Optical features associated with thermohaline structures

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Abstract

A subset of the Optical Dynamics Experiment (ODEX) data set taken from the R/P FLIP in the eastern North Pacific on November 8, 1982 is used to examine the relationships among physical and bio-optical parameters. Rapid profiling was done with a CTD equipped with a beam transmissometer and an in situ fluorometer. Intense thermohaline structures are observed to vary on time scales as short as 15 min. Interestingly, the temporal and vertical spatial variability in the physical parameters are often well-correlated with the corresponding variability in the optical parameters. In addition, the extent and intensity of the fluorescence maximum region appears to be modulated by a low frequency internal wave.

Introduction

The Optical Dynamics Experiment (ODEX) is an interdisciplinary research program which is motivated by fundamental questions concerning temporal and spatial variability of optical properties and their prediction in the open ocean. The ODEX field study was unique because of its contemporaneous collection of physical, optical, and biochemical data over a relatively long time period and over a large region of the ocean. The study involved measurements of meteorological, physical, chemical, and biological as well as optical parameters because of the observed dependence of optical properties upon the states of the atmospheric and oceanic environments. More specifically, the temporal changes and spatial distributions of the light field in the ocean are affected by variations in the atmosphere (i.e., clouds, water vapor, etc.) and the types, amounts, and distributions of biogenic and non-biogenic absorbing and scattering matter in the water column. These materials are in turn affected by physical, chemical, and radiation processes. A detailed conceptual model illustrating the multiple relationships (and feedback loops) among the interdisciplinary data fields is presented in Dickey, Siegel, and Bratkovich[1].

The primary ODEX field program was conducted in the eastern North Pacific in October and November of 1982. Horizontal scales of variability were observed using the following platforms: M/V Pacific Viking, O(20km); R/V Acania, O(1000km); and R/V deSteiguer, O(1000km). These vessels were used to obtain vertical profiles of optical, physical, and biochemical variables typically to depths of 250m. Satellite Coastal Zone Color Scanner (CZCS) observations of near surface color were also collected. These data sets are described in Zaneveld, et al.[2], Mueller, et al.[3], and Dickey, et al.[1].

Whereas the aforementioned platforms were utilized primarily to address questions relating to horizontal (and vertical) scales of variability, the R/P FLIP was used to obtain temporal (and vertical) data. It was chosen for this aspect of the study because of its inherently high degree of vertical stability, thus decoupling platform motion from the meteorological and oceanographic instrument packages. In addition, several instrument packages can be deployed simultaneously which is particularly advantageous for this interdisciplinary study. The R/P FLIP was used to characterize temporal scales of variability (on order of 2h to 10d) in atmospheric forcing and water column properties including: mass, heat, salinity, momentum, nutrients, dissolved oxygen, chlorophyll-a and phaeo-pigments, in situ fluorescence, beam transmissivity, and downwelling spectral irradiance. Physical processes which can be addressed using this data set include double diffusive mixing, internal gravity waves, inertial motion, internal tides, and diurnal heating.

Instrumentation deployed from the R/P FLIP included: a meteorological system, a CTD/rosette package, an autonomous profiling current meter (Cyclesonde) with a temperature sensor, and an optics package which was used to measure downwelling spectral irradiance, temperature, and beam transmissivity. The R/P FLIP deployment configuration is shown in Figure 1. Observations made with the optics package are described by Siegel and Dickey[4], Siegel, et al.[5], and Dickey, et al.[1]. The observations presented here were taken with the CTD/rosette package. The package consisted of a Neil Brown Mark 3 CTD/O_2 instrument with a General Oceanics rosette bottle sampler, a one meter pathlength SeaTech beam transmissometer (at 660nm), and a SeaMarTech Model 6000AR in situ fluorometer.

