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# The Coastal **Transition Zone Program**

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## Introduction

The Coastal Transition Zone (CTZ) Program, sponsored by the Office of Naval Research (Coastal Sciences and Oceanic Biology programs), is designed to investigate the cold tongues ("filaments") often observed in satellite sea surface temperature images of the waters off the west coast of North America. The cold filaments are not unique to this region, since similar features have also been observed along other coasts around the world, including those near Portugal and southwestern Africa. The discovery of these features is an excellent example of the power of satellite observations, because although the filaments are quite prominent in the satellite images, years of regular shipboard observations did not reveal them. On the other hand, the study of cold tongues also illustrates the necessity of on-site observations, because the nature, structure, causes, and effects of filaments cannot be determined from the satellite observations alone.

The causes, dynamics, and reasons for the growth and decay of cold filaments are unknown, as is the reason that they seem to appear most often in certain locations along a coastline and not in others. We don't know whether the process behind them continues year round or whether it is seasonal. Filaments may be very important, not only for a description of the events occurring along the world's coasts but also for knowledge of-the processes through which coastal waters interact with the open ocean. Cold filaments are only now giving up their secrets to a concerted multi-investigator, multi-institutional effort that has its basis in a combination of shipboard observations and remotely sensed data.

Before the CTZ program began, on-site observations, which amounted to a few snapshots [e.g., Kosro and Huyer, 1986; Flament et al., 1985], indicated that the features off northern California consisted of cold, salty inshore water that had been carried offshore, well beyond the continental shelf. They were associated with currents that are strongest in the upper few hundred meters of the water column.

The CTZ program brings together a group of about 34 investigators from 12 institutions (Table 1) to address interdisciplinary descriptive and dynamical questions relating to filaments. Program components include modeling, remote sensing, meteorology, hydrography, current measurements, microstructure, and phytoplankton and zooplankton biology. This article provides an outline of the major questions addressed by the project, includes

Investigator, Institution\*

TABLE 1. Program Components

1988 Activity

M. R. Abbott, OSU	remote sensing, biological rate studies
	assimilative numerical modeling
R.ST ABlamber SUChavez, MBARI	nutrient distributions
K. H. Brink/R. C. Beardsley, WHOI	instrumented drifters
A. Bucklin, SIO	zooplankton genetics
D. R. Caldwell/J. Moum, OSU	microstructure
D. Carlson, OSU	surface microlayer
T. Cowles/L. Small, OSU	pigment distributions, zooplankton grazing
C. Davis, JPL	marine optics
R. E. Davis, SIO	acoustic Doppler currents
K. Denman, IOS	remote sensing, modeling
D. B. Haidvogel, CBI	numerical modeling
T. Hayward, SIO	primary productivity
E. Hofmann, TAMU	biological modeling
A. Huyer/P. M. Kosro, OSU	hydrography, acoustic Doppler currents
B. H. Jones, USC	nutrient and pigment distributions
D. Kadko, OSU	radon tracer studies
G. Lagerloef, SAIC	remote sensing
D. Mackas, IOS	zooplankton distributions
T. Maxworthy, USC	laboratory modeling
P. P. Niiler, SIO	drifter measurements
C. A. Paulson, OSU	towed thermistor chain
S. R. Ramp, NPS	hydrography and acoustic Doppler currents
R. L. Smith, OSU	moored current measurements
S. L. Smith, BNL	zooplankton production
T. Strub, OSU	remote sensing
D. W. Stuart, FSU	meteorology
L. Washburn, USC	hydrography

\*Institutional abbreviations: BNL, Brookhaven National Laboratory; CBI, Chesapeake Bay Institute; FSU, Florida State University; IOS, Institute of Ocean Sciences; JPL, Jet Propulsion Laboratory; MBARI, Monterey Bay Aquarium Research Institute; NPS, Naval Postgraduate School; OSU, Oregon State University; SAIC, Science Applications International Corporation; SIO, Scripps Institution of Oceanography; TAMU, Texas Agriculture and Mechanical University; USC, University of Southern California; WHOI, Woods Hole Oceanographic Institution.

some preliminary results from our 1987 field program, and discusses the field plan for 1988.

