as determined by primary production measurements) from Sta. 1.5 to 2 to 2.5 is positively correlated with the increase of nutrient entrainment by the mixed layer (Table 2). However, the dynamic balance of all terms suggests advection or a cross-frontal process may be important as well. Taken together, the data from Stas 1.5, 2 and 2.5 show the increased uptake of nutrients by phytoplankton is positively correlated with the net of entrainment and the advection (see Fig. 8).

Advection was not obtained independently but by algebraically summing the observed rate of change of nutrient concentration (between 23 and 26 July 1983 at the same location), the entrainment, and the biological term. It therefore could include processes, such as grazing and sinking of phytoplankton, bacterially mediated nutrient recycling

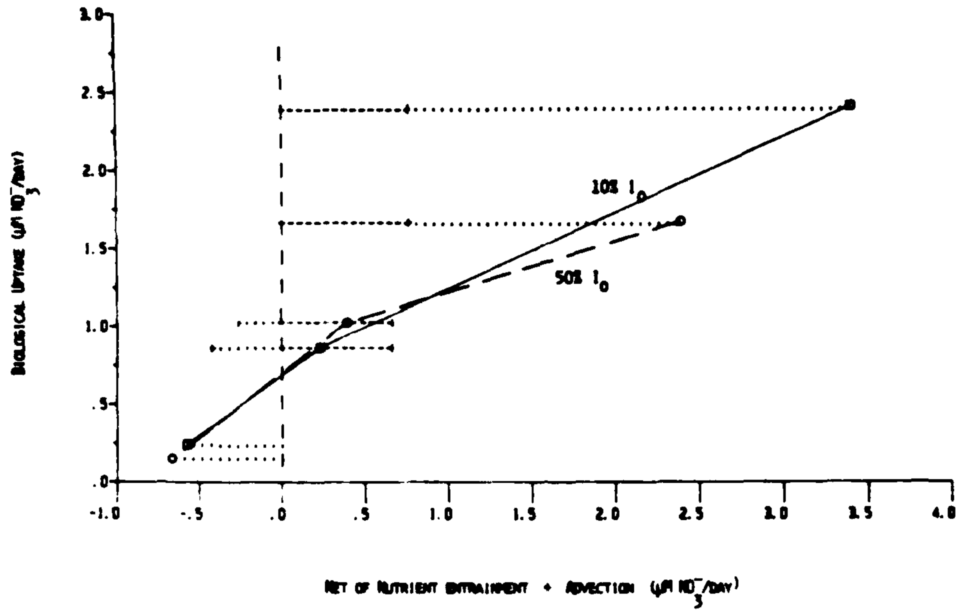

Fig. 8. Correlation of biological nutrient uptake with nutrient entrainment and advection into the mixed layer adjacent to an upwelling front off Pt. Sur, California, 1983. Biological uptake is based on carbon-14 primary production measurements and a C:N ratio of 7.

(POMEROY, 1974; WILLIAMS, 1981), NH_4^+ as an additional source to nitrogen uptake, and the affect of photoadaptation on the C:N ratio.

Notwithstanding possible error inherent to flux balancing, this study shows that both the chemical flux and phytoplankton growth rates are high, and that both nutrient entrainment and cross-frontal mixing may be important determinants of primary production at upwelling fronts. Traditionally, the cause of phytoplankton blooms in regions of upwelling has been attributed to a lack or lag of grazing by herbivores (CUSHING and WALSH, 1976). However, this bloom could have resulted from a continued supply of nutrients to sustain it even during grazing. Phytoplankton growth would have to be high for the blooms to persist at the observed chlorophyll concentrations. Phytoplankton growth rates at Sta. 2.5 increased from <1 to nearly 2 cell divisions per day during the course of the study. The bloom was sustained with these high growth rates. Primary production could be sustained even at low ambient nutrient levels under steady winds. The mechanism could be that of a quasi-chemostat (TRAGANZA *et al.*, 1981) driven by the winds, with nutrients being more or less continuously supplied by upwelling and entrained by the mixed layer or mixed laterally across the front.

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REFERENCES

ADAMEC D. and R. W. GARWOOD Jr (1985) The simulated response of an upper-ocean density front to local atmospheric forcing. *Journal of Geophysical Research*, **90**, 917–928.

CUSHING H. and J. J. WALSH, editors (1976) *Ecology of the seas*. Blackwell, Oxford, 467 pp.

