A Working Paper on the California Current System:
Its features, scales of variability and modeling domain initialization

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TABLE OF CONTENTS

INTRODUCTION

This document describes the present status of our approach to describe the features and variabilities of the California Current System (CCS) that are anticipated to influence the Monterey Bay Circulation during AOSN-II in the summer of 2003. The intended purposes of this "working paper" are to input to the final fine tuning of the ship and spray glider tracks, and the fine tuning of the HOPS modeling domains, especially the innermost "stand-alone" domain. Comments, feedback and scientific input are more than welcome, and are in fact, solicited.

In the following, we provide the background of the feature oriented modeling system (1), describe the important circulation features and their variability in the CCS (2), discuss the modeling domain alternatives (3) and present some of the regional climatologies (4) that may be appropriate for use as the background climatology for the synoptic feature-based initialization.

1. BACKGROUND ON FEATURE ORIENTED REGIONAL MODELING SYSTEMS

The western coast of the U.S. includes both an offshore region and a very dynamic coastal region. The offshore region is primarily dominated by the large-scale California Current, the California Under Current and parts of subtropical and sub-polar gyre circulations in the eastern Pacific. The coastal region, includes features such as upwelling fronts, cold pools inshore of these fronts, filaments, squirts, mushroom-head vortices, mesoscale and sub-mesoscale eddies, and meanders.

One of the approaches for regional modeling of such regions in the world oceans is the use of 'knowledge-based feature models'. These feature-oriented approach have been used for regional simulations and operational forecasting for the past two decades. Specifically, the studies by Robinson *et al*. (1989), Hurlburt *et al*. (1990, 1996), Fox *et al*. (1992), Glenn and Robinson (1995), Cummings *et al.* (1997), Gangopadhyay *et a*l. (1997) and Robinson and Glenn (1999) have applied the feature modeling technique for use in nowcasting, forecasting and assimilation of various *in situ* (XBT, CTD) and satellite (SST, SSH [GEOSAT, TOPEX/Poseidon] and SSC [SeaWiFS]) observations in the western North Atlantic.

Gangopadhyay and Robinson (2002) have generalized the feature-oriented approach for strategic application to any regional ocean. A feature-oriented regional modeling system (FORMS) for the Gulf of Maine and Georges Bank region has been developed for real-time applications for medium-range (7-10 days) and mesoscale to sub-mesoscale forecasting (Gangopadhyay *et al*., 2003). This feature-oriented methodology is also model-independent and can be applied in lieu of satellite or *in situ* observations, especially in coastal regions.

Feature-oriented methodology requires developing a synoptic circulation template for the region. This template is designed from a feature-based synthesis of the regional circulation patterns. From this "basis template", a map of strategic sampling locations for placing feature model profiles is produced. This concept is illustrated in Figure 1 for the Gulf of Maine/Georges Bank (Fig. 1a) and Strait of Sicily (Fig. 1b) regions. The green squares outline the modeling domains. The red dots indicate the strategic sampling locations. These profiles provide "synthetic synoptic expressions" for fronts, jets, eddies, gyres, and other circulation structures and water masses at the initialization or updating phases.

Feature models are represented by both analytical structures and by synoptic sections and profiles. The feature model profiles for a typical feature are developed by analyzing past synoptic high-resolution observations for that feature. Gangopadhyay and Robinson (2002) described the generalized mathematical forms for some of the typical feature models developed so far (See their Appendix A). Gangopadhyay *et al*. (2003) described a number of applications for coastal regions such as a coastal current, a tidal mixing front, eddy and gyres. An example feature model structure for a meandering jet velocity distribution and that for a temperature/salinity front is shown here in Figure 1c) and 1d).

The following form is used as a simple model for the three-dimensional velocity structure of a <u>large-scale frontal system (Fig. 1c)</u>:

$$u(x,y,z)=\gamma(y)\{[U^T(x)-U^B(x)]\phi(x,z)+U^B(x)\} \qquad (1)$$

Here, $\gamma(y)$ is the non-dimensional horizontal velocity distribution with a value of unity at the jet axis; $\Phi(x,z)$ is the non-dimensional vertical shear profile; U^T and U^B are top and bottom velocities; while x is the dimensional downstream coordinate, y is the cross-stream coordinate (positive to the left of the flow) and z is the dimensional vertical coordinate (positive upward).

The following general form can be used as a simple model for the tracer, i.e., the temperature or salinity structure for a current/front/flow system (Fig. 1d):

$$T(x,\eta,z) = T_a(x,z) + \alpha(x,z)\,\Gamma(\eta,z) \qquad 2(a)$$

where

$$T_a(x,z) = [T_o(x) - T_b(x)]\,\varphi(x,z) + T_b(x) \qquad 2(b)$$

Here, x is the dimensional along-stream direction, η is the cross-stream coordinate with origin at the axis (center of the current), and z is the dimensional vertical coordinate (positive upward).

For any new region such as the California Current system, such structures and parameterized forms can be implemented to characterize the relevant circulation entities. Such implementation require careful and detailed scientific analyses to identify the spatial and temporal scales and variability that defines and distinguishes these features from one another while preserving its own characteristics. After identification of major features and their choice of representation, they are used in the initialization of a basic dynamical model (e.g. HOPS). Dynamical adjustment accomplishes two important tasks: i) a consistent dynamical interaction of the features, and, ii) the generation of smaller scales, such as squirts and sub-mesoscale eddies.

2. FEATURES IN THE CALIFORNIA CURRENT SYSTEM

We are in the process of researching various aspects of the synoptic variability of the prevalent circulation features in the Monterey Bay and its adjacent areas including the CCS, focusing on the summer (July-August) season. Some of these features can be seen in Fig. 2 (from Strub *et al*., 1991) that depicts surface pigment concentration from the CZCS satellite data from June 15, 1981. The characteristic CCS surface features can be seen in similar SST and color images. The features that we are proposing to study and characterize are the:

- California Current (mean and its core jets)
- California Under Current
- Inshore Current (Davidson Current)
- coastal transition zone that separates the shelf circulation to the offshore flows
- eddies
- anomalous pools
- baroclinic jets along upwelling fronts
- filaments

as have been used other places, and we will also attempt to represent:

- squirts
- mushroom heads

In particular, we are investigating the typical synoptic width, location (distance from the coast), vertical extent, and core characteristics of these features. A preliminary synopsis is provided in Table 1. The dominant spatial and temporal scales of variability of each of these features are being identified from past observational, theoretical and modeling analyses and are indicated in Table 2. Appropriate literature references in all cases are provided.

The California Current

For the summer 2003 experiment we expect to develop a first-order feature model for the California Current mean flow and its meandering jet structure at the core. We will follow the synthesis developed by Brink *et al*. (1991) and define the jet characteristics on the basis of the studies listed in Table 2. For the implemented feature model, the initial path of the jet will be based on the flow field shown by Brink *et al*. (1991) in their Figure 5 (Fig. 3 here). During summer 2003, we will analyze the available SST and develop a feature-oriented protocol to define the synoptic realization of the CC meandering flow field.

In a recent high-resolution analysis of the hydrographic data (1988-2002) along line 67, Collins *et al*. (2003) have observed the California Current jet at about 100-200km offshore near Monterey Bay. There analysis suggests that the "mean" CC jet is at the inshore edge of the broader mean seasonal equatorward flow of the California Current. The mean jet's maximum velocity (6-10 cm/sec) is much weaker than that of the baroclinic jet (50-100 cm/sec) identified by Brink *et al*. (1991), and was presented here in Fig. 3. One interpreatation is that the average currents over the 50km or so mean CC jet width are on the order of 10 cm/sec but much higher velocities are found in the narrow frontal regions within the California Current (Chavez, personal communication).