# **Motivating** Questions

What is the Nature and Structure of the Cold "Filaments" Seen in the Satellite Images of Sea Surface Temperatures?

Before the 1987 field season, we knew that the cold filaments contained salty, upwelled inshore water and that they were associated with strong cross-shelf near-surface currents. It was generally thought that the inshore water was carried offshore by jetlike westward currents. Beyond these basic facts, little was known of where the water in the cold jet went or of the regional context of the fea-

Cover. Infrared AVHRR image from the National Oceanic and Atmospheric Administration NOAA 9 satellite, taken June 16, 1987, of the ocean off the coast of northern California. Light shades represent cold sea surface temperatures, and darker shades represent warmer temperatures. White patchy areas on the left side of the figure represent the filaments discussed in the article, The Coastal Transiture. Although we now have tentative results on some of these issues (see below), several questions still exist about their generality and the degree to which these findings can be used to interpret satellite imagery.

### What Causes These Features to Form?

We presently hypothesize that cold filaments result from meanders of the California Current, with eddies subsequently breaking off from them. What process causes these eddies? Is it an instability process? Is it related to the coastal topography? What is the role of stratification? Because the features are so often found near capes and promontories (Cape Mendocino and Point Arena, for example), it is tempting to conclude that the shape of the coast plays an important role. Is

tion Zone Program, on p. 698. This image is contemporaneous with the hydrographic and current measurements displayed in this article. Taken together, it becomes clear that the features apparent in this satellite image represent important in situ structures. The image was processed by M. Abbot and M. Ciandro of the Scripps Satellite Oceanography Facility.



the bathymetry important? Does the **geo**graphical variation of the wind forcing play a role in the formation process?

# What are the Characteristics of the Cold Filaments?

After formation, the features possess distinct physical, biological, and chemical properties. Questions about these properties are various, including the following: What **are** 



Fig. 1. Results from the June 9–18, 1987. mapping cruise. (a) Doppler  $\log^{\alpha}$ . Current measurements at \* m depth. The scale is on the lower left. (b) Surface dynamic height relative to 500 db. (c) Surface temperature. (d) Surface salinity (practical salinity units). (e) Surface chlorophyll concentration.

the local dynamics of the features? Are they in geostrophic balance? How is energy propagated and lost in them? How do they decay? Additionally, how do the features interact physically with their surroundings? Vertical shears are large in these features. Are the rates of vertical and horizontal mixing enhanced? Dramatic interleaving of water masses has been observed in and near them [e.g., Flament et al., 1985]. How important is the interleaving for mixing and dissipation? Intense internal waves have also been observed near the features. What is their effect? What are the biological and chemical distributions within a feature? Do the features contain unique planktonic assemblages of plants and animals? Do the assemblages or populations form independently of or in conjunction with the physical advective fields? Are primary and secondary production enhanced in and around a feature? Are optical properties of the water modified by the biological and chemical distributions?

### The Pilot Program

Preliminary measurements were made dur ing 1986 and 1987 to prepare for the major 1988 field program. There were three **moti**vations for these measurements. First, we needed preliminary sampling, especially in microstructure and biological measurements, to refine hypotheses and sampling schemes for the 1988 field study. Second, hydrographic and acoustic Doppler current surveys elucidated the large-scale structure. Finally, repeated surveys were used to explore whether filamentary patterns exist all year round or only during the upwelling season.

