Adriatic Circulation Experiment- Mesoscale Dynamics and Response to Strong Atmospheric Forcing

Craig M. Lee
Senior Oceanographer
craig@apl.washington.edu

ABSTRACT

We propose a study focused on understanding the dynamics of fronts, eddies, filaments and freshwater plumes in the Adriatic Sea. These investigations will concentrate on how seasonally variable atmospheric forcing, ambient stratification and coastal freshwater discharge act to govern mesoscale variability. Processes of interest include eddy generation and watermass formation by wintertime convective overturning, the generation of filaments and eddies by instabilities of the atmospherically forced coastal currents and the response of buoyant river plumes to strong atmospheric forcing. The proposed study will employ a towed, undulating sensor platform to make highly resolved, three-dimensional measurements of physical and optical variability associated with specific mesoscale features. Three distinct regimes will be studied: (1) Bora- downwelling favorable winds, weak ambient stratification, (2) Sirocco- upwelling favorable winds, weak ambient stratification and (3) Spring freshette- strong freshwater outflow, downwelling favorable winds, stratified waters. Rapidly repeated surveys will document the spatial structure and temporal evolution over the multi-day span of individual atmospheric events.

LONG-RANGE OBJECTIVES

Long-range objectives are to:

- Understand how outflow strength, wind-forcing, ambient stratification and mixing govern the dynamics of fronts, eddies and buoyant plumes.
- Investigate watermass formation and subduction in a shallow sea regime.

These objectives contribute to long-term efforts to understand:

- Processes governing exchanges between the shelf and deep ocean.
- The mesoscale dynamics of coastal waters.
- Processes that communicate atmospheric forcing to the ocean interior.

Proposed Research

1. Introduction

The Adriatic Sea offers a convenient laboratory for studying how interactions between strong atmospheric forcing, freshwater inflow and seasonally variable stratification govern the generation and evolution of mesoscale variability. The Adriatic is an elongated (200 km by 800 km) semi-enclosed sea (Fig. 1) forced by a combination of (1) Freshwater discharge from the numerous rivers ringing its edge, (2) Strong, episodic atmospheric events that produce wind-driven currents and drive intense mixing and dense water formation and (3) Exchange flow with the Ionian Sea through Otranto Strait. Together, these produce a basin-wide cyclonic circulation, with seasonally variable northwestward (southeastward) boundary currents flowing along the east (west) coast (*Artegiani et al.*, 1997b; *Poulain*, 1999). River discharge produces strong salinity contrasts between shelf and mid-basin and maintains year-round stratification over the shelf (*Artegiani et al.*, 1997a; *Orlic et al.*, 1992). During winter, strong winds and intense surface cooling (Fig. 2a) drive convective overturning and dense water formation. The strongest losses occur over the shallow Northern Adriatic, where the resulting north-south density contrasts support a wintertime cyclonic gyre (*Rizzoli and Bergamasco*, 1983). This feature disappears with the onset of springtime stratification, though two cyclonic gyres form farther to the south. Wintertime dense water formation also occurs over the South Adriatic Gyre, where strong, Bora-driven latent heat loss drives intermediate- (and sometimes full-) depth convective overturning (*Cushman-Roisin et al.*, 2001). The collapse of convectively generated chimneys generates O(10 km) scale eddies which populate the northwestern corner of the Southern Adriatic. An exchange flow through Otranto Strait, modulated at low frequencies by the strength of the freshwater flux into the Adriatic and at higher frequencies by synoptic scale atmospheric events, imports surface Ionian Sea water and Leventine Intermediate waters and exports Adriatic surface waters and, along a the sill bottom, Adriatic Deep water (*Poulain et al.*, 1996).