FITZWATER S. E., G. A. KNAUER and J. H. MARTIN (1982) Metal contamination and its effect on primary production measurements. *Limnology and Oceanography*, **27**, 544–551.

GARWOOD R. W. (1977) An oceanic mixed layer model capable of simulating cyclic states. *Journal of Physical Oceanography*, **7**, 455–458.

GARWOOD R. W., Jr (1979) Air–sea interaction and dynamics of the surface mixed layer. *Review of Geophysics and Space Physics*, **17**, 1507–1524.

GOLDMAN J. C. (1980) Physiological processes, nutrient availability, and the concept of relative growth rate in marine phytoplankton ecology. In: *Primary productivity in the sea*, P. G. FALKOWSKI, editor, Plenum Press, New York, pp. 179–194.

KLEIN P. and B. COSTE (1984) Effects of wind-stress variability on nutrient transport into the mixed layer. *Deep-Sea Research*, **31**, 21–37.

MARTIN P. J. (1985) Simulation of the mixed layer at OWS November and Papa with several models. *Journal of Geophysical Research*, **90**, 903–916.

MOOERS C. N. K., C. N. FLAGG and W. C. BOICOURT (1977) Prograde and retrograde fronts. In: *Oceanic fronts in coastal processes*, M. J. BOWMAN and W. E. ESAIAS, editors, Springer-Verlag, Berlin, pp. 43–58.

MULLER P., R. W. GARWOOD Jr and J. P. GARNER (1984) Effect of vertical advection on the dynamics of the oceanic surface mixed layer. *Annales Geophysicae*, **2**, 387–398.

POMEROY L. R. (1974) The ocean's food web, a changing paradigm. *Biological Science*, **24**, 499–504.

REDALJE D. G. (1983) Phytoplankton carbon biomass and specific growth rates determined with the labeled chlorophyll *a* technique. *Marine Ecology–Progress Series*, **11**, 217–225.

REDALJE D. G. and E. A. LAWS (1981) A new method for estimating growth rates and carbon biomass. *Marine Biology*, **62**, 73–79.

SHAY T. J. and M. C. GREGG (1984) Turbulence in an oceanic convective mixed layer. *Nature*, **310**, 282–285.

SIMPSON J. J. (1984) An offshore eddy in the California current system. Part III: Chemical structure. *Progress in Oceanography*, **13**, 71–93.

TRAGANZA E. D. (1984) Application of satellites to chemical oceanography. In: *Mapping strategies in chemical oceanography*, A. ZIRINO, editor, Plenum Press, New York, pp. 373–392.

TRAGANZA E. D., D. A. NESTOR and A. K. McDONALD (1980) Satellite observations of a nutrient upwelling off the coast of California. *Journal of Geophysical Research*, **85**, 4101–4106.

TRAGANZA E. D., J. C. CONRAD and L. C. BREAKER (1981) Satellite observations of a cyclonic upwelling system and giant plume in the California Current. In: *Coastal upwelling*, F. A. RICHARDS, editor, American Geophysical Union, Washington, D.C., pp. 228–241.

TRAGANZA E. D., V. M. SILVA, D. M. AUSTIN, W. E. HANSON and S. H. BRONSINK (1983) Nutrient mapping and recurrence of coastal upwelling centers by satellite remote sensing: Its implication to primary production and the sediment record. In: *Coastal upwelling: Its sediment record*, E. SUESS and J. THIEDE, editors, Plenum Press, New York, pp. 61–83.

WILLIAMS P. J. (1981) Incorporation of microheterotrophic processes into the classical paradigm of the planktonic food web. *Kieler Meeresforsch.*, Sonderh., **5**, 1–28.

ZILITINKEVICH S. S., D. V. CHALIKOV and YU. D. RESNYANSKY (1979) Modelling the oceanic upper layer. *Oceanologica Acta*, **2**, 219–240.

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SOUTHAMPTON, N. Y. 11968 U.S.A.

Vdone 4/10/87

ID. Data Report (Camera ready graphs available on request)

1. Infrared Satellite Images: Specifications and raw images, 3-4, and 7-11 May, 1984, NOAA-6 AVHRR..........

2. 3-D subsurface variability of thermal structure in a coastal upwelling system, Pt. Sur, California, as represented by the 12 degree isotherm, 3 May 1984....