The R/P FLIP was towed to a site in the eastern North Pacific Ocean near 34N and 142W (the North Pacific Sub-Tropical Gyre) where it was allowed to drift during the observational period from October 20 through November 12, 1982. This is a transitional period from summertime conditions of shallow mixed layers and high sea surface temperatures to wintertime conditions of deep mixed layers and low sea surface temperatures.

The present paper focuses upon a small portion of the data set which was taken on November 8, 1982. During a period of approximately 4h on this date, the CTD package was profiled (nominally every 15 min) in order to observe relatively short time scale processes. This segment of the data set is chosen for special consideration because it exhibits strong thermohaline structures as opposed to the earlier portion of the data set which is characterized by relatively modest thermohaline activity[1]. It is hypothesized that the R/P FLIP encountered a major frontal feature associated with the North Pacific Sub-Tropical Convergence Zone (NPSTCZ) as it drifted south-southeast from November 5 through November 10, 1982. The NPSTCZ is not strictly fixed in space or time but has been observed in the general geographical region (from 28N to 36N) of concern[6,7,8]. A detailed summary of the theory and observations pertinent to the NPSTCZ is given by Roden[6]. For the present work, the important point is that widely varying water masses intermingled within the observation region.

The particular frontal feature of interest is manifest in elevated surface salinity (change of ~0.3psu within 1 day or ~25 km) and increasing sea surface temperature (change of ~0.3C within 1 day or ~25 km) during its encounter by R/P FLIP from November 7 to November 8, 1986 (Julian days 311 and 312). The frontal region is also marked by intense subsurface horizontal gradients in temperature and salinity throughout the upper 200 m. Although there is an associated increase in the near-surface potential density, the intense subsurface frontal structure in temperature and salinity is not evident in the potential density (nor the buoyancy frequency) structure. It is likely that temperature/salinity compensation can explain the relatively horizontally homogeneous density field. Interestingly, subsurface frontal structures are observed in the evolution of relative beam transmissivity, but not in that of the in situ fluorescence. More details concerning this aspect may be found in Dickey, et al.[1].

The evolution of the vertical structure of the temperature, salinity, potential density, relative beam transmissivity, and in situ fluorescence is shown in Figures 2a-e. The individual profiles are shifted proportionately with respect to time in order to facilitate the interpretation. The nominal time interval between profiles is 15 min although occasional departures from this increment are evident as wider gaps between profiles. It should be noted that these observations are not strictly Eulerian in that the R/P FLIP drifted approximately 4 km during the ~4h observational period. Thus, the interpretation of the data set requires some degree of consideration in regard to temporal versus horizontal spatial variability.

It is convenient to subdivide our discussion of the evolution of vertical structure in thermohaline and optical fields into the following topics: (1) the near-surface (upper 50 m) variability, (2) a deep (160 to 200 m) thermohaline intrusion, and (3) intensification of the fluorescence maximum.