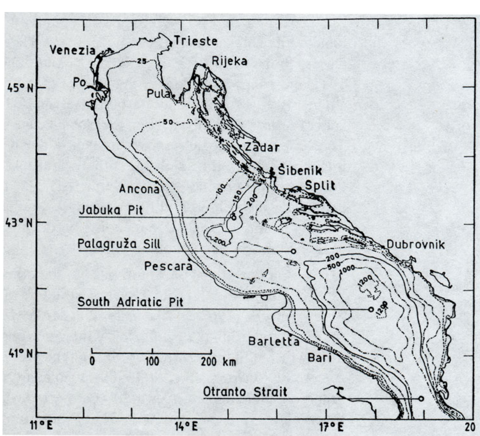


Figure 1*. (from Orlic et al., 1992) Chart of the Adriatic Sea.*

Basin topography strongly influences both the structure of atmospheric forcing and the resulting response. A broad, gently sloping shelf occupies the northern Adriatic, with average bottom depths of 35 m, deepening to 140 m in the central basin (Fig. 1). The west coast exhibits smooth isobaths that follow the coast, gently sloping from a relatively wide shelf into the deeper mid-basin waters. The opposite shore rises steeply from mid-basin depths to a rough coastline marked with headlands and islands. Mountain ranges array the eastern coastline, channeling the wintertime winds and imparting energetic small-scale lateral variability to the surface windstress.

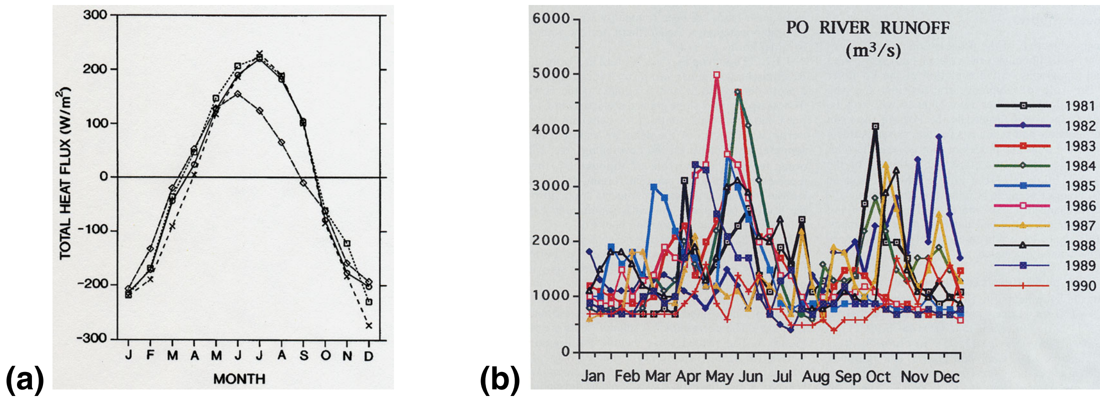


Figure 2. ***(a)*** *(from Artegiani et al., 1997a) Monthly mean heat flux derived from NMC, Hellerman-Rosenstein and May climatologies and* ***(b)*** *(from Kourafalou, 1999) Po River discharge from 1981-1990.*

Po River discharge varies seasonally (Fig. 2b), with an annual mean runoff rate of approximately 1700 m^3/s and peak flows of 4000-5000 m^3/s during the spring (April-June) and fall (September-December) freshettes (*Kourafalou*, 1999). In the presence of ambient stratification (spring though fall), the plume spreads across much of the northern basin, maintaining a wide cross-shelf profile as it flows southward (*Artegiani et al.*, 1997b; *Kourafalou*, 1999; *Rizzoli and Bergamasco*, 1983). During this period, the thin, surface trapped plume (Fig. 3a) may be particularly susceptible to wind-driven advection and mixing. Moderate southwestward winds can restrict the plume's offshore extent, confining it to a narrow coastal region and accelerating the flow (*Kourafalou*, 1999). Summertime stratification also supports enhanced mesoscale activity (e.g. filaments, jets and eddies with O(10 km) length scales) (*Artegiani et al.*, 1997b; *Mauri and Poulain*, 1999).