The California Under Current (CUC)

The development of a feature model for the California Under Current (CUC) needs further careful research. The availability of synoptic data for this feature is sparse. Difference in periods of analysis, geographical coverage, and lack of high-resolution synoptic surveys provided a challenge to pinpoint the location and behavior of this feature. Notably, Collins *et al*. (1996) showed that the path of the CUC during summer 1993 was close to the continental slope between San Francisco (37.8N) and St. George Reef (41.8N). Pierce *et al*. (2000) analyzed a follow-up survey of 105 shipboard ADCP velocity sections during July to August 1995 in detail. They found that, on monthly average, the CUC has a core speed of >10cm/sec from 200-275m depth at 20-25km off the shelf break. These sections and the core path is available from the website http://diana.oce.orst.edu. A first-order feature model for the CUC will be implemented on the basis of these data sets and other supporting temperature-salinity observations.

It is however worthwhile to note that, the location of the CUC offshore of the Monterey Bay region (the focus of AOSN-II during summer 2003) is highly variable. Early observations of the CUC in this region (36N to 37N) by Wickham (1975) indicated a complex alongshore flow near the coast, in both poleward and equatorward directions in the upper 500 meters offshore close to 123W. In particular, he observed a poleward flow being subdivided into two parts by a strong (60 cm/sec) equatorward jet down to 500 meters (Fig. 11 of Wickham, 1975). The recent NMFS survey sections (Fig. 4a) by Pierce *et al*. (2000) indicates a maximum of the CUC shifted offshore at 36.47N and at 36.8N, while flowing very close to the coast north of 37N (Fig. 4b). A section at 35.97N shows a clear equatorward jet in the middle of the weak poleward flow.

In fact, Rischmiller (1993) found that the area of poleward flow off of Point Sur extended well beyond the upper continental slope up to a distance of 200km from the coast and to a depth of 750-1000m or greater (Garfield *et al*., 1999). Based on Lagrangian drifters during 1992-95, Garfield *et al*. (1999) plotted the ensemble and individual spaghetti diagrams (Figs. 5 and 6 of their paper), which clearly shows that the CUC flow is further offshore across the Monterey Bay region than it is to the north of this region.

With this background, we have identified the July 1984 CALCOFI data set as a candidate analysis data set for the basis of a CUC template (Sect. 1). Preliminary analysis suggests that a warm and saline water mass can be traced in the 200-300 meter depth level. The path of this water mass curiously follows the 2500m isobath in the latitudinal range of 34-37.5N. This offshore trajectory resembles the single drifter trajectory of Garfield *et al*. (1999), as was shown in their Figure 6, and reproduced as Figure 5. At the present time, we plan to analyze this data set and some of the section plots of Pierce *et al*. to realize a reasonable configuration for the CUC offshore of the Monterey Bay region.

The Inshore Current (Davidson Current)

The inshore region of the Coastal Transition Zone is complicated by the poleward flow being interrupted by the summer upwelling jets flowing equatorward near the mouth of the Monterey Bay (Collins *et al*., 2003). According to Collins *et al*. (2003), during fall and winter, when the upwelling is not present, the Inshore Current (Davidson Current) had two distinct cores, one on the coast and one 50km offshore. Observations such as these may be reconciled with the CUC flow in a broader 'Poleward Flow' feature model framework.

The shallow features in the Coastal Transition Zone

Apart from these two currents, there are very energetic and important shallow water features in the coastal transition zone (CTZ) around the coastal region of Monterey Bay and the California Current System. The filaments, coastal eddies, anomalous pools, jets along the upwelling fronts and mushroom-like vortices are critical to AOSN-II. The scales and variability of these features have been identified in Table 1, with relevant references cited in Table 2.

The complex dynamical processes that generate these shallow features, and their interaction with the surrounding water masses will be examined before, and studied during and after the AOSN-II experiment. A separate ONR-funded project led by Gangopadhyay will investigate the development of ‘shallow water feature models’ for these features. Collaboration and participation of the AOSN-II group scientists in this effort will ensure timely feedback and transfer of methodology for future AOSN-II efforts. Our choice of feature parameters is naturally based on their individual temperature and salinity structures, called temperature-salinity feature models or TSFMs. Parameterization of individual features will enable one to apply this methodology for nowcasting, forecasting, assimilation and inter-disciplinary process studies in the Monterey Bay AOSN-II exercise.

During AOSN-II experiment in 2003, it will be profitable to adequately sample the above features, especially, the CUC; the Upwelling fronts (across) and the associated inshore cold water pools; and the filaments and eddies from the CCS generated near the Monterey Bay coastal region. There is a need for high-resolution observations through these features, which will help develop ‘dynamical feature models’ for usage in the next phase of AOSN-II. Such high-resolution feature implementation will enhance the validity and predictability of the operational modeling and data assimilation systems.

Two particular directions of research are sought in the immediate future: (1) employ the concept of spiciness (Rudnick and Ferrari, 1999; Ferrari and Rudnick, 2000; Flament, 2002) to identify and characterize the various water masses in the CTZ and possibly relate these water masses to the shallow water features, and (2) to use zeroth-order dynamical processes to describe the characteristics of the ‘features’. First, the anomalous pools and filaments may be multi-lobed in the T-S space, with a monotonic and stable density profile. So, inferring the T-S properties of a filament becomes a challenge from only SST observations. Since the spiciness bounds the T-S curves in the orthogonal direction to the density lines, predetermining spiciness values for a specific feature, along with an SST observation may help resolve the salinity and in turn the density inference. Second, the features such as filaments, jets, mushroom-vortices are related to specific dynamical processes including instability, upwelling and wind-driving. It has been proposed by Brink *et al.* (1991) that subduction plays a very important role inside the filaments, forcing these cold filaments downwards, below the ambient warm surface waters. The mushroom vortices are generated only if certain conditions of the flow field are met (Mied *et al*., 1991). Processes such as these will be incorporated and investigated for feature model development.

3. HOPS Domains – Considerations and Nested Configurations

In addition to providing the basis for a synoptic initialization, the typical occurrence of these features, their scales and variabilities provide the dynamical considerations that enter the criteria used to determine a suitable nested configuration. Important constraints are: influences from the California Current and Undercurrent; upwelling centers, especially at Ano Nuevo and Point Sur; and, resolution of off-shore plumes. Important numerical constraints are: a required 3:1 ratio in grid resolution for collocated, nested grids; the ability to produce 7 day simulations in a real-time setting; and, to orient the domains roughly normal and parallel to the coast/topography. The domain selection should give proper consideration to the active and relaxation phases of upwelling and the conditions expected in summer 2003. Potential HOPS modeling domains and their relationship to observed oceanographic conditions can be found at http://oceans.deas.harvard.edu/haley/AOSN2/Domains/domains.html.

There are two potential sets of HOPS domains. They differ primarily in the extent of the largest domain. Either of these largest domains provides sufficient horizontal resolution (9km) to resolve the California Current meandering, its eddies and the broad poleward flow system. The "minimalist" largest domain (Fig. 6a) is defined with the following constraints:

- The off-shore extent just covers the furthest off-shore extent of the California current
- The northern boundary is limited by an underwater escarpment.
- The southern boundary is limited by the indentation of the coast (keeping the SE corner under land while minimizing wasted land points)

The "maximal" largest domain (Fig. 6b) was designed to push the northern and southern open boundaries further from the nested sub-domains

- The northern boundary cuts through least steep portion of the escarpment
- The southern boundary is roughly equidistant from the middle domain as is the northern boundary

The off-shore extent is increased just enough so that a purely physical simulation in this largest domain is load balanced with coupled interdisciplinary simulations in the smaller domains.