3. 3-D chlorophyll distribution at 2.5 m in an upwelling front Pt. Sur, California, 3, 7, 9-10, and 10-11 May, 1984..

4. 3-D temperature distribution at 2.5 m in an upwelling front Pt. Sur, California, 3, 7-8, 8-9, 9-10, and 10-11 May, 1984....................................

5. 3-D nitrate distribution at 2.5 m in an upwelling front, Pt. Sur, California, 3 and 7 May, 1984.....

6. 3-D phosphate distribution at 2.5 m in an upwelling front Pt. Sur, California, 3, 7, and 11-12 May, 1984..

7. Temperature profiles at 3 stations adjacent to an upwelling front, Pt. Sur , California, each sampled 3 times, 8, 10 and 11 May, 1984....................

8. Chlorophyll profiles at 3 stations adjacent to an upwelling front, Pt. Sur, California, each sampled 3 times, 8, 10 and 11 May, 1984.................

9. Nitrate profiles at 3 stations adjacent to an upwelling front, Pt. Sur, California, each sampled 3 times, 8, 10 and 11 May, 1984................

10. Cross-shelf surface temperatures transecting an upwelling front, Pt. Sur, California, 8, 10 and 11 May, 1964.................................

11. Temperature cross-section in an upwelling front Pt. Sur, California, 8, 10 mand 11 May, 1984....

12. Primary production,growth rate, biomass and chlorophyll at 3 stations transecting an upwelling front, Pt. Sur, California, each sampled 3 times 8-9, 10-11 and 11-12, May, 1984................

IE. Photochemistry Proposal

(Submitted under separate cover.)

IF. Summary of accomplishments and future possibilities.

Summary of Accomplishment

Discovery of "Nutrient Cells"

A. Initial hypothesis; nutrients cells in CalCOFI data may be coincident with cyclonic thermal features seen in NOAA satellite IR images.

B. Nutrient cell hypothesis verified by underway sampling with autoanalyzer (Traganza et al., 1980).

Discovery of "Chemical Fronts"

A. Chemical fronts are shown to be characteristic of upwelling systems (Traganza et al., 1981).

B. Horizontal nitrate and phosphate gradients show excellent inverse correlation with thermal fronts observed from satellites.

. Discovery of "Cyclonic Upwelling Systems"

A. Satellite & shipboard data show cyclonic upwelling systems are formed by interaction between California Current and Coastal upwelling (Traganza et al., 1981).

B. Chemical fronts are found in cyclonic upwelling systems.

C. Series of cruises show upwelling systems recur and persist off Pt. Sur.

D. Biochemical age (N:P ratio) of upwelling varies seasonally.

Conceptual Model Of Cyclonic Upwelling System Appeared on Cover of EOS

A. Conceptual model was selected from text of Coastal Upwelling for cover of American Geophysical Union Publication, EOS (Traganza, 1981).

Discovery Of "Giant Plumes" Across The California Current

A. Chemical fronts are found in giant plumes which satellite shows extending across the surface of the California Current (Traganza, et al., 1981).

Chemical Mesoscale & Biological Patchiness Interrelated

A. Phytoplankton blooms are shown to be concentrated along chemical fronts by underway fluorescence, chlorophyll, and adenosine triphosphate (ATP) analysis (Traganza et al., 1981).

. CZCS Chlorophyll Mapping Show Fronts Determine Regional Primary Production

A. Satellite CZCS ocean color measurement verifies blooms are in gradients (Traganza et al., 1983).

B. CZCS indicated upwelling frontal systems determine distribution of primary producers and productivity in California Current & along coastal boundary.

C. C-14 and GTP/ATP measurements indicate high rate of primary production associated with chemical fronts; especially equatorward of cyclonic systems.

. Sea Surface Nutrient Maps Are Produced From Satellite IR Images

A. Satellite IR radiance is correlated with below surface (2.5m) temperature field by algorithm for radiative transfer equation to to produce corrected thermal image as 2.5m sea surface temperature map.

B. Nutrients and temperature from sharpest gradients are correlated, then

C. IR image is converted to nitrate and phosphate 2.5m sea surface nutrient maps (SD = 5%) (Traganza et al., 1983).

D. Real time mesoscale chemical structure (chemical weather) of sea surface is revealed and feasibiltity for prediction of mean nutrient flux from satellite derived nutrient maps is established.

E. Show initial concentrations of N and P in source water masses and slope of nutrients vs. temperature vary seasonally; more is needed to develop oceanic nutrient climatology model.