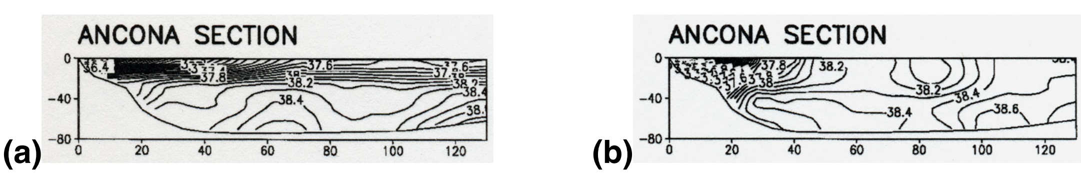
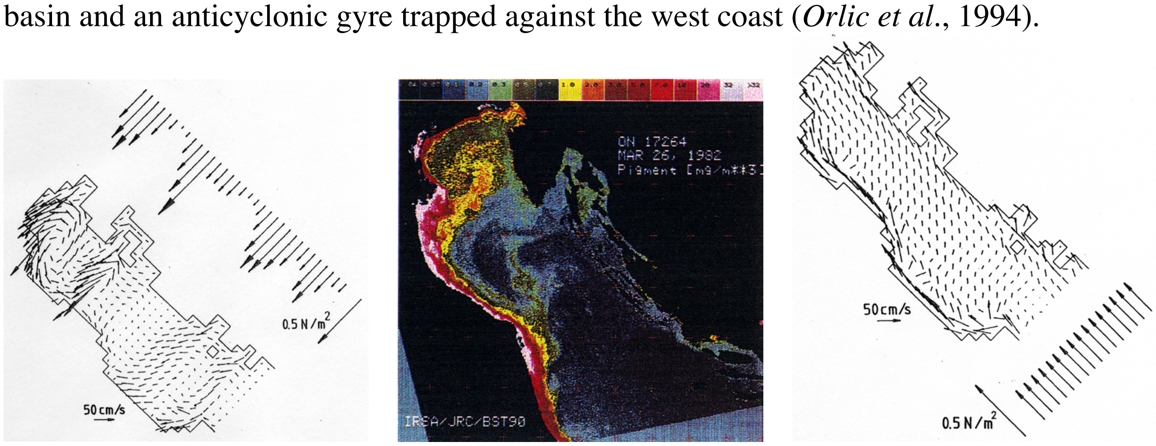


Figure 3. *(from Artegiani et al., 1997a) Sections of salinity extending from Ancona across the Po River plume during* ***(a)*** *spring and* ***(b)*** *autumn.*

Two episodic wind patterns dominate wintertime atmospheric variability. Intense (mean speeds of 15 m/s) outbreaks of cold, dry continental air, known as Bora, channel through the mountains lining the east coast and blow southwestward across the basin (*Orlic et al.*, 1994). These events occur on fortnightly timescales, last 4-6 days (*Smith*, 1987) and drive strong evaporative cooling, full-depth convective overturning and dense water formation in both the shallow waters of the northern basin and in the South Adriatic gyre (*Artegiani et al*., 1997a; *Bergamasco et al*., 1996; *Rizzoli and Bergamasco*, 1983). In the north, this intense cooling and overturning produces a strong front between dense, vertically homogenous waters in the north and the lighter (colder, fresher), stratified waters of the Po River plume (Fig 3b). The front supports cyclonic circulation in the Northern Adriatic (Fig. 4a) and may be a site of dense water formation and subduction (*Zore-Armanda and Gacic*, 1987). Dense Northern Adriatic Deep Water (NadDW, which eventually becomes Eastern Mediterranean Bottom Water) is subducted at the front and flows southward in a narrow vein following the isobaths of the Italian coast (*Artegiani et al*., 1989; *Artegiani and Salusti*, 1987). Although not strictly an alongshore wind, Bora are downwelling favorable and might be expected to drive southward currents along the west coast. However, orographic effects impart small-scale (tens of km) lateral variability to the wind field. Both modeling studies (*Orlic et al*., 1994) and remote sensing (*Mauri and Poulain*, 1999; *Sturm et al*., 1992) present evidence suggesting that windstress curl effects may drive downwind flow beneath the windstress maxima and upwind flow under the minima, producing a complex pattern of cyclonic and anticyclonic cells that may pull coastal waters far into the middle basin (Figs. 4a and b).