For both sets of nested domains, the middle domains are virtually identical.
The middle domains are designed to:

- provide sufficient resolution (3km) for off-shore advected plumes
- properly contain the California Under Current.

The domains extend:

- westward to roughly the in-shore edge of the California current.
- north and south to roughly center the smallest domains.

The middle domains are sized identically (in number of grid points) to the smallest domains.

For both sets of nested domains, the small domains are virtually identical.
The small domains are designed to provide high resolution (1km) for:
- the upwelling centers at Ano Nuevo and point Sur
- the region of *in situ* data sampling.

The domains extend:
- "comfortably" north of Ano Nuevo
- "comfortably" south of point Sur
- off-shore to roughly the expected limits of the survey vessel tracks.

The domains are projected to compute 1 model week of coupled physics and biology dynamics in 5.4 hours.

4. REGIONAL CLIMATOLOGY (In consultation with Dr. Yi Chao)

The FORMS protocol for synoptic initialization utilizes a regional climatology as the background field for the synoptic features. The melding of the synoptic-scale features with appropriate regional climatology is achieved by a two-scale objective analysis (Lermusiaux, 1999). Another factor for generating a suitable climatology is to ascertain its compatibility with the synoptic feature parameters. Due to the effect of El Nino in the eastern Pacific, a suggestion has been made to look at developing a Warm Climatology and a Cold Climatology. These could relate to the opposing phases of the Pacific Decadal Oscillation, as well as related to the El Nino vs. La Nina years. However, sparse data availability in the offshore regions might restrict such a development. In lieu of such desirable climatology, the GDEM climatology has been selected for any synoptic initialization scheme.

Based on the PDO time-series (http://tao.atmos.washington.edu/pdo) during the last 50 years two different periods have been selected to develop two different climatologies. The Warm phase PDO climatology (WPDO) will be developed by averaging the temperature and salinity observation for the years 1978 to 1990. Similarly, a Cold phase climatology (CPDO) will be developed based on the data for the period 1962 to 1974.

Additionally, three different sets of years during El Nino, La Nina and Normal periods have been identified. The available data (temperature and salinity) during the summer months (June, July and August) for these three periods at the surface and at 5m are shown in the website: http://oceans.deas.harvard.edu/haley/AOSN2/Climo/.

We plan to objectively combine the ENSO-related datasets with the two PDO climatologies and compare them with ROMS-derived (5-year average and 10-year average) climatologies to assess the importance and likelihood of using such combined climatologies as a background for feature-oriented initialization.

Feature	Width	Location	Vertical extent	Core Characteristics	Scales of Variability
California Current (Mean flow + Southwestward meandering Jet)	Mean southward flow between 100-1350 km offshore	Inshore edge is 100-150km away from coast Jet location default (Fig. 5 of Brink *et al.*, 1991)	0-500m	0-300m, Baroclinic jet's V_max = 50-70cm/s; salinity minimum (32.9psu); sigma-t=25 Meandering jet from 39N (Strong) to 30N (Weak)	Meander longshore wavelength O(300km); onshore-offshore amplitude O(100-200km); temporal synoptic scales: Eulerian (5 days), Lagrangian (10 days)
Poleward Flows (California Under Current and Inshore Current) Research in progress for IC.	10-40km	Variable Near Pt. Sur 10-40km offshore, another branch offshore following 2500m isobath, about 100km offshore	0-300m	Offshore and inshore (coastal) Cores! 100-200m. 15-20cm/s .	Meanders with what Wavelengths and what time-periods?
Coastal Transition Zone (CTZ)	The Coastal Transition Zone is a region offshore of the continental shelf (Brink and Cowles, 1991) where filaments, eddies, upwelling fronts and anomalous pools occur in this eastern boundary current system				
Coastal Eddies	Less than 100 km	South of promontories of C. Mendocino and Pt. Arena	Up to 300m (Bucklin, 1991)	Cool, Saline and nutrient-rich water relative to the warmer and less saline jet and offshore waters	Temporal scales ~40-60 days
Coastal jets along Upwelling fronts	Narrow ~10-40km	Over the shelf	Above the halocline (σ_θ < 26.5)	Energetic, Vm=1m/sec	Active to Relaxation periods (weeks)
Anomalous Pools	20-30 km wide	Inshore side of upwelled fronts	Less than 60m	Fresh and Cool	Weeks
Large Filaments	<100km wide extends 200km offshore	Recurrent off Pt. Arena (inshore of baroclinic jets)	Surface-intensified ~100m and below	Cool (12-13C) Salty (32.7-33psu) Offshore speed 60-87 cm/s Onshore speed 69-92 cm/s	2-4 weeks upwelling ~40 m/day; subduction ~25 m/day
Squirts (smaller filaments)	30km wide 50-100km long	Inshore of baroclinic jets (upwelling fronts)	Surface – intensified (High nutrient)	Very cold (10-12C) and highly saline (>33psu)	6-10 Days
Mushroom heads	T- shaped	Instability-generated or wind-forced!	Above seasonal thermocline (H_1/H_2 ~ 1/50)	Ageostrophic and asymmetric	1-3 days to develop; 3-5 days to diffuse

Feature	References
California Current (Mean and its baroclinic jet core)	Brink *et al*., 1991;Lynn and Simpson, 1987; Chelton, 1984; Ramp (website); Tisch *et al*., 1992; Chereskin *et al*., 1998; Miller *et al*., 1999; Ramp *et al*., 1997a,b; Collins *et al*., 2003
Poleward Flow (California Under Current and Inshore Current (Davidson Current))	Ramp *et al*., 1997a,b; Wooster and Jones, 1970; Wickham, 1973; Pierce *et al*., 2000; Oey, 1999; Swenson and Niiler, 1996; Huyer *et al*., 1992; Chavez *et al*., 1997, Garfield *et al*., 1999; Collins *et al*., 1996; Marchesiello *et al*., 2003; Collins *et al*., 2000, 2002, 2003
Coastal Transition Zone (CTZ)	Brink and Cowles, 1991; Brink *et al*., 1991; Chelton and Schlax, 1991; Kosro *et al*., 1991; Haynes and Barton, 1991; Strub *et al*., 1991; Marchesiello *et al*., 2003
Coastal Eddies	Hayward and Mantyla, 1990; Bucklin, 1991; Hickey, 1998.
Coastal jets along Upwelling fronts	Huyer *et al*., 1991; Smith and Lane, 1991; Pierce *et al*., 1991; Allen *et al*., 1991; Kosro *et al*., 1991; Strub *et al*., 1991; Rosenfeld *et al*., 1994; Chavez *et al*., 1997; Huyer, 1983; Washburn *et al*., 1991
Anomalous Pools	Hayward and Mantyla, 1990; Strub *et al*., 1991
Large Filaments	Bernstein *et al*., 1977; Traganza *et al*., 1980, 1981; Flament *et al*., 1985; Abbott and Zion, 1987; Brink, 1991; Strub *et al*., 1991; Mackas *et al*., 1991; Ramp *et al*., 1991; Dewey *et al*., 1991; Kadko *et al*., 1991; Chavez *et al*., 1991; Chereskin and Niiler, 1994
Squirts (Smaller filaments)	All of the above, specially Ramp *et al*., 1991; Dewey *et al*., 1991; Hickey, 1998
Mushroom heads	Ikeda and Emery, 1984; Sheres and Kenyon, 1989; Smith *et al*., 1991; Mied, 1990; Mied *et al*., 1991; Munk *et al*., 2000