One major result of the pilot studies was a new vision of the structure and kinematics of flow in the coastal transition zone during the upwelling season. Before 1987, measurement programs tended to emphasize study of the cold, offshore-directed jets that were dramati cally manifest in remotely sensed data [e.g., Flament et al., 1985]. This approach revealed much about the structure of the jet but little about where the jet eventually went or about its regional setting. Our new tentative synthe-sis is exemplified by data shown in Figure 1 and by the schematic diagram in Figure 2. Specifically, we now envision a continuous meandering jet (identified with the Californi;a Current), bounded on its offshore edge by a surface salinity front. This front marks the offshore boundary of upwelled water: Highnutrient surface waters are found only be tween it and the coast, and high chlorophyll a concentrations (and hence phytoplankton biomass) occur primarily inshore of and at the front. The cold sea surface temperature tongue, so evident in satellite imagery, traces only the offshore-flowing part of the feature before the surface waters become warmer. Hence sea surface temperature provides an incomplete (almost misleading) image of the structure, while salinity provides a much better impression. These meanders are not evident in wintertime measurements, but they grow through the upwelling season, accounting for the accompanying seasonal growth of filaments as observed by remote sensing. Finally, it appears that the meanders may be centered at prominent headlands, but be-







cause their shapes change, the cold filaments (which represent only the offshore-directed limb) need not be so closely linked to the topography.

pography. The **circulation** in the meanders may not be entirely horizontal: Some preliminary results suggest that the waters within the jet subside as they flow around the meander. The evidence for this is tentative, but it comes from several sources. First, there is a tendency for chlorophyll a (representing the nearly neutrally buoyant phytoplankton) to have a maximum in the upper 10 m, near the surface on the northern, offshore-flowing lee of the meander, and to have a subsurface maximum (about 30 m) in the onshore-flowing leg (see Figure 3). This deepening, by -30 m is consistent with subsidence. Second, preliminary results from dissolved radon concentrations show mid-depth depletions at depths as great as 80-100 m, which are consistent with the water having been near the surface within the previous 10 days. Third, temperature records from surface drifters indicate anomalously rapid (relative to surface heat fluxes) warming, which is also consistent

with subsiding cold water being replaced by ambient warmer water. These results are tentative and are certainly open to alternative interpretation, but they do seem consistent with a downward motion. The microstructure program yielded re-

markably clear-cut results. The measurement program consisted of very frequent (roughly 8/hour) measurements of momentum dissipation  $\bullet$  (a measure of mixing activity) along cross-filament transects. The measurements (see Figure 4) show a remarkably clear picture: Dissipation is strongly proportional to the wind stress to the 3/2 power. While this result is consistent with simple models [e.g., Kraus and Turner, 1967], it is remarkable in that diurnal variability and enhanced turbulence at fronts are only faintly apparent, if at all. The absence of a strong diurnal cycle in dissipation stands in marked contrast to recent results from the equatorial ocean [e.g., Moum and Caldwell, 1985].

The results of the 1987 program are prom-

ising and lead to a sequence of new questions to be addressed during the CTZ program's main field program. Particularly important objectives are the refinement of the new kinematic model (especially with regard to subsidence) and the completion of process studies to understand the structures (for example, fronts), dynamical balances, and biological development. Finally, there is a clear need to develop a well-sampled time series of threedimensional surveys of the meandering features so that their development can be clearly related to quantitative models.

### Summary of 1988 Observational Plan

The 1988 field program will concentrate on a region near Point Arena that covers about one third the along-coast extent of the 1987 measurements. The reason for this restriction is that more detailed and synoptic spatial coverage is needed, as well as coverage farther from the coast. Such coverage can only be obtained by reducing the alongshore dimension to cover roughly one meander of the California Current.

The components of the three-ship 1988 experiment can be divided into four major ef-

Mapping. A series of maps will be obtained of the current, hydrographic, nutrient, and particle fields, using CTDs (conductivitytemperature-depth sensors, equipped in this instance with fluorometers, transmissionmeters, and water samplers) and acoustic Doppler current profilers. The sampling grid (Figure 5) will extend 100 miles (-160 km) in both alongshore and offshore directions and will be located west and south of Point Arena. Maps will be obtained more or less weekly over a 6-week period beginning in late June. This series of maps will form the basis of the interpretation of all field data, along with the satellite images for the period. In addition, surface maps of temperature, salinity, fluorescence, and nutrient concentration will be plotted from underway measurements



Fig. 4. Time series results from the microstructure program, June 1987. The ship was maneuvering through a number of features in and about the filament. (a) Transect numbers. Odd numbers are south-to-north transects, and even numbers are north-to-south transects. (b) Solar insolation, illustrating the diurnal heating cycle. (c) Wind speed. (d) Surface temperature. (e) Surface salinity. (f) Sigma t at 3, 60, and 120 m. (g) Kinetic energy dissipation averaged between 10 and 110 m depth.



on all ships, thus providing fine-scale resolution of the surface features.