Wintertime Sirocco winds blowing to the northwest (mean speeds of 10 m/s) carry warm, moist Mediterranean air into the Adriatic. Though the Sirocco lack the small-scale variability present during the Bora, some evidence suggests that winds are strongest along the eastern coast, weakening to the west (*Orlic et al*., 1994). Sirocco events produce elevated sea surface height at the northern end of the basin with broad downwind surface flow across the basin (Fig. 4c). Upwelling favorable winds along the west coast can eliminate or even reverse the baroclinic coastal current, advecting plume waters northward and into mid-basin (*Kourafalou*, 1999; *Rizzoli and Bergamasco*, 1983). Ultimately, this may produce a two-gyre response, with a cyclonic gyre over much of the basin and an anticyclonic gyre trapped against the west coast (*Orlic et al*., 1994).



(a) Bora **(b) Bora** **(c) Sirocco**

Figure 4. *(from Orlic et al., 1994; Sturm et al., 1992) Model surface currents and wind fields for **(a)** Bora and **(c)** Sirocco wind events. Note the alternating onshore (offshore) currents and cyclonic/anticyclonic gyres associated with Bora windstress maxima (minima). Following a Bora event in March, 1982, CZCS derived pigment concentrations **(b)** reveal highly productive plume waters being drawn offshore by Bora-driven upwind flow.*

2. Observational Program and Analysis

We propose to study externally forced mesoscale dynamics using a towed, undulating instrument platform to make highly resolved, quasi-synoptic three-dimensional surveys of physical and optical variability. The seasonal cycle of winds over the Northern Adriatic provides strong, predictable forcing and an opportunity to study response under three dramatically different wind, stratification and outflow regimes: (1) Bora- downwelling favorable winds, weak ambient stratification, (2) Sirocco- upwelling favorable winds, weak ambient stratification and (3) Spring freshette- strong outflow, downwelling favorable winds, stratified waters. Although the weakly stratified winter period exhibits decreased mesoscale activity, strong wind events can produce steep coastal current meanders, filaments and eddies. Numerical studies (e.g. *Fong, 1998*; *Kourafalou, 1999*) indicate that wind-forcing, ambient stratification and background currents dominate plume evolution and highlight the three-dimensional nature of the response. Unfortunately, because of the difficulties involved in making three-dimensional, high-resolution synoptic surveys, observational support for these results remains sparse. We believe that a logical next step towards understanding these dynamics is to document the three-dimensional structure and temporal evolution of specific features under varied forcing regimes. The proposed high-resolution towed profiling measurements will provide the observations needed for a quantitative assessment of the dynamics governing response in each of the above-mentioned regimes.

The proposed measurement program involves two 21-day cruises, the first in winter 2002/2003 and the second in the following spring. The timescales associated with strong atmospheric events dictate cruise durations, as we wish to maximize the probability of observing one or more wind episodes. Both cruises will be planned to coincide with the presence of the moored arrays deployed by H. Perkins (NRL) and colleagues. Each cruise will make quasi-synoptic three-dimensional surveys documenting the physical and optical variability associated with specific mesoscale features. Surveys in the Northern Adriatic will provide highly-resolved, three-dimensional measurements to complement the time series gathered by the ACE mooring program.

The winter cruise will take place during the period marked by frequent Bora and Sirocco events (December-January). Our primary goals will be to:

- Quantify the relative roles of Ekman dynamics, bottom friction, mixing and discharge strength in governing the structure and evolution of the Po River plume under alternating Bora and Sirocco forcing.
- Investigate the possible importance of small-scale windstress curl in driving offshore advection of coastal waters.
- Test the idea that the front separating dense, vertically homogenous northern waters from fresh, buoyant coastal waters is a site of formation and subduction of AdDW.
- Investigate watermass formation, subduction and eddy generation along the northern end of the South Adriatic Pit.

The spring measurement program will be conducted during the period of maximum freshwater discharge and will be designed to:

- Determine the processes governing plume evolution under downwelling favorable winds given stratified coastal waters and strong discharge.
- Examine whether mixing plays an enhanced role when the plume is thin and broadly distributed in the cross-shelf direction.
- Investigate the dynamics of mid-basin filaments and eddies that form with the onset of spring stratification.