References

1. Abbott, M.R., and P.M. Zion, 1987. Spatial and temporal variability of phytoplankton pigment off Northern California during CODE-1. *J. Geophy. Res*. **92**, 1745-1756.
2. Abbott, M.R., and B. Barksdale, 1991. Phytoplankton Pigment Patterns and Wind Forcing off Central California. *J. Geophys. Res.,* **96**, 14,649-14,667.
3. Allen, J. S., L.J. Walstad, and P.A. Newberger, 1991. Dynamics of the Coastal Transition Zone Jet, 2. Nonlinear finite amplitude behavior, *J. Geophys. Res.,* **96**, 14,995-15,016.
4. Bernstein, R.L., L. Breaker, and R. Whritner, 1977. California Current eddy formation: Ship, air and satellite results. *Science*, **195**, 353-359.
5. Brink, K.H., R.C. Beardsley, P.P. Niiler, M. Abbott, A. Huyer, S. Ramp, T. Stanton, and D. Stuart, 1991. Statistical properties of near-surface flow in the California coastal transition zone. *J. Geophys. Res.,* **96**, 14,693-14,706.
6. Brink, K.H. and T.J. Cowles, 1991. The coastal transition zone program. *J. Geophys. Res.,* **96**, 14,637-14,647.
7. Bucklin, A., 1991. Population Genetic Responses of the Planktonic Copepod *Metridia pacifica* to a Coastal Eddy in the California Current, *J. Geophys. Res.,* **96**, 14,799-14,808.
8. Chavez, F. P., T.J. Pennington, R. Herlien, H.W. Jannasch**,** G. Thurmond and G. Friederich, 1997. Moorings and drifters for real-time interdisciplinary oceanography, *J. Atmos. and Ocean. Tech.,* **14,** 1199-1211.
9. Chavez, F.P., R.T. Barber, P.M. Kosro, A. Huyer, S.R. Ramp, T.P. Stanton, and B. Rojas de Mendiola, 1991. Horizontal transport and the distribution of nutrients in the coastal transition zone off northern California: effects on primary production, phytoplankton biomass and species composition. *J. Geophys. Res.,* **96**, 14,833-14,848.
10. Chelton, D. and M. Schlax, 1991. Estimation of time averages from irregularly spaced observations: With application to Coastal Zone Color Scanner estimates of chlorophyll concentration. *J. Geophys. Res.,* **96**, 14,669-14,692.
11. Collins, C.A., J.T. Pennington, C.G. Castro, T.A. Rago and F.P. Chavez, 2003. The California Current system off Monterey, California: physical and biological coupling. *Deep Sea Res*., Submitted.
12. Collins, C.A., C.G. Castro, H. Asanuma, T.A. Rago, H.-K. Han, R. Durazo, and F.P. Chavez, 2002. Changes in the hydrography of Central California waters associated with the 1997-98 El Niño. *Progr. in Oceanog*., **54**, 184-204.
13. Collins, C.A., N. Garfield, T.A. Rago, F.W. Rischmiller, and E. Carter, 2000. Mean Structure of the Inshore Countercurrent and California Undercurrent off Point Sur, California. *Deep Sea Res*., **47**, 765-782.
14. Collins, C. A., N. Garfield, R.G. Paquette, and E. Carter, 1996. Lagrangian Measurement of subsurface poleward Flow between 380N and 430N along the West Coast of the United States during Summer, 1993. *Geophys. Res. Letters*, September 1, 1996, **23**, No. 18, 2461-2464.

15. Cummings, J.A., C. Szczechowski and M. Carnes, 1997. Global and regional ocean thermal analysis systems. *Marine Tech. Soc. J.*, **31**, 63-75.

16. Dewey, R.K., J.N. Moum, C.A. Paulson, D.R. Caldwell, and S.D. Pierce, 1991. Structure and dynamics of a coastal filament, *J. Geophys. Res.*, **96**, 14,885-14,907.

17. Flament, P., 2002. A state variable for characterizing water masses and their diffusive stability: spiciness. *Prog. Oceanogr.*, **54**, 493-501.

18. Flament, P., L. Armi, and L. Washburn, 1985. The evolving structure of an upwelling filament. *J. Geophys. Res.*, 90:1765-1985.

19. Ferrari, R. and D.L. Rudnick, 2000. Thermohaline variability in the upper ocean., *J. Geophys. Res.*, **105**, 16,857-15,883.

20. Fox D.N., M.R. Carnes and J.L. Mitchell, 1992. Characterizing Major Frontal Systems: A Nowcast /Forecast System for Northwest Atlantic. *Oceanography*, **5**, 49-53.

21. Gangopadhyay, A., A.R. Robinson, and H.G. Arango, 1997. Circulation and Dynamics of the Western North Atlantic, I: Multi-scale Feature Models. *J. Atmos. and Oceanic Tech.,* **14**(6), 1314-1332

22. Gangopadhyay, A. and A.R. Robinson, 2002. Feature-Oriented Regional Modeling of Oceanic Fronts. *Dynamics of Atmospheres and Oceans*, **36**, 201-232.

23. Gangopadhyay, A., A.R. Robinson, P.J. Haley, Jr., W.G. Leslie, C.J. Lozano, J.J. Bisagni and Z. Yu, 2003. Feature Oriented Regional Modeling and Simulations (FORMS) in the Gulf of Maine and Georges Bank. 2003, *Continental Shelf Research*. 23 (3-4), 317-353.

24. Garfield, N., C.A. Collins, R.G. Paquette, and E. Carter, 1999. Lagrangian Exploration of the California Undercurrent, 1992-1995. *J. Phys. Oceanogr*., **29**, 560-583.

25. Glenn, S.M., and A.R. Robinson, 1995. Validation of an operational Gulf Stream forecasting model, Qualitative Skill assessment for coastal models, AGU Estuarine/Coastal Series, Vol. 47, American Geophysical Union, 469-499.

26. Haidvogel, D. B., A. Beckmann, and K.S. Hedstrom, 1991. Dynamical simulations of filament formation and evolution in the Coastal Transition Zone, *J. Geophys. Res.,* **96**, 15,017-15,040.

27. Haynes, R., and E.D. Barton, 1991. Lagrangian observations in the Iberian coastal transition zone, *J. Geophys. Res.,* **96**, 14,731-14,742.

28. Hayward, T. L. and E.L. Venrick, 1988. Nearsurface pattern in the California Current: coupling between physical and biological structure. *Deep-Sea Res. II*, **45**, 1617-1638.

29. Hayward, T.L. and A.W. Mantyla, 1990. Physical, chemical and biological structure of a coastal eddy near Cape Mendocino, *J. Mar. Res*., **4**, 825-850.

30. Hickey, B.M., 1998. Coastal Oceanography of Western North America from the tip of Baja California to Vancouver Is., pp 345-393 in Volume 11, Chapter 12, THE SEA, eds. K.H. Brink and A.R. Robinson, Wiley and Sons, Inc.

31. Hofmann, E.E., K.S. Hedstrom, J.R. Moisan, D.B. Haidvogel, and D.L. Mackas, 1991. Use of simulated drifter tracks to investigate general transport patterns and residence times in the coastal transition zone. *J. Geophys. Res.*, **96**, 15,041-15,052.

32. Hurlburt, H.E., A.J. Wallcraft, W.J. Schmitz, Jr., P.J. Hogan and E.J. Metzger, 1996. Dynamics of the Kuroshio/Oyashio current system using eddy-resolving models of the North Pacific Ocean, *J.Geophys.Res*., **101**, 941-976.