Natural Chemostat Is Proposed As Hypothetical Model Of Fronts

A. Hypothesis: chemical fronts regulate recycling rate of non-conservative elements by phytoplankton; specific growth rate = f (nutrient flux and light availability); a chemostat effect may explain pronounced phytoplankton growth along frontal boundaries (Traganza et al., 1981).

B. May 1983 experiment: Dr. Redalje measures specific growth rates of phytoplankton in blooms concentrated along a front; underway C-14 uptake measurements are made to assess total biomass growth in response to nutrient levels.

C. Light level is measured to determine if it is limiting on mixing side of front vs. nutrient limited, stratified side.

D. Trial measurement of scalar irradiance field made form TOSS.

Subsurface Three Dimensional Mapping Is Related To Satellite Imagery

A. May 1982 experiment: towed seawater sampling system (TOSS) deep maps nutrients, temperature, and chlorophyll at 15 & 25 m with surface (2.5m) map; from XBTs related thermal structure is plotted in three dimensions by computer.

B. Discovery of chlorophyll maximum associated with downwelling of the mixed layer within an upwelling system.

C. Sea surface thermal pattern seen as surface expression of mixed layer topography in satellite imagery of upwelling region. (Traganza, 1984).

Discover Chlorophyll Max. Assoc. With Downwelling In An Upwelling System

A. May 1982 3-D mapping experiment discovers chlorophyll maximum associated with downwelling (Traganza, 1984).

B. May 1983 experiment: Adopted Garwood's mixed layer model to compare estimated "nutrient entrainment flux" with Redalje's C-14 specific growth rate measurements, and estimated non-conservative nutrient uptake in the mixed layer to nutrient uptake calculated from C-14 uptake, biomass & C/N.

C. Pursue 3-D approach to understanding and relating subsurface ecosystem variability to satellite imagery.

Future Plans:

Light Maps To Relate Optical Properties To Chemical & Biological Processes

A Scalar irradiance field will be measured from TOSS to produce K-maps which will relate light as well as nutrient flux to chemostat and nutrient entrainment models.

B. Vertical profiles will be used to set TOSS at one attenuation length; the depth within which most of the CZCS signal originates.

C. Alternately, TOSS may be used as an isolume follower to map chlorophyll.

D. TOSS II in concept stage for 3-D.

Measurements Of Other Systems

A. Plan comparison of anticyclonic vs cyclonic systems; see image from 31 January; biogeochemical transport mechanisms may be different.

B. Plan to investigate a recurrent, large eddy in the California Current which appears to interact with coastal upwelling to form recurrent frontal systems in the central California oceanographic regime.

C. Plan "experiments of opportunity" in other ocean regions where frontal systems are known. (First one with NOSC, Al Zirino's group in Mediterranean, Mar 30 to April 20, 1984)

Biogeochemical Cycle

A. Identify dominant primary producer and primary consumer species.

B. Determine phytoplankton C:N:P covariance vs. max growth rate.

C. Determine dissolved C:N:P covariance vs. phytoplankton C:N:P covariance.

D. Isotopic fractionation vs. growth rate: C13/C12; N15/N14; determine N recycling in surface layer vs. upwelling N.

E. Test satellite remote analysis of pH and alkalinity to bring CO_2 system and nutrient cycle into one unifying biochemical model.

Ocean Prediction

A. Test satellite prediction of ocean nutrients from temperature; approach: monitor seasonal thermal structure with AXBT flights and correlate with nutrients when ship data are available; use periodically updated seasonai climatological water mass model for nutrient prediction from satellites.

B. Couple biogeochemical model to nutrient prediction model for predicting biomass from satellites.

Joint Experiments: Bioluminescence: Isotope Biogeochemistry: Trace Metals: CO_2

A. Bioluminescence experiment with Bill Hemhill USGS & Richard Lynch NRL off California in July, 1983.

B. Isotope biogeochemistry experiment with Greg Rau, NASA-AMES.

C. Trace metal-nutrient cycle-CO_2 system study in the Peruvian upwelling area; in talking stage with Dana Kestor, URI; 1/84.