Each cruise will follow a similar plan, with initial sampling strategies chosen based on an analysis of climatological data (see accompanying proposal) and on plume variability observed in AVHRR and SeaWiFS imagery in the weeks prior to sailing. During previous experiments (Arabian Sea and Japan/East Sea) access to real time remotely sensed imagery allowed us to modify and focus our sampling plans in response to maps of surface conditions. We intend to collaborate with a remote sensing group (Dr. R. Arnone, NRL and/or Dr. F. Askari, SACLANTCEN) to obtain this capability. Survey design involves balancing the need to: (1) Resolve small scale physical and optical variability, (2) Map a three-dimensional volume that spans features of interest and (3) Maintain synopticity over each occupation of the pattern. Real time, remotely sensed maps of sea surface temperature (AVHRR) and ocean color (SeaWiFS) will be used to identify specific features and guide sampling strategy. Rapidly repeated surveys will then document spatial structure and temporal evolution over the multi-day span of individual atmospheric events. A sample survey plan (Figure 5) illustrates several likely measurement regions, including: (i) the Po river plume, (ii) an instability in the Western Adriatic Coastal Current and the resulting filament, (iii) the frontal system over the Mid-Adriatic Pit and (iv) the region over the Southern Adriatic where strong wintertime convection drives watermass formation and small-scale eddy generation. Tides and near-inertial (18.6 hours) motions represent possible sources of noise in our survey data. In the northern basin, both can achieve speeds of approximately 0.1 m/s (*Orlic et al*., 1992; *Krajcar and Orlic*, 1995; *Orlic*, 1987), with near inertial oscillations present only during the stratified summer season. The central and southern basins exhibit weaker tidal and near-inertial variability. Although tidal and inertial signals are significant, variability associated with the coastal currents, fronts and eddies should dominate the observations. Experience from Georges Bank, where tides represented over 90% of the velocity variance, suggests sampling and filtering methodologies that may aid in our analysis.

Our observational efforts will involve underway surveys using ADCP current measurements, meteorological sensors and especially our towed profiling vehicle (Triaxus). Manufactured by MacArtney A/S, a highly experienced Danish marine technology firm, Triaxus is an undulating vehicle based on a box-kite design. Integral fiber optic telemetry provides both control and extensive bandwidth for real time data acquisition. Electrically driven control surfaces provide precise, predictable control of vertical and lateral position, while an altimeter-based bottom avoidance system facilitates profiling from the surface to within a few meters of the seabed. In the shallow waters of the Northern Adriatic (< 100 m), the vehicle can achieve horizontal resolutions of better than 1 km while moving at 8 knots, with finer resolutions possible at slower speeds