33. Huyer, A.E., 1983. Coastal upwelling in the California Current system. *Progr. Oceanogr*. **12**, 259-284.

34. Huyer, A., P.M. Kosro, J. Fleischbein, S.R. Ramp, T. Stanton, L. Washburn, F.P. Chavez, T.J. Cowles, S.D. Pierce, and R.L. Smith, 1991. Currents and water masses of the Coastal Transition Zone off northern California, June to August, 1988, *J. Geophys. Res.*, **96**, 14,809-14,831.

35. Huyer, A., J. A. Barth, P. M. Kosro, R. K. Shearman, and R. L. Smith, 1998. Upper-ocean water mass characteristics of the California Current, summer 1993, Deep Sea Res., 45, Part II, 1411-1442.

36. Ikeda, M. and W.J. Emery, 1984. Satellite observations and modeling of meanders in the California Current System off Oregon and Northern California, *J. Phys. Oceanography*, 14, 1434-1450.

37. Kadko, D.C., L. Washburn, and B. Jones. 1991. Evidence of subduction within cold filaments of the northern California coastal transition zone. *J. Geophys. Res.*, **96**, 14,909-14,926.

38. Kosro, P.M., A. Huyer, S.R. Ramp, R.L. Smith, F.P. Chavez, T.L. Cowles, M.R. Abbott, P.T. Strub, R.T. Barber, P. Jessen and L.F. Small, 1991. The structure of the transition zone between coastal waters and the open ocean off northern California, winter and spring 1987. *J. Geophys. Res*., **96**, 14,707-14,730.

39. Lermusiaux, P.F.J., 1999. Data Assimilation via Error Subspace Statistical Estimation, Part II: Mid-Atlantic Bight Shelfbreak Front Simulations and ESSE Validation. *Mon Weath. Rev*, **127**(8), 1408-1432.

40. Mackas, D.L., L. Washburn, and S.L. Smith. 1991. Zooplankton community pattern associated with a California Current cold filament. *J. Geophys. Res.*, **96**, 14,781-14,797.

41. Marchesiello, P., J.C. McWilliams, and A. Shchepetkin, 2003. Equilibrium structure and dynamics of the California Current System. *J. Phys. Oceanogr*., **33**, 753-783.

42. McWilliams, J.C., 1985. Submesoscale, coherent vortices in the ocean, *Rev. of Geophys.*, **23**, 165-182.

43. Miller, A.J., J.C. McWilliams, N. Schneider, J.S. Allen, J.A. Barth, R.C. Beardsley, F.P. Chavez, T.K. Chereskin, C.A. Edwards, R.L. Haney, K.A. Kelly, J.C. Kindle, L.N. Ly, J.R. Moisan, M.A. Noble, P.P. Niiler, L.Y. Oey, F.B. Schwing, R.K. Shearman, and M.S. Swenson. 1999. Observing and Modeling the California Current System, *Eos, Transactions, American Geophysical Union*, **80**, 533-539.

44. Mied, R.P., 1990. Mushroom-Like Patterns of the Ocean Surface, *Eos, Transactions, American Geophysical Union*, **71 (49)**, 1837.

45. Mied, R.P., J.C. McWilliams, and G.J. Lindemann, 1991. The generation and evolution of mushroom-like vortices, *J. Phys. Ocean.*, **21**, 490-510.

46. Munk, W., L. Armi, K. Fischer. and F. Zachariasen, 2000. Spirals on the sea, *Proc. R. Soc. Lond.*, **456**, 1217-1280.

47. Oey, L., A forcing mechanism for the poleward flow off the southern California coast, J. Geophys. Res., 104, 13,529-13,539, 1999

48. Olivieri, R.O. and F.P. Chavez, 2000. A model of plankton dynamics for the coastal upwelling system of Monterey Bay, California. *Deep Sea Res*., **47**, 1077-1105.

49. Paduan, J.D. and L.K. Rosenfeld, 1996. Remotely sensed surface currents in Monterey Bay from shore-based HF radar (CODAR), *J. Geophys. Res.*, **101**, 20,669-20,686.

50. Pennington, J.T. and F.P. Chavez, 2000. Seasonal fluctuations of temperature, salinity, nitrate, chlorophyll and primary production at station H3/M1 over 1989-1996 in Monterey Bay, California. *Deep Sea Res.*, **47**, 947-974.

51. Petruncio, E.T., L.K. Rosenfeld, and J.D. Paduan, 1998: Observations of the internal tide in Monterey Submarine Canyon. *J. Phys. Oceanogr.*, **28**, 1873-1903.

52. Pierce, S.D., J.S. Allen, and L.J. Walstad, 1991. Dynamics of the Coastal Transition Zone jet, 1, linear stability analysis, *J. Geophys. Res*., **96**, 14,979-14,993.

53. Pierce, S. D., R.L. Smith, and P.M. Kosro, 1996. Observations of the poleward undercurrent along the eastern boundary of the mid-latitude Pacific, 1996. *Trans. American Geophys. Union*, **77**, p. F345.

54. Pierce, S. D., R.L. Smith, P.M. Kosro, J.A. Barth, and C.D. Wilson, 2000. Continuity of the poleward undercurrent along the eastern boundary of the mid-latitude Pacific, *Deep Sea Res*., **47**, 811-829.

55. Ramp, S. R., and C.A. Abbott, 1998. The vertical structure of currents over the continental shelf off Point Sur, CA during Spring 1990. *Deep Sea Res*., **45**, 1443-1470.

56. Ramp, S.R., J.L. McClean, C.A. Collins, A.J. Semtner and K.A.S. Hays, 1997. Observations and modeling of the 1991-1992 El Nino signal off central California, *J. Geophys. Res.*, **102**, 5553-5582.

57. Ramp, S. R., R.W. Garwood, Jr., C.O. Davis, and R.L. Snow, 1991. Surface heating and patchiness in the coastal ocean off central California during a wind relaxation event. *J. Geophys. Res.*, **96**, 14,947-14,957.

58. Ramp, S.R., P.F. Jessen, K.H. Brink, P.P. Niiler, F.L. Daggett and J.S. Best, 1991. The physical structure of cold filaments near Point Arena, California, During June 1987. *J. Geophys. Res.*, **96,**, 14,859-14,883.

59. Ramp, S.R., L.K. Rosenfeld, T.D. Tisch, and M.R. Hicks, 1997. Moored observations of the current and temperature structure over the continental slope off central California, 1, A basic description of the variability, *J. Geophys. Res.*, **102**, 22,877-22,902.

60. Robinson, A. R., S.M. Glenn, M.A. Spall, L.J. Walstad, G.M. Gardner, and W.G.Leslie, 1989. Forecasting meanders and Rings, *EOS*. Oceanogr. Report, **70**(45), 1464-1473.

61. Robinson, A. R. and S.M. Glenn, 1999. Adaptive Sampling for Ocean Forecasting. *Naval Research Reviews*, **51**(2), 28-38.

62. Rudnick, D.L. and R. Ferrari, 1999. Compensation of horizontal temperature and salinity gradients in the ocean mixed layer. *Science*, **283**, 526-529.

63. Sheres, D. and K.E. Kenyon, 1989. A double vortex along the California Coast, *J. Geo. Res.*, 94, 4989-4997.

64. Smith, S.L., and P.V.Z. Lane, 1991. The jet off Point Arena, California: its role in aspects of secondary production in the copepod *Eucalanus californicus* Johnson. *J. Geophys. Res.*, **96**, 14,849-14,858.

65. Strub, P.T., P.M. Kosro and A. Huyer, 1991. The nature of the cold filaments in the California Current system. *J. Geophys. Res*., **96**, 14,743-14,768.