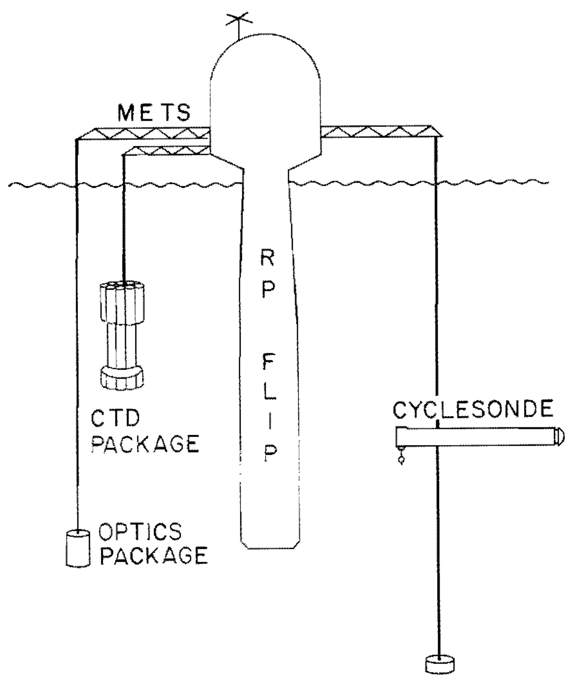
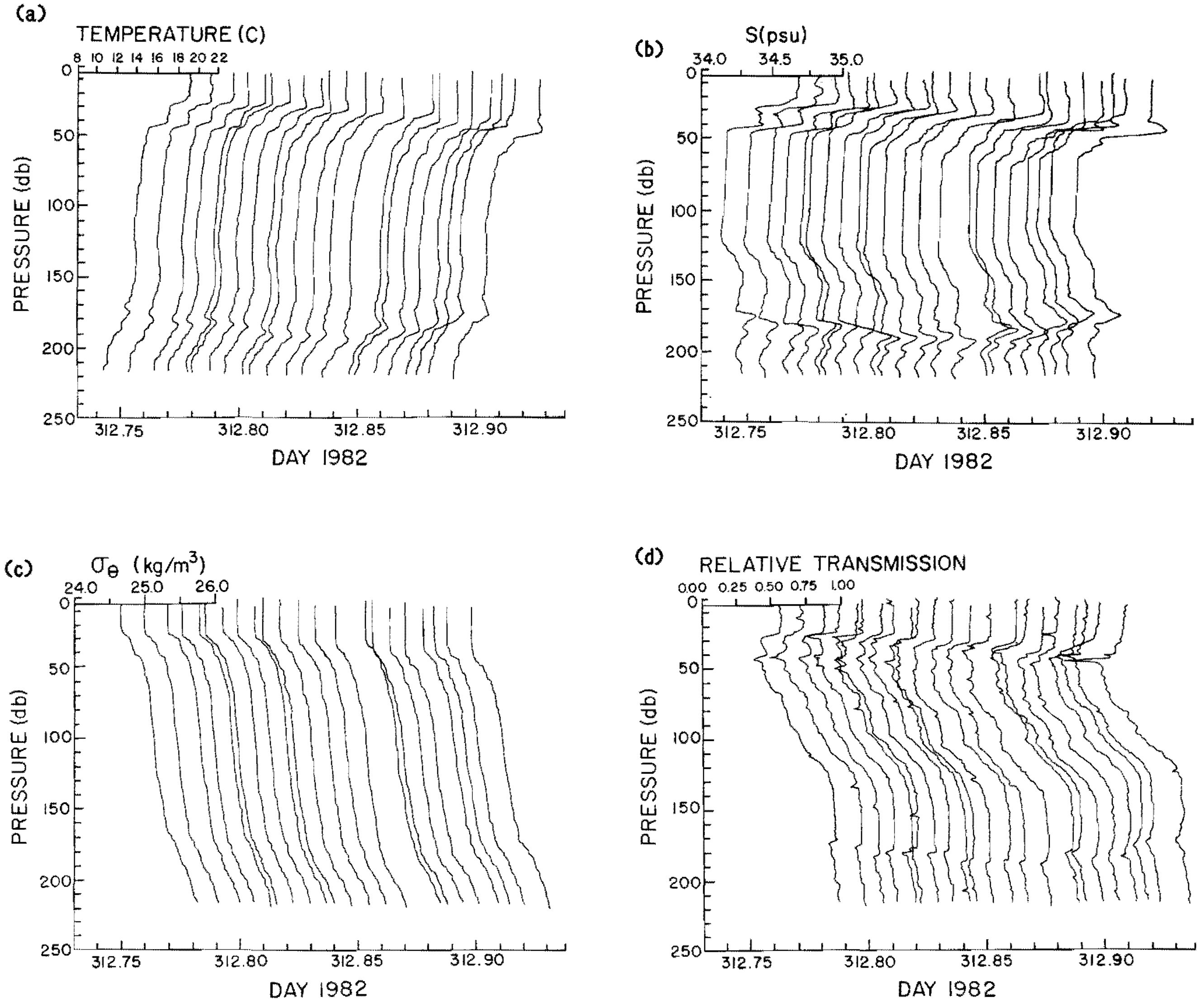


Figure 1. Sampling configuration of the R/P FLIP during the ODEX field study.