Adriatic Sea

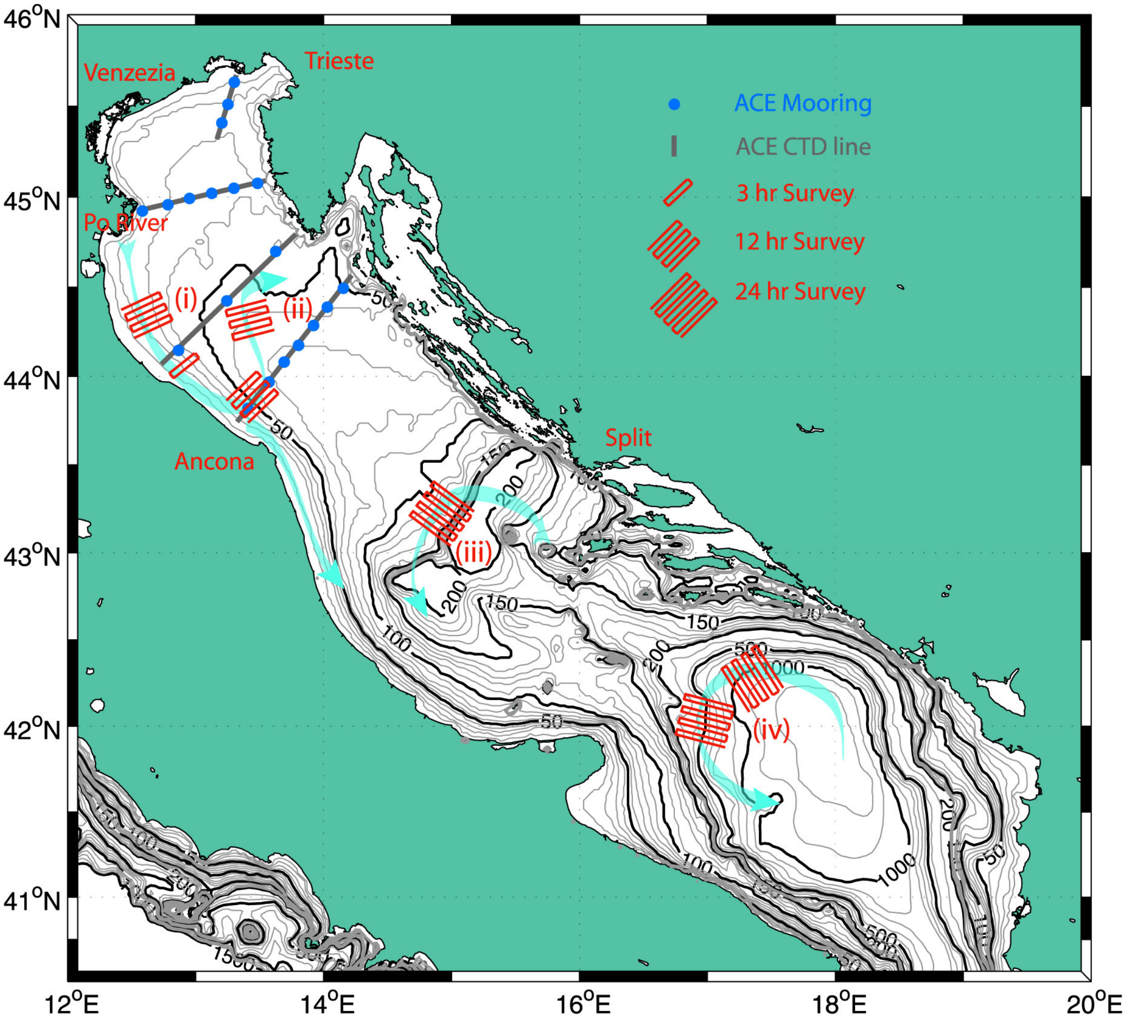


Figure 5. *Potential survey locations and patterns. Surveys would be adjusted to accommodate specific features. The patterns depicted can be repeated within the specified time interval (3, 12 and 24 hours) at a tow speed of 8 knots. Potential sampling includes: (i) The Po River plume, (ii) Coastal filaments, (iii) Mid-basin fronts and (iv) Regions of wintertime deep convection, watermass formation and eddy generation.*

(trading spatial coverage and/or synopticity for enhanced resolution). We will exploit rapid tow speeds and full-depth profiling capability to make repeated, synoptic, three-dimensional surveys resolving finescale structure and documenting temporal evolution. Previous shallow water towed profiling experiences in strong winds and heavy seas (Georges Bank GLOBEC and the Japan/East Sea Experiment) provide us with confidence in our ability to operate successfully under the adverse conditions expected during the winter cruise. However, for winter we request a large, stable vessel capable of maintaining appropriate tow speeds in difficult seas.

Triaxus will make simultaneous measurements of physical and bio-optical parameters, allowing us to investigate how plume dynamics influence optical variability over a shallow shelf and providing optical data to support observations of subduction and secondary circulations associated with the plume. In addition to dual Seabird temperature, conductivity and pressure sensors, Triaxus payload will include chlorophyll and DOM fluorometers, a transmissometer and a dissolved oxygen sensor. We may also deploy new sensors (chlorophyll fluorescence, DOM fluorescence and backscatter) developed by Dr. M. J. Perry and Wetlabs for an autonomous vehicle (Seaglider) as part of a recent NOPP effort. We anticipate strong optical signals associated with a combination of terrestrial material delivered via river (e.g. Po River) discharge, phytoplankton response to the nutrient flux associated with the plume and sediment suspended from the bottom. Observations of absorption (as a function of wavelength) and salinity off southern California illustrate small scale optical variability associated with a river plume (Dr. Burton Jones, personal communication) (Fig. 6). The freshest waters mark recent discharge, while slightly higher salinities farther offshore reflect older plume waters that may have mixed with saltier coastal waters. The nearshore absorption spectra decrease monotonically from blue to red, consistent with a primarily detrital signal, while farther offshore, a secondary maximum in the red signifies the presence of phytoplankton. The phytoplankton respond to the nutrients and stratification of the plume, and thus the absorption spectra from the older part of the plume reflect both signals (*Jones, personal communication*). While the optical sensors listed above will provide useful measurements, it is our hope that a separate proposal from Dr. Jones will allow us to add multi-wavelength absorption and attenuation sensors (AC-9 or Hi-Star) for use in the Northern Adriatic.