66. Strub, P. T. and C. James, 2000. Altimeter-derived variability of surface velocities in the California Current System: 2. Seasonal circulation and eddy statistics. *Deep-Sea Res. II*, **45**, 831-870.

67. Swenson, M. S., and P. P. Niiler, 1996. Statistical analysis of the surface circulation of the California Current, *J. Geophys. Res*., **101**, 22,631-22,645.

68. Tisch, T. D., S.R. Ramp, and C.A. Collins, 1992. Observations of the geostrophic current and water mass characteristics off Point Sur, California, from May 1988 through November 1989. *J. Geophys. Res.*, **97**, 12,535-12,555.

69. Tracy, D., 1990. Source of cold water in Monterey Bay observed by AVHRR satellite imagery, MS thesis, Naval Postgraduate School, Monterey, CA.

70. Traganza, E.D., D.A. Nestor, and A.K. McDonald, 1980. Satellite observations of a nutrient upwelling off the coast of California, *J. Geophys. Res.,* **85**, 4,101-4,106.

71. 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. pp. 229-241 in *Coastal Upwelling*, F. A. Richards (ed), American Geophysical Union, Washington, DC.

72. Walstad, L.J., J.S. Allen, P.M. Kosro, and A. Huyer, 1991. Dynamics of the Coastal Transition Zone through data assimilation studies, *J. Geophys. Res.,* **96**, 14,959-14,978.

73. Washburn, L., D.C. Kadco, B.H. Jones, T. Hayward, P.M. Kosro, T.P. Stanton, S. Ramp, and T. Cowles, 1991. Water mass subduction and the transport of phytoplankton in a coastal upwelling system. *J. Geophys. Res*., **96**, 14,927-14,945.

74. Wickham, J.B., 1975. Observations of the California countercurrent. *J. Mar. Res*., **33**, 325-340.

75. Wickham, J. B., A.A. Bird, and C.N.K. Mooers, 1987. Mean and variable flow over the central California continental margin. *Cont. Shelf Res*., **7**, 827-849.

76. Wooster, W.S. and J.H. Jones, 1970. California Undercurrent off Northern Baja California, *J. Mar. Res*., **28**, 235-250.

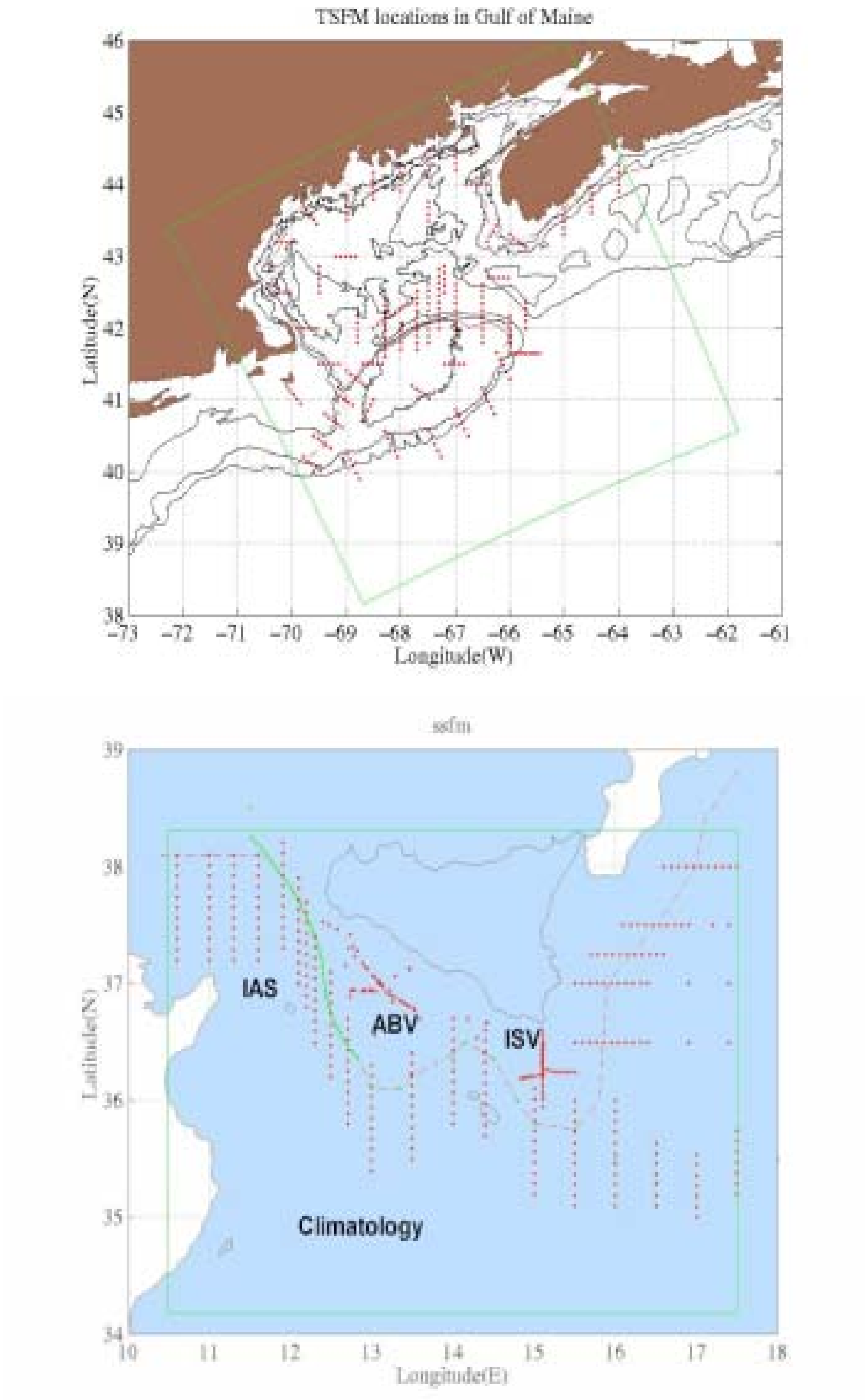


Fig. 1. Synoptic feature-oriented circulation template or "basis template" for two regional oceans: (a-top) Gulf of Maine/Georges Bank (GOMGB); (b-bottom) the Strait of Sicily

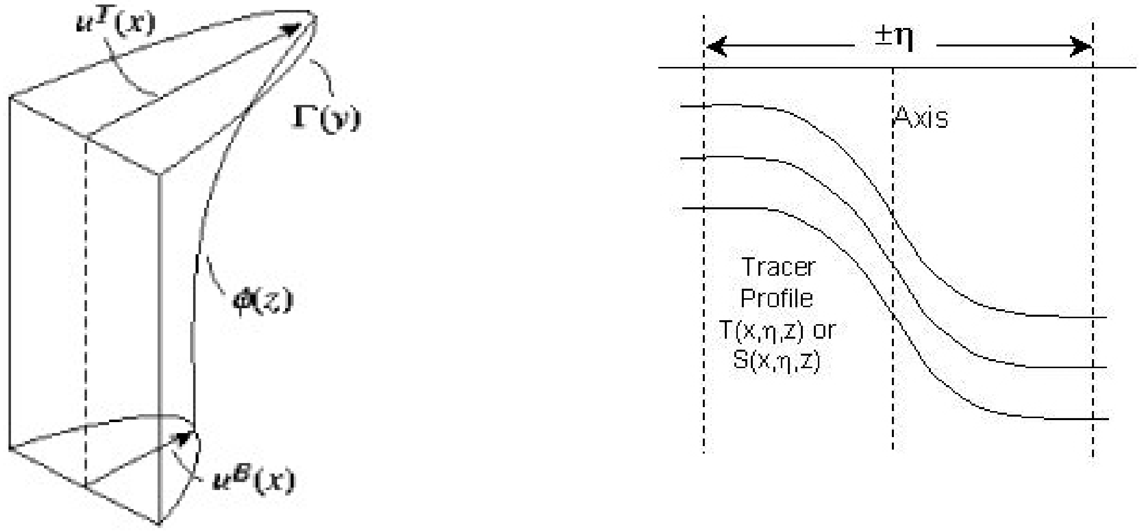


Fig. 1 c) A typical velocity feature model parameters for a meandering jet. 1d) A schematic generic temperature or salinity structure feature model (TSFM) across a front, eddy or gyre. (SS).