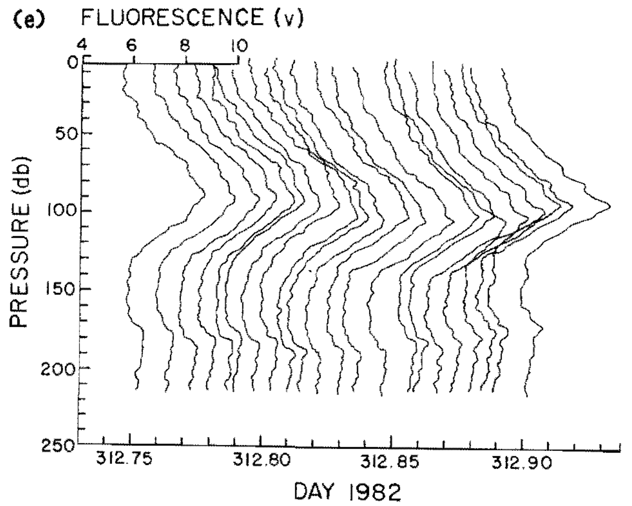


Figure 2. R/P FLIP observations (November 8, 1982) of the temporal evolution of vertical profiles of (a) temperature, (b) salinity, (c) potential density, (d) relative beam transmission, and (e) relative *in situ* fluorescence.

The Near-surface Variability

Considerable vertical structure is apparent in all profiles (Figures 2a-e) within the upper 50 m. A two step structure (two relatively homogeneous layers separated by a high gradient region) is seen in the temperature, salinity, density, and relative beam transmissivity profiles during the first part of the sampling period. This may be due to restratification, internal wave straining, horizontal advection, or some combination of these processes. Analogous evolution of the salinity profiles is seen. However, it should be noted that whereas the temperature structure contributes to gravitationally stable or neutral conditions for the water column within the upper 50 m, the salinity structure generally acts to reduce static stability (with a few exceptions) in this region as higher salinity water overlies lower salinity water. The region of the deeper step eventually increases in salinity and finally (as was the case for temperature) disappears.

Over the short span of data considered here, the mixed layer depth has apparently increased from about 20 m to about 45 m. This would represent a major deepening event if it were created by local atmospheric forcing. The wind speed did not exceed ~10 m/s during these deployments. This degree of atmospheric forcing could cause some of the "deepening" observed, but it is unlikely that local atmospheric forcing is the only source of the observed variability. During these measurements, the R/P FLIP drifted across a major thermohaline frontal feature and differing water masses were encountered, as was discussed previously. Thus, the "deepening event" observed may be primarily due to horizontal advection with respect to the R/P FLIP. In addition, a major temperature and salinity inversion (compensating density effect) is observed at the base of the mixed layer for the final profile. It is unlikely that this feature is produced by local atmospheric forcing. Also, it is conceivable that some of the upper ocean variability can be explained by vertical displacements induced by internal waves (see discussion of intensification of the fluorescence maximum below).

The near-surface step structure and the "deepening process" are clearly manifest in the relative transmissivity profiles (Figure 2d), but appear rather weakly in the *in situ* fluorescence profiles (Figure 2e). The relatively high values of transmissivity near the surface indicate that the near surface waters may be characterized by low particle concentration. The inferred particle maximum region falls in the depth range from about 20 to 50 m and tends to correlate well with large changes in the vertical structure of temperature, salinity and density. The spikes in the transmissivity profiles are possibly related to biological materials (i.e., large oceanic particles, zooplankton, marine snow, etc.). These spikes generally coincide with high vertical gradient portions of the thermohaline fields.