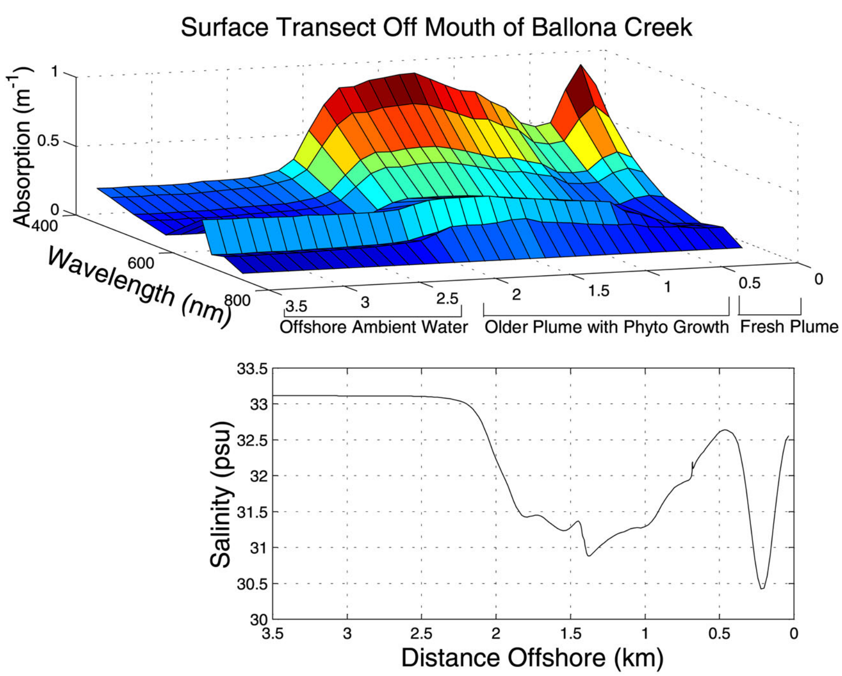


Figure 6. *(from Dr. B. Jones, USC) Absorption spectra and salinity within a runoff plume off southern California.*

Underway measurements of currents will be essential to understanding plume dynamics and watermass formation. We plan to use a shipboard Acoustic Doppler Current Profiler in conjunction with P-code GPS and bottom tracking to measure water velocities. Because the much of the Adriatic is shallow and features such as river plumes can be confined to the upper 20-30 m, a high frequency ADCP (600 or 1200 kHz) might be used to augment the lower frequency units (longer range but coarser vertical resolution) typically mounted on UNOLS research vessels. If a high frequency unit is available, we will seek to mount it either as an additional hull or over-the-side mount on the research vessel or directly on the profiling vehicle (looking upward). Dr. Michael Gregg's group (UW/APL) has been funded to integrate ADCPs onto their tow-yo platform, and we would leverage their efforts if we decide to add an ADCP to our vehicle.

Meteorological measurements will be required for our investigations of plume response to atmospheric forcing. To assure a full suite of wind and heat flux measurements, we will seek to supplement the standard shipboard sensors with self contained ASIMET packages. Drs. R. Beardsley (WHOI) and C. Dorman (SIO) used these sensors during our recent wintertime Japan/East Sea cruise, achieving good data return under extremely adverse conditions. Synoptic, two-dimensional wind fields will also be important to understanding our observations. Scatterometer winds can provide 25 km resolution and have a demonstrated ability to resolve topographically induced small-scale structure (Dr. K. Kelly, personal communication), but the averaging of multiple passes required to cover the basin degrades temporal and spatial resolution. Drs. J. Pullen and J. Doyle (NRL Monterey) have developed a high resolution, assimilating ocean-atmosphere model of the Adriatic that will provide wind fields at 4 km resolution. Severe discrepancies between different climatological wind products (*Artegiani et al*., 1997a; *Cavaleri et al*., 1997) highlight the need for additional *in situ* meteorological measurements. Many of the existing long-term measurement sites are either on or near the landmass. Because strong orographic effects impart small lateral scales to the Adriatic wind field, these observations may not accurately represent conditions farther offshore. Additional in situ meteorological measurements, perhaps from other research vessels or ships of opportunity, could aid in validating the scatterometer and model winds and ultimately contribute to an improved climatology.