The mapping operations will produce data directly relevant to the nature and structure of the features. Our concept of these features was radically changed by the maps obtained in 1987. The 1987 findings need to be confirmed and refined through the more extensive and detailed 1988 measurements. In addition, the maps will be incorporated into an assimilative numerical model. They are required to provide the basic data against which the diagnostic models must be compared in investigating the causes of the features. They will supply not only the background into which the process studies are embedded but also real-time data for determining the spatial locations of the process experiments.

Current meter moorings will be deployed in conjunction with the mapping effort. Their records will supply a time series with which the time evolution of the mapped fields will be interpreted. The time series data will also be used to evaluate the effects of time lag (asynopticity)on the observed fields. The moorings will be located by using information from the first map as well as from satellite images.

Remote sensing is necessary to keep track **cf** the features and to provide planning data for the process studies. Images and meteorological data will be transmitted to the ships at sea in near real time. In addition, remotely sensed data will be studied in its own right to extract information on the geographical distribution and the temporal occurrence of cold filaments.

**Basic Phenomena.** Lagrangian drifters will provide a look at the basic phenomena from a different point of view. These instruments will yield the paths that the water follows as it proceeds through the area and out of it. A few drifters equipped with thermistors, optical devices, and **nutrient/phytoplank**ton samplers will also indicate the changes in properties experienced by a parcel of water. Additionally, clusters of drifters will be used to estimate vorticity balances and hence vertical velocities.

Somewhat similar in principle to these Lagrangian studies are the tracer studies, which employ natural radioactivity and zooplankton genetics. They supply mixing information on the time scales of the apparent life of a feature (weeks), information which cannot be obtained otherwise.

**Process Measurements.** To investigate the processes and properties of the features, it is necessary to use methods that examine the features in more detail, at smaller space and time scales. This is the role of the process studies, which include the following:

 Physical studies will focus on such phenomena as fine-scale structure, mixing rates, energy dissipation, the role of intrusions, and internal wave activity. **With** instruments designed specifically to investigate these phenomena (towed thermistor chain, rapid microstructure profiler, and current profiler), measurements will be obtained on the scales necessarily missed by the mapping components. These investigations are mainly expected to address the issues of local dynamics and physical interactions with the surroundings. Surface microlayer sampling will address the question of slick signatures.

• The questions associated with the relationships between the biological processes and physical processes will be addressed by an interdisciplinary group of investigators. This group will use, among other techniques, Lagrangian drifters to track movement of water parcels, and will investigate short-time scale (day to week) variations in the biological distributions and processes within and around a feature.

The biological studies can be conceptually divided into two groups:

- Population studies to determine the changes in distribution and composition of phytoplankton and zooplankton assemblages, and
- Productivity studies to determine the response of the biological processes to shortterm changes in physical and chemical processes, with emphasis on primary production processes and the associated response of the secondary producers.

**Modeling.** The question of the cause of the features will be addressed by the use of numerical and laboratory models. Work with these models will discovery what dynamics, what driving forces, what topography, and what stratification need to be incorporated in a model to obtain features with the observed characteristics. The assimilative numerical modeling will have a similar bearing on the question of causation, as well as making possible a systematic interpretation and interpolation of the observations. The biological modeling efforts are directed toward determining the effect of the physical features on the biology, dealing with such issues as, How do the biological distributions respond to physical forcing? Which of the biological processes are most important in defining a feature?

### Conclusion

It is obviously too early to claim that the coastal transition zone is fully understood, or even that existing results are fully interpreted. Nonetheless, the CTZ program has already provided some striking preliminary results, especially with regard to the structure of filaments within a regional context. Given results to date, we are already excited as we anticipate the new findings that will result from the highly focused **1988** field study.

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