The Deep Thermohaline Intrusion

An interesting thermohaline feature is observed between approximately 165 and 190 m (see Figures 2a and b). It is likely that this structure, which is marked by a temperature inversion and a density compensating salinity increase, results from the intrusive interleaving of different water masses. Although these features are statically stable (Figure 2c), the dynamics of these structures may be controlled in part by double diffusive processes (see review by Turner[9]).

The optical signal associated with this thermohaline feature is quite interesting. The transmissivity structure in this portion of the water column is characterized by a local minimum (inferred particle maximum) which coincides with the temperature inversion (and local salinity maximum). Apparently, the more turbid water is associated with a warmer, more saline water mass which has advected into the region. The *in situ* fluorescence data suggest a correlation of relatively high fluorescence (high biopigment concentrations) with the temperature inversion, anomalous salinity structure, and the particle maximum. One can infer that the warm, saline, and turbid water mass is also high in biomass. The explanation for the high biopigment concentrations within the temperature inversion is not obvious in that this feature lies considerably deeper than the euphotic zone (~ upper 85 m). It is possible that this water mass was once near the surface in the euphotic zone, but was later submerged through a combination of lateral advection and vertical processes such as frontal subduction[10]. Thermohaline intrusions have been commonly observed in the NPSTCZ, particularly in the water masses south of the front[6,7].

Intensification of the Fluorescence Maximum

The shape of the fluorescence maximum region changes during the course of the observations (Figure 2e). More specifically, the values of fluorescence in the maximum region increase and the vertical extent of the region decreases throughout these deployments. The salinity structure is characterized by a relatively thick isohaline region which is nearly coincident with the extent of the fluorescence maximum region. This isohaline region originally extended between about 45 and 120 m or a depth range of 75 m. Later, the extent of this region is reduced to about 50 m (or from about 60 to 110 m). Analogous, although more subtle, changes are evident in the temperature field as well. Thus, a 30% reduction in the vertical extent of this region occurs within a few hours. It is likely that the isohaline and fluorescence maximum regions are compressed during these observations in response to low frequency internal waves. This explanation is supported by data taken before and after the sampling period considered here. The biomass as indicated by the fluorescence may be conserved during this short period and thus more biomass may be concentrated within a more limited depth range.

Discussion and Summary

Thermohaline structure was observed during the latter portion of the ODEX field study in the eastern North Pacific Ocean. Time series profiles of temperature, salinity, potential density, relative beam transmissivity, and fluorescence have been utilized to study the temporal evolution of vertical structures in physical and optical parameters. It was found that optical parameters often covaried with physical parameters under these environmental conditions. This suggests the possibility of causal relationships among the physical, biological, and optical parameter fields. The modeling of the inter-relationships among these variables and the processes which govern them is of particular current interest.

Another interesting observation was the apparent compression of the fluorescence maximum region, which may have been caused by low frequency internal waves. Models of upper ocean internal wave variability indicate that a realistic scaling value for vertical strain (the root mean square value of the vertical derivative of the internal wave induced vertical displacement field) is 0(0.5) according to Desaubies and Smith[11]. That is, a feature of vertical scale, H, would modulate its apparent thickness between 0.66H and 1.50H a large percentage of the time. The present data, as indicated by the isohaline feature at depth (a vertical scale of 50 m), appear to be consistent with this scaling range (~30-70 m). For more energetic wave fields, the vertical straining of such features would be significantly larger.

The present data showed a high degree of variability on time scales as short as 15 min. Therefore, appropriate sampling schemes for the observations of interactions among physical and bio-optical variables require relatively high resolution in both space and time. The present observations suggest that sampling intervals should be chosen small enough to resolve surface and internal gravity wave induced variability and upper ocean mixing events. In addition, longer term observational schemes will be required to quantify the effects of processes acting on seasonal and interannual time scales. Similarly, spatial scales ranging from a few centimeters to the basin scale must be considered for questions relating to optical variability in the ocean.

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