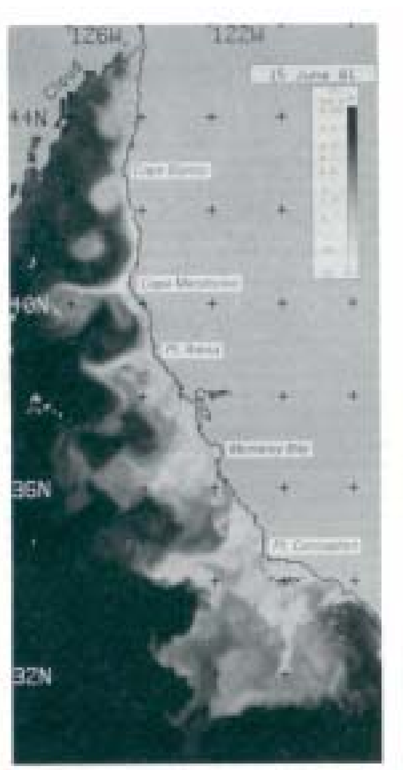


Fig. 2 – CZCS image from 15 June 1981 from Strub *et al*., 1991

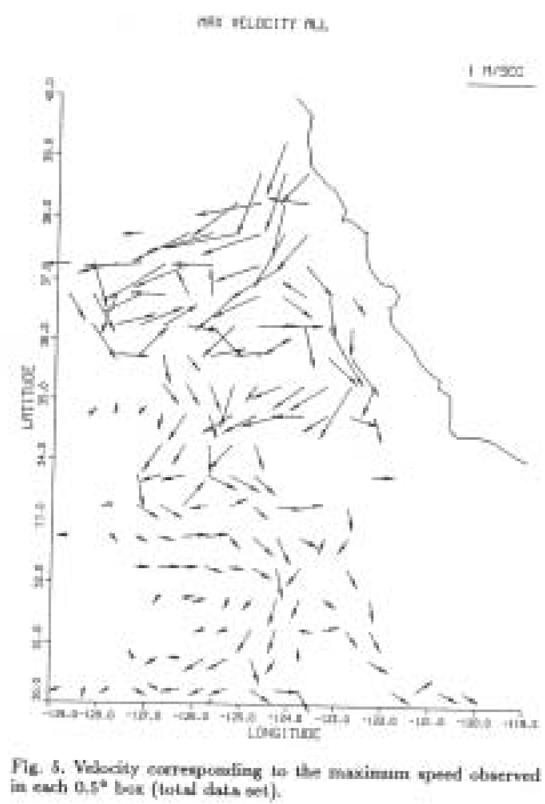
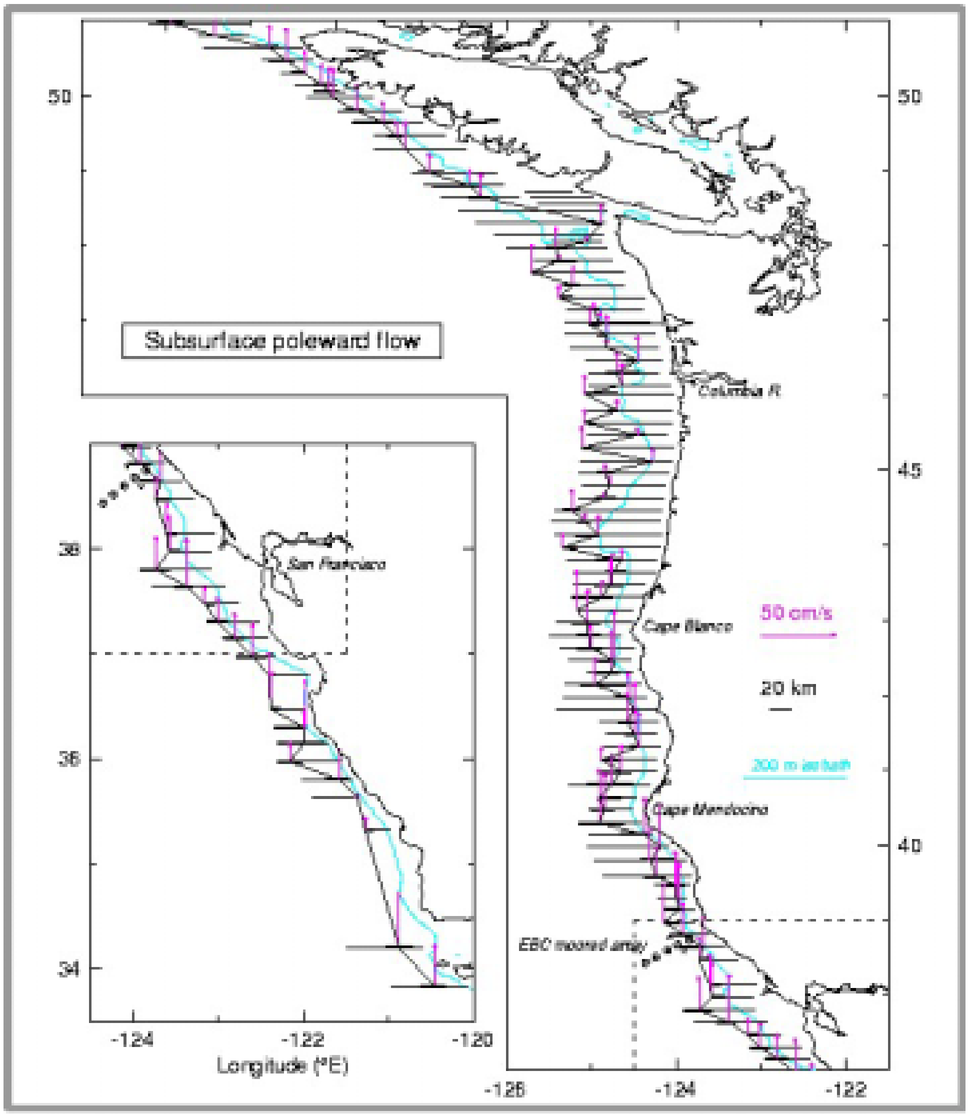


Fig. 3 – California Current mean flow field from Brink *et al*., 1991



ADCP sections were made across the continental margin from 32-51°N at about 20 km spacing during the 1995 upwelling season. The depth of the core of poleward flow at each section is determined by taking the center of mass (these depths range from 118–258 m). The vertical arrows show the speed and location of the maximum poleward flow found at this depth. The thick horizontal lines show the width of the poleward flow at half-maximum velocity. The whiskers show the full lengths of the **ADCP** sections.

Fig. 4a. From Pierce *et al*., 2000. Locations of ADCP sections and maximum speed and locations of the California Undercurrent.

