2015

Sediment dynamics in the Adriatic Sea investigated with coupled models

Christopher R. Sherwood

Jeffrey W. Book

(...)

Courtney K. Harris
Virginia Institute of Marine Science

et al

Recommended Citation
Sherwood, Christopher R.; Book, Jeffrey W.; (...); Harris, Courtney K.; and et al, Sediment dynamics in the Adriatic Sea investigated with coupled models (2015). *Oceanography*, 17(4), 58-69.
doi: 10.5670/oceanog.2004.04

Sediment Dynamics in the Adriatic Sea Investigated with Coupled Models

BY CHRISTOPHER R. SHERWOOD, JEFFREY W. BOOK, SANDRO CARNIEL, LUIGI CAVALERI, JACOPO CHIGGIATO, HIMANGSHU DAS, JAMES D. DOYLE, COURTNEY K. HARRIS, ALAN W. NIEDORODA, HENRY PERKINS, PIERRE-MARIE POULAIN, JULIE PULLEN, CHRISTOPHER W. REED, ANIELLO RUSSO, MAURO SCLAVO, RICHARD P. SIGNELL, PETER TRAYKOVSKI, AND JOHN C. WARNER

Several large research programs focused on the Adriatic Sea in winter 2002-2003, making it an exciting place for sediment dynamics modelers (Figure 1). Investigations of atmospheric forcing and oceanic response (including wave generation and propagation, water-mass formation, stratification, and circulation), suspended material, bottom boundary layer dynamics, bottom sediment, and small-scale stratigraphy were performed by European and North American researchers participating in several projects. The goal of EuroSTRATAFORM researchers is to improve our ability to understand and simulate the physical processes that deliver sediment to the marine environment and generate stratigraphic signatures. Scientists involved in the Po and Apennine Sediment Transport and Accumulation (PASTA) experiment benefited from other major research programs including ACE (Adriatic Circulation Experiment), DOLCE VITA (Dynamics of Localized Currents and Eddy Variability in the Adriatic), EACE (the Croatian East Adriatic Circulation Experiment project), WISE (West Istria Experiment), and ADRICOSM (Italian nowcasting and forecasting) studies.

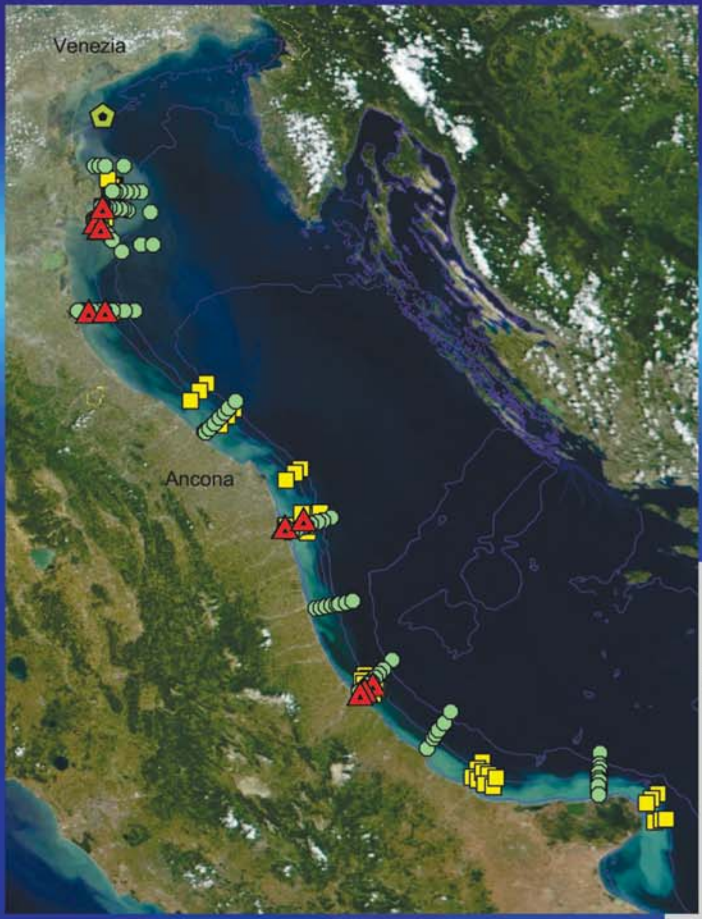
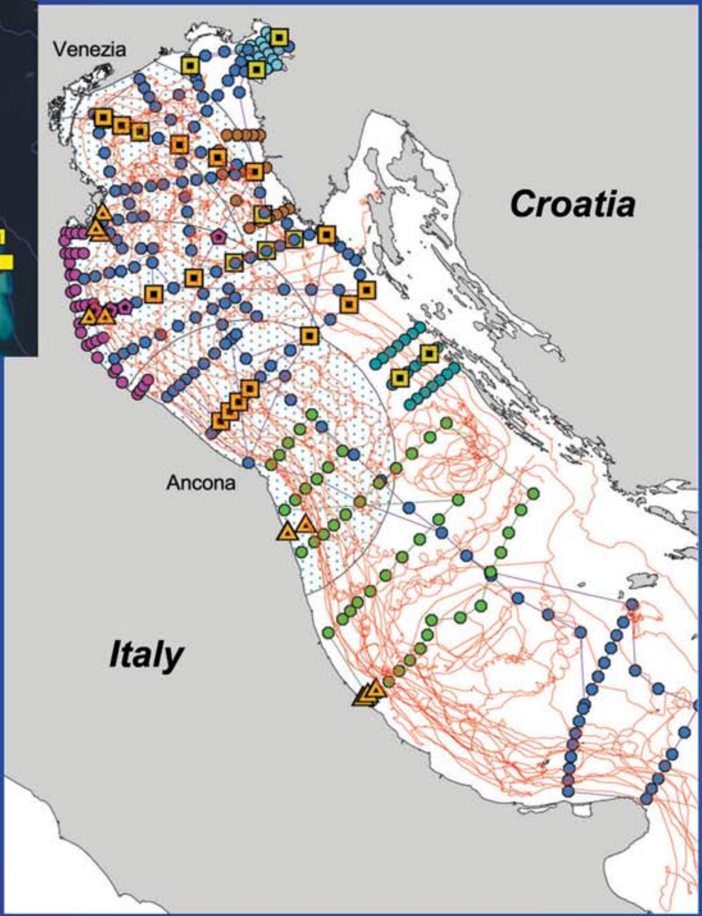


Figure 1. (a) Suspended particulates help mark the western Adriatic coastal current (WACC) in this MODIS image of the Adriatic Sea. EuroSTRATAFORM researchers deployed tripods (triangles), recovered box cores (squares), and made water-column observations (circles) in the WACC. (b) Researchers working on ACE, EACE, DOLCE VITA, WISE, and ADRICOSM projects established radars for measuring surface currents (gray shading), deployed acoustic Doppler profilers (squares), tracked drifters (red lines), completed hydrographic surveys (blue circles) and made other water-column measurements during the 2002-2003 experiments (circles).



CHALLENGING DEPOSITIONAL PATTERNS

A motivation for studying the Adriatic Sea is the shape of Holocene deposits and the separation between the sources of sediment supply and regions of long-term sediment deposition (see Figure 1 in Nittrouer et al., this issue). The Po River is the largest single source of sediment to the Adriatic and provides about one quarter (12 Mt/yr) of the ~ 47 Mt/yr sediment delivered to the Adriatic Sea. Several short, steep rivers draining the rapidly uplifting Apennine mountains have the potential for delivering high sediment loads at concentrations that make the river waters more dense than seawater (hyperpycnal flows). The Apennine rivers contribute about 32 Mt/yr, but since World War II these rivers have been highly regulated, and now are less likely to deliver sediment in concentrations high enough to trigger hyperpycnal flow. Geophysical surveys indicate that about 180 km^3 of sediment have accumulated along the western margin of the Adriatic in elongate depositional features termed clinoforms, with the locus of deposition in 40 to 50 m water depths (Cattaneo et al., 2003; Cattaneo et al., this issue). Local accumulations occur near sediment sources at the Po delta and along the Apennine margin, where they thicken southward, presumably reflecting the cumulative contribution of multiple rivers. However, the thickest accumulations are located north of the Gargano promontory, nearly 400 km from the Po and 100 km from other significant sources of sediment. How can numerical models of waves, circulation, bottom boundary layer dynamics, and sediment transport be used to understand these patterns?