D. Zooplankton in fronts; sea trials with Valerie Loeb, MLML; March 1983.

E. Colaboration with Jim Mueller, NPS; a possibility for summer and fall 1983.

TOSS III

A. Plans are laid for a 3-port variable depth, transportable (go anywhere), towed seawater sampling & analysis system.

Remote Chemistry

A. Remote chemical analysis from shipboard is an exciting new possibility which could advance chemical oceanography; more will be said in the future.

I6. Sample of Citations in Science Citation Index

II. INDEX OF TECHNICAL REPORTS

Van Leer, J.C. and E.D. Traganza (1983). Towed Underway Sampling System Test and Recommendations; Naval Postgraduate School, Monterey, California (unpublished manuscript).

Traganza, E.D. (1979). The use of temperature and color in satellite detection of ocean fronts and eddies for ASW applications: A summary of selected literature condensed and edited by the author. Naval Postgraduate School, Monterey, CA 93943, Tech. Rpt. (NPS-68-79-008), 58 pp.

III. INDEX OF PUBLICATIONS

Papers in refereed journals

Traganza, E.D., D.G. Redalje and R.W. Garwood (1987). Chemical flux, mixed layer entrainment and phytoplankton blooms at upwelling fronts in the California coastal zone Continental Shelf Research 7(1):89-105.

Traganza, E.D. (1985). Application of Satellites to Chemical Oceanography. In: Mapping Strategies in Chemical Oceanography. Zirino, A. (ed.), American Chemical Society, Washington, D.C.

Traganza, E.D., V.M. Silva, D.J. Austin, W.L. Hanson, and S.H. Bronsink (1983). Nutrient Mapping and Recurrence of Coastal Upwelling Centers by Satellite Remote Sensing: Its Implication to Primary Production and the Sediment Record. In: Coastal Upwelling: Its Sediment Record. Suess, E., Thiede, J. (eds.), Plenum Press, New York, pp. 61-83.

Traganza, E.D., J.C. Conrad, and L.C. Breaker (1981). Satellite observations of a "cyclonic upwelling system" and "giant plume" in the California Current. In: Coastal Upwelling. Richards, R.A. (ed.), American Geophysical Union, Washington, D.C., pp. 228-241.

Traganza, E.D., D.A. Nestor and A.K. McDonald (1980). Satellite observations of a nutrient upwelling off the coast of California. Journal of Geophysical Research 85:4101-4106.

Published Abstracts

(excepting invited talks and poster papers given below)

Traganza, E.D., D.G. Redalje, M.J. Began and R.W. Garwood (1984). Dynamics and chemistry of chlorophyll blooms at upwelling fronts. EOS, Transactions, American Geophysical Union 65(45):958.

Traganza, E.D., D.G. Redalje and M.J. Began (1984). A new view of coastal upwelling ecosystems from satellite IR images and a 3-dimensional approach to in situ sampling and analysis. EOS, Transactions, American Geophysical Union, Jan. 23-27, New Orleans, 510-07.

Redalje, D.G., E.D. Traganza and M.J. Began (1984). Phytoplankton growth rates and biomass for populations associated with chemical fronts in the California coastal upwelling zone. EOS Transactions, American Geophysical Union, Jan. 23-27, New Orleans, 520- 05.

Traganza, E.D. (1981). Satellite and in situ studies of upwelling frontal systems in the California current. In: Proceedings of the National Research Council Symposium and Workshop on Water Sampling While Underway. Feb. 11-12, 1980. National Academy of Sciences Press.

Traganza, E.D., W.E. Hanson, S.H. Bronsink, and D.M. Austin (1980). Satellite inferences, GTP-microplankton productivity and chemodynamic effects of upwelling systems off Pt. Sur, California. EOS Transaction, American Geophysical Union 61(46):1013.

Traganza, E.D., J.C. Conrad (1980). Satellite and in situ observations of nutrient upwelling and microplankton biomass in the California current system. In: IDOE International Symposium on Coastal Upwelling." Feb. 4-8, 1980, USC, Los Angeles, California; AGU, AMS, ASLO, NSF.

Traganza, E.D. (1980). Satellite and synoptic studies of the Pt. Sur cyclonic upwelling system. IN: Proceedings of the 27th Annual Eastern Pacific Oceanic Conference. October 8-10, 1980, UCLA Conference Center, Lake Arrowhead, California.

Poster Papers

Traganza, E.D. Satellite Observations of a Nutrient Upwelling off the Coast of California; Canadian Institute of Chemistry Conference on Marine Chemistry into the Eighties; University of Victoria, B.C., Canada, 1979.