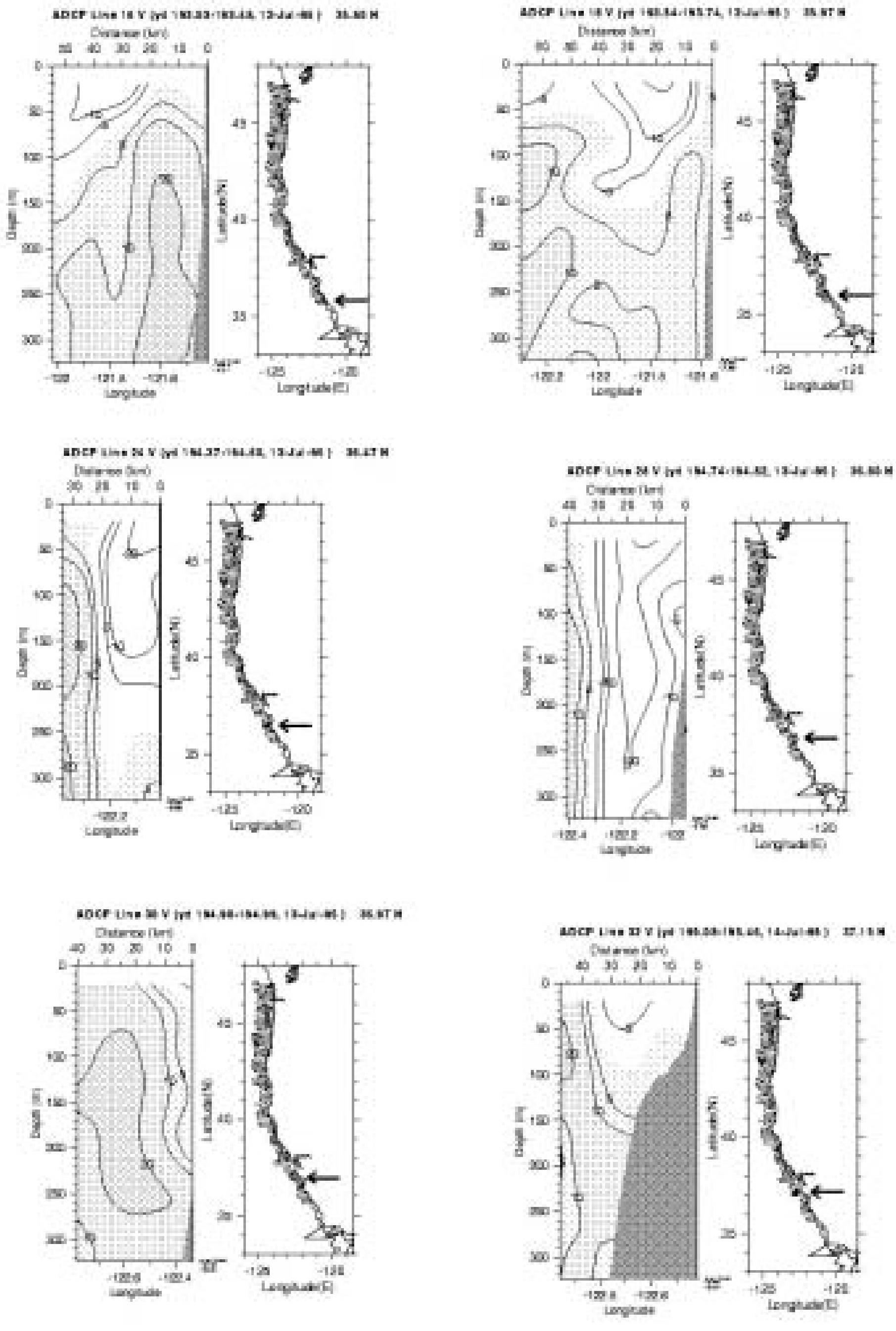


Fig. 4b. From Pierce *et al*., 2000. Example ADCP cross-sections along the California coast

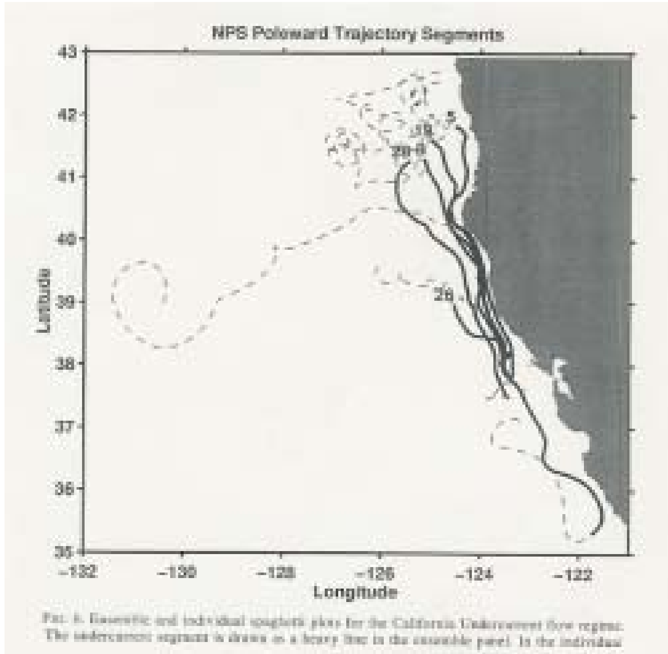


Fig. 5. From Garfield *et al*., 1999.
Ensemble and individual spaghetti plots for the California Undercurrent flow regime.

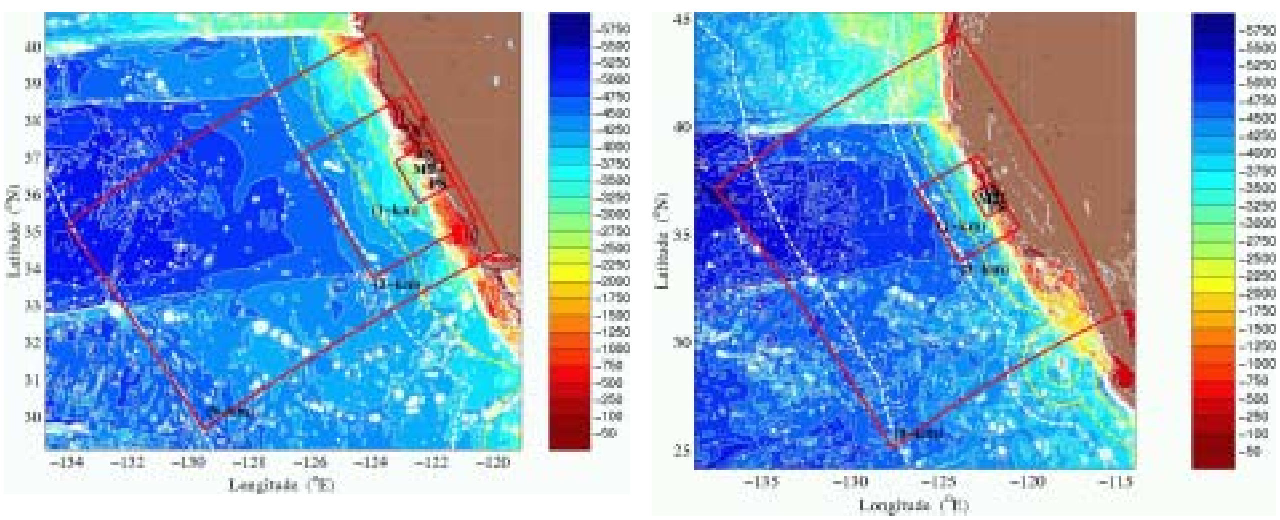


Fig. 6. Proposed sets of HOPS nested modeling domains: (a) smaller large domain; (b) largest large domain