Although preliminary processing while at sea produces a near-real time data set usable for cruise planning and initial analysis, extensive post processing will take place upon our return. All sensors will be post-calibrated and the resulting corrections applied to the data. Following careful post cruise analysis, quality control and editing, we will produce a scientific data set that will be made available to other investigators participating in the Adriatic program. We anticipate that scientific data will be available approximately 6 months after the completion of each cruise.

Scientific analysis will proceed in collaboration with other Adriatic investigators. Time series of highly-resolved, three-dimensional surveys will be used to quantify the processes governing mesoscale response to strong atmospheric forcing. Plume surveys will be used to trace the fate of the Po outflow as it enters the Adriatic, and to investigate the role atmospheric forcing plays in modulating its offshore spreading (including filament generation) and southward flow. Measurements of convective deepening at the edge of the South Adriatic Gyre will facilitate an investigation of wintertime watermass formation and eddy generation. Our initial approach will employ survey data and two-dimensional surface flux fields to quantify heat, salt, momentum and vorticity budgets and to estimates of the three-dimensional flow field using an omega equation (or similar) technique.

3. Interactions with Other Programs

The Adriatic Circulation Experiment (ACE): Drs. Perkins, Miller, Teague and Hwang (NRL), in collaboration with SACLANTCEN investigators and Italian and Croatian colleagues will deploy multiple arrays of bottom mounted ADCPs and profiling CTDs for the period spanning autumn 2002 to late spring 2003. Their efforts also include real-time data assimilation and modeling. We will schedule our cruises to coincide with the presence of the moored array, and anticipate coordinating survey sites and array locations. Our surveys can provide high-resolution spatial information to complement the long time series collected by the moored array. We have worked with Dr. Perkins previously in the Japan/East Sea, and anticipate close collaborations with his efforts.

Littoral Turbidity and Drift Modeling and NRL Monterey Coupled Ocean-Atmosphere Model: Dr. Richard Signell (SACLANT Center) is developing relocatable turbidity and drift models for nearshore environments, and intends to use the Adriatic as a testbed for these efforts. This study will employ a high-resolution Adriatic circulation model and include detailed investigations of the Po River plume. Drs. Pullen and Doyle (NRL) have developed an assimilating Adriatic model running at 1 km (4 km) ocean (atmosphere) resolution. Their model is capable of producing detailed hindcasts using a combination of observed meteorological fluxes and analysis products. Our observations could be used to evaluate model performance under strong forcing and should provide direct tests of several aspects of the dynamics. We also expect that the model results will be an important tool for enhancing our understanding of the plume's dynamics and for interpreting our observations.

Euro STRATAFORM: An interdisciplinary study of the processes governing sediment transport and accumulation will make intensive measurements of the Po river system. Although this effort focuses on sedimentary processes, preliminary plans include observations within the plume. We intend to collaborate with Euro STRATAFORM investigators to develop a comprehensive assessment of plume dynamics.

Other Proposed Programs: As previously mentioned, we hope that separate proposals submitted by other investigators (e.g. Drs. Jones and Beardsley) might provide additional optical and meteorological studies. We have worked closely with these individuals in the past (Arabian Sea and Japan/East Sea experiments), and expect extensive integration of our measurement and analysis programs if these efforts are funded. Lastly, a separate request from the PI proposes developing techniques to improve the capabilities of climatologies and analysis products in shallow water environments. The Northern

Adriatic will be used as a testbed for these ideas, and the results will be valuable for planning our field program. More importantly, the synoptic surveys collected as part of this study will provide fully resolved test cases for evaluating and refining nowcast techniques.

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