OLD AND NEW TRANSPORT MECHANISMS

Traditional views of sediment transport on continental shelves have focused on wave-induced resuspension and current-induced suspended-sediment transport. In many of the well-studied systems, the combination results in dispersal systems that combine advection and diffusion in varying amounts (Swift et al., 1972). In most cases, however, the locus of deposition is close to the source of sediment supply, and accumulation rates decrease with distance in a pattern that reflects the long-term correlation among sediment concentrations and current velocities. Observations made during the STRATAFORM study of the Eel River margin offshore California revealed a paradox that challenged these traditional views. There, measurements during the fifth largest flood in 93 years indicated that rapid deposition of flood sediments occurred beneath the river plume in shallow water, but long-term accumulation was centered in deeper water (Sommerfield and Nittrouer, 1999; Wheatcroft and Borgeld, 2000). Wave-induced remobilization of the muddy flood deposits and subsequent downslope density flows were key mechanisms of cross-shelf sedi-

Christopher R. Sherwood *(csherwood@usgs.gov) is Oceanographer, U.S. Geological Survey, Woods Hole, Massachusetts, United States of America.* **Jeffrey W. Book** *is Oceanographer, Naval Research Laboratory, Stennis Space Center, Mississippi, United States of America.* **Sandro Carniel** *is Research Scientist, Consiglio Nazionale delle Ricerche-Istituto di Scienze Marine (CNR-ISMAR), Venice, Italy.* **Luigi Cavaleri** *is Senior Research Scientist, Consiglio Nazionale delle Ricerche-Istituto di Scienze Marine (CNR-ISMAR), Venice, Italy.* **Jacopo Chiggiato** *is Consultant, Servizio Idro Meteorologico-ARPA Emilia Romagna, Bologna, Italy.* **Himangshu Das** *is Research Scientist, URS Corporation, Tallahasee, Florida, United States of America.* **James D. Doyle** *is Head, Mesoscale Modeling Section, Marine Meteorology Division, Naval Research Laboratory, Monterey, California, United States of America.* **Courtney K. Harris** *is Assistant Professor, Virginia Institute of Marine Sciences, Gloucester Point, Virginia, United States of America.* **Alan W. Niedoroda** *is Senior Research Scientist, URS Corporation, Tallahasee, Florida, United States of America.* **Henry Perkins** *is Oceanographer, Naval Research Laboratory, Stennis Space Center, Mississippi, United States of America, now retired.* **Pierre-Marie Poulain** *is Senior Research Scientist, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Trieste, Italy.* **Julie Pullen** *is Oceanographer, Naval Research Laboratory, Monterey, California, United States of America.* **Christopher W. Reed** *is Senior Research Scientist, URS Corporation, Tallahasee, Florida, United States of America.* **Aniello Russo** *is Research Scientist, Università Politecnica delle Marche and Consiglio Nazionale delle Ricerche-Istituto di Scienze Marine (CNR-ISMAR), Ancona, Italy.* **Mauro Sclavo** *is Head, Venice Section, Consiglio Nazionale delle Ricerche-Istituto di Scienze Marine (CNR-ISMAR), Venice, Italy.* **Richard P. Signell** *was Oceanographer, NATO/SACLANT Undersea Research Centre, La Spezia, Italy, now is Oceanographer, U.S. Geological Survey, Woods Hole, Massachusetts, United States of America.* **Peter Traykovski** *is Associate Scientist, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, United States of America.* **John C. Warner** *is Oceanographer, U.S. Geological Survey, Woods Hole, Massachusetts, United States of America.*

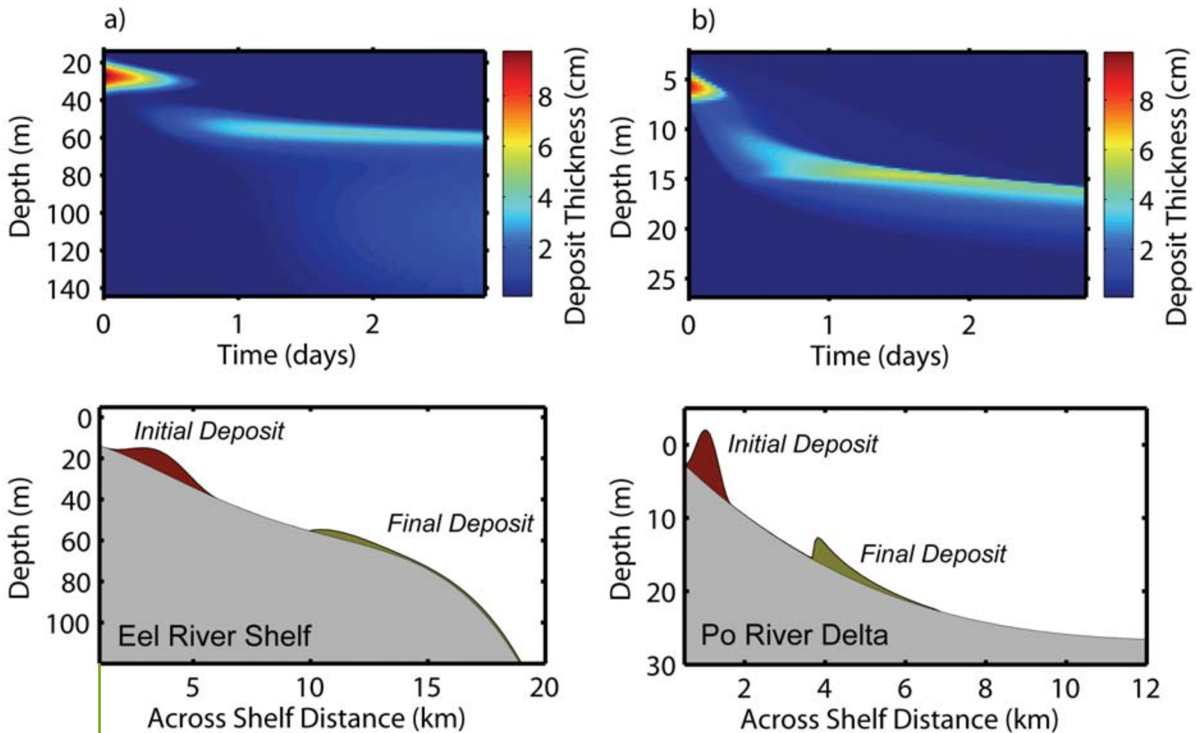


Figure 2. (a) Mud initially deposited in shallow water (20-40 m) beneath the Eel River plume is remobilized by waves and moved downslope as a gravity current, producing a final deposit in deeper water (50-60 m), according to these model simulations. The first field observations of this process were made during the STRATAFORM project, and fluid muds were again observed on the flanks of the Po River delta during EuroSTRATAFORM. The model (b) indicates that these processes occur in shallower depths in the Adriatic Sea, where waves are smaller. Note the deposits are plotted with ~10x vertical exaggeration. Nittrouer et al. (this issue) show maps of the final location and thickness of fluid mud deposits after the Po flood of 2000 predicted from a two-dimensional model.

ment transport (Traykovski et al., 2000) (Figure 2). However, the Eel margin has large waves and high rates of sediment supply. Another important objective of the EuroSTRATAFORM program was to determine whether wave-induced density flows occur in more moderate environments such as the Adriatic Sea.

SCALING FROM EVENTS IN A SINGLE SEASON TO GEOLOGICAL TIME SCALES

One of the big challenges in sediment modeling is scaling. We do not have the computer power to resolve processes at the finest scales and also cover the necessary temporal and spatial scales. Even if we could, uncertainty in boundary conditions and forcing would require us to consider even the most deterministic model results in a statistical sense. One response to this dilemma is to adopt a hierarchy of models that inform each other across a range of domains and scales. The Adriatic modeling work presented here is an example of this approach. We use multiple nested meteorological models to transfer information from global scales to local scales (consisting of a few square kilometers). The coupling of atmospheric, hydrologic, wave, and oceanographic models allows us to evaluate the importance of regional and local forcing on the detailed physics of the bottom boundary layer, which we can examine in detail with the gravity-flow models. Coupled circulation and sediment-transport models allow us to verify processes against measurements during specific events and over the course of a winter transport season. Stratigraphic models let us extend the effect of annual processes over decades and centuries and factor in long-term changes in sea level and sediment supply. In the end, we hope to achieve a cascade of models that, although they are calibrated at small scales and over short periods, still allow us to build insight about cumulative effects because they are based on a fundamentally correct representation of the processes.

OBSERVATIONS

EuroSTRATAFORM researchers deployed instrumented tripods and moorings for nine months (November 2002 to May 2003); made water-column measurements in the western Adriatic coastal current (WACC) during voyages in November, February, and May; made short-term (~2 day) studies of particle dynamics; and analyzed cores to determine characteristics of near-surface sediments and accumulation rates over time scales ranging from weeks to millennia. Participants in the ACE, EACE, and WISE programs deployed acoustic Doppler current meter moorings in the northern Adriatic and collected hydrographic data in September to October 2002 and late May 2003 (Figure 1). DOLCE VITA scientists tracked scores of drifters and measured water-column sections of temperature, salinity, fluorescence, and light attenuation during two cruises in February and May/June. ADRICOSM researchers conducted monthly surveys of water-column properties in several key near-coastal regions. These measurements provide a rich set of data for initializing, forcing, and critically evaluating numerical models of the major processes that ultimately write the stratigraphic record in the Adriatic Sea.

MODELING

We have linked a sequence of models that (1) characterize river flow and sediment discharge, (2) estimate time-varying meteorological conditions and waves, (3) compute circulation and sediment transport for a nine-month winter period, (4) simulate the remobilization, transport, and deposition of sediments during fluid mud events, and (5) simulate the development of stratigraphy.

Winter circulation in the Adriatic Sea is strongly controlled by local wind and river input (e.g., Orlic et al., 1994; Cushman-Roisin et al., 2001), so it is an excellent natural laboratory for numerical modeling studies. Time series of the supply of freshwater and sediment from the Po River and smaller Apennine rivers are required, as are fields of meteorological conditions (such as winds, temperature, humidity, precipitation) that control air-sea exchanges of momentum, heat, and freshwater. Waves play a critical role in sediment resuspension, so accurate knowledge of near-bottom wave motions is necessary. Once sediment is resuspended by waves or delivered by rivers, regional currents transport it; hence, a detailed description of circulation is required, particularly during transport events. The data collected in 2002 to 2003 and the suite of models now available have allowed us to estimate depositional patterns and compare them with the long-term accumulation patterns observed in sediment cores and seismic data.

Meteorology

Meteorological forcing for the wave and circulation models was output from two models: LAMI (Limited Area Model Italy) and COAMPS™ (Coupled Ocean-Atmosphere Mesoscale Prediction System). Both solve finite-difference approximations of the three-dimensional, non-hydrostatic equations that govern atmospheric motions. LAMI is an Italian operational model for medium- and small-scale weather prediction based on a model developed by the German meteorological service (Deutscher Wetterdienst) (Steppler et al., 2003). COAMPS (Hodur and Doyle, 1999) is the operational mesoscale prediction system used in support of the U.S. Navy, and it can be coupled with the Navy Coastal Ocean Model (NCOM). Both atmospheric models were nested into regional and global weather models. COAMPS model results were generated more frequently and on a finer grid (1 hr at 4 km, compared with 3 hrs at 7 km for LAMI), and COAMPS runs assimilated data from radiosondes, surface satellite, and aircraft observations. In "one-way" coupled runs, the atmospheric models provided forcing for the ocean models and measured or modeled sea-surface temperature was used to estimate air-sea heat exchange. When "two-way" coupled with NCOM, COAMPS forced the ocean model with momentum and heat flux and NCOM supplied sea-surface temperatures as feedback to COAMPS.

River Discharge

Rivers are a primary source of sediment, and the freshwater they deliver influences coastal circulation; thus, correct representation of river contributions in the model is vital. We set flow according to daily-average measurements for the Po, Pescara, and Biferno Rivers. We set the flow of other rivers to monthly mean values using climatological estimates. Sediment discharge was estimated using the one-dimensional flow model *HydroTrend* (Syvitski et al., 1998), which creates synthetic river discharge and sediment-load time series as a function of climate trends and basin morphology. The sediment rating curves generated by *HydroTrend* were combined with measured discharges to generate time series of sediment concentrations in the Po River for input to

2002-2003 model simulations. River-supplied sediment was broadly characterized as either silt, with a low settling velocity of 0.1 mm/s, or flocculated finer material, with an aggregate settling velocity of 1 mm/s (Fox et al., 2004; in press).

Waves

Waves were simulated using SWAN (Simulating WAves in the Nearshore), which models the evolution of wave energy imparted by wind as waves propagate across the sea; are transformed (in frequency and direction) by shoaling, refraction, and wave-wave interactions; and are dissipated by whitecapping and bottom friction (Booij et al., 1999). We modeled waves in the Adriatic Sea on a rectangular grid with ~2-km spacing. Evolution of the non-stationary wave field was calculated at 15-minute time steps, driven by wind fields provided at three-hour intervals and ~7-km spacing from the LAMI model output.

Circulation and Suspended-Sediment Transport

Oceanic circulation and sediment transport were simulated using ROMS (Regional Ocean Modeling System) (more information available at http://marine.rutgers.edu/po/models/roms/). ROMS solves finite-difference approximations of the three-dimensional Reynolds-averaged equations for conservation of mass, momentum, and heat using a two-equation submodel for turbulent mixing. Effects of waves in the bottom boundary layer, which include increased drag and bottom stresses, were parameterized with a modified version of the Grant and Madsen (1979) model. Sediment supplied by rivers or resuspended from the seafloor was advected, vertically mixed, and allowed to settle in the model, which also records changes in upper stratigraphy (to ~0.1 m) of the seafloor caused by erosion or deposition. Wind-driven circulation, mixing, and heating or cooling of surface waters were calculated using bulk flux algorithms with input from the atmospheric models. Initial water temperatures and salinities were set by interpolating from hydrographic data collected during September 2002 surveys. A range of model runs were performed on a ~4-km grid with 20 vertical levels using both atmospheric models and alternative parameterizations for various processes to explore the fate of sediment supplied by rivers or resuspended from existing deposits.

Gravity Flows of Fluid Mud

Gravity-flow processes on the Po River delta front were simulated with a one-dimensional (cross-shelf) time-dependent model that resolves the suspended sediment concentration in the thin wave-current boundary layer and calculates transport and deposition associated with gravity-driven downslope flows. The model was forced with observed waves and currents, and assessed for skill against near-bottom measurements of flow and suspended-sediment. A two-dimensional model (across shelf and along shelf) based on several simplifying assumptions was also used to predict the spatial distribution of the flood deposit on the Po delta (see Nittrouer et al., this issue). These models allow us to evaluate the displacement of flood deposits from their initial depocenters beneath the river plume to their eventual locus of long-term accumulation.

Stratigraphy

Stratigraphy was considered on two scales: detailed (upper 2 to 10 cm) and shallow (upper ~2 to 30 m). Two models, HSM-3D and CST (Coastal Sediment Tract), have been developed to allow diagnosis and predictions at these scales. HSM-3D is a three-dimensional, time-dependent numerical model for hydrodynamics, sediment dynamics, and morphodynamics. It includes suspended transport, bedload, and the effect of gravity flows in the bottom boundary layer and incorporates evolving bottom morphology caused by erosion or deposition. The model has variable grid spacing in the water column and fixed bins for stratigraphy, which can extend several meters below the seafloor. We embedded the HSM-3D grid in the ROMS domain to resolve length scales of ~0.1 km, while incorporating information about the larger scale mean circulation and wave fields.

The CST model simulates sedimentation over decades and millennia by parameterizing sediment dynamics in terms of time-averaged and spatially averaged relationships that are consistent with long-term system forcing (Cowell et al., in press). The CST model represents a number of sedimentary systems including the river watershed, estuary, inlet, beach/surf zone, and shoreface/shelf systems (see Pratson et al., this issue).

RESULTS

Meteorology and Wave Models

Wind fields and air-sea heat fluxes derived from both meteorological models COAMPS and LAMI matched each other and field measurements (e.g., winds measurements offshore Venice) in a broad sense (correlation ~0.65; error in amplitude response ~10 percent), but differed in the details (Cavaleri, 1999). Compared to the coarser resolution runs, the highest-resolution COAMPS nest (4 km) demonstrated better skill in producing the spatial pattern of Bora winds, and this led to improvements in modeled wind-forced ocean currents (Pullen et al., 2003). These wind patterns also seem to be captured by LAMI. Some of the small-scale structure is deterministic and reflects improved resolution of orographic effects, but some is random and can degrade single-point correlations between model results and measurements (Signell et al., in press). Wave fields and ocean heat content naturally integrate meteorological forcing; good agreement among measured and modeled ocean temperatures, waves, and currents in the Adriatic Sea model suggests the meteorological models were generally accurate.

COAMPS/NCOM simulations demonstrate the advantages of two-way coupling, where more accurate water temperatures improve the parameterizations for atmospheric boundary layer structure and heat fluxes (Figure 3). But the one-way LAMI/ROMS simulations seem to capture key aspects of the oceanic response to atmospheric forcing, and produced heat fluxes and sea-surface temperatures that fell within the uncertainty of preliminary estimates derived from five cloud-free satellite images and *in situ* temperature data (Figure 3b). Atmospheric forcing is the most important input to our sediment-transport models in the Adriatic Sea and an ongoing research topic.

The wave climate in winter 2002 to 2003 was dominated by a few Sciroccos and a series of Bora wind events. Maxi-