Traganza, E.D. Chemical Fronts in the California Current; Gordon Research Conference on Chemical Oceanography, January 28 - February 1, 1980, Santa Barbara, California, 1980.

Traganza, E.D. Satellite Mapping of Nutrients off the Central California Coast and 3-Dimensional Relationships of Biomass in the Surface Layer; EOS Transactions; American Geophysical Union, 63(45), 1982, p. 956.

Covers

Traganza, E.D. Conceptual Model of a Cyclonic Upwelling System; Cover of EOS Transactions; American Geophysical Union, 62(36), 1981, September 8.

Master's Theses

Nestor, D.A., M.S. Thesis, A Study of the Relationship Between Oceanic Chemical Mesoscale and Sea Surface Temperature as Detected by Satellite IR Imagery; Naval Postgraduate School, Monterey, California, 1979.

Conrad, J.C., M.S. Thesis, Relationship Between Sea Surface Temperature and Nutrients in Satellite Detected Oceanic Fronts; Naval Postgraduate School, Monterey, California, 1980.

Johnson, J.E., M.S. Thesis, Subsurface Dynamical Properities of Variable Features Seen in Satellite IR Imagery off Point Sur, California and Their Acoustic Significance; Naval Postgraduate School, California, 1980.

Bronsink, S.H., M.S. Thesis, Microplankton ATP-biomass and GTP-productivity Associated with Upwelling off Point Sur, California; Naval Postgraduate School, Monterey, California, 1980.

Hanson, W.E., M.S. Thesis, Nutrient Study of Mesoscale Thermal Features off Point Sur, California; Naval Postgraduate School, Monterey, California, 1980.

Phoebus, R.W., M.S. Thesis, Distribution of Chlorophyll Biomass in Chemical Mesoscale Features Detected by IR Satellite Imagery; Naval Postgraduate School, Monterey, California, 1981.

Jori, C.D., M.S. Thesis, Estimating the Distribution and Production of Microplankton in a coastal Upwelling Front, from the Cellular Content of Guanosine-5'-triphosphate and Adenosine-5'-triphosphate; Naval Postgraduate School, Monterey, California, 1981.

Silva, V.M., M.S. Thesis, Thermal Calibration of Satellite Infrared Images and Correlation with Sea Surface Nutrient Distributior; Naval Postgraduate School, Monterey, California, 1981.

Howard, S.J., M.S. Thesis, Subsurface Thermal and Bio-Chemical Structure of Fronts Inferred from Satellite Infrared Imagery; Naval Postgraduate School, Monterey, California (in progress).

8. Invited Talks

Traganza, E.D. The Use of Satellite Infrared Imagery for Investigating Nutrient Fronts in the Ocean; Gordon Research Conference on Chemical Oceanography, Plymouth, N.H.; announcement in Science 1981, 211, no. 4487.

Traganza, E.D. Nutrient Distribution and Recurrence of Upwelling Centers by Satellite Remote Sensing; NATO Advanced Research Institute Abstracts, Villamoura/Algarve, Portugal, 1981.

Traganza, E.D. Application of Satellite Radiometry to Study of Chemical Fronts; listing in program, 185th National Meeting American Chemical Society, Seattle, Washington, 1983, no. 166, p.40.

Traganza, E.D. Satellite and Synoptic Studies of Chemical Fronts; NOAA-AMOL, Key Biscayne Florida, 1981.

Traganza, E.D. Satellite and Synoptic Studies of Chemical Fronts in the California Current and Coastal Upwelling Zone, NRL, Washington, D.C., 1981.

Traganza, E.D. CZCS Imagery and Chemical Fronts in the California Current; NASA-AMES, Moffett Field, California, 1982.

Traganza, E.D. Chemical Fronts: Remote Analysis From Satellites; in symposium "Oceanographic Advances from New Technologies"; International Association for the Physical Sciences of the Ocean of the International Union of Geodesy and Geophysics, Hamburg, Germany, 1983.

Traganza, E.D. Chemical Fronts: Relation to Phytoplankton Biomass and Productivity; Marine Plankton and Productivity Symposium, European Society for Comparative Physiology and Biochemistry, 5th Conference and General Assembly; Taormina, Sicily, 1983.

Traganza, E.D. Chemical Fronts: NORDA workshop on "Chemical Varialbility in Ocean Frontal Areas", NSTL Station MS, 1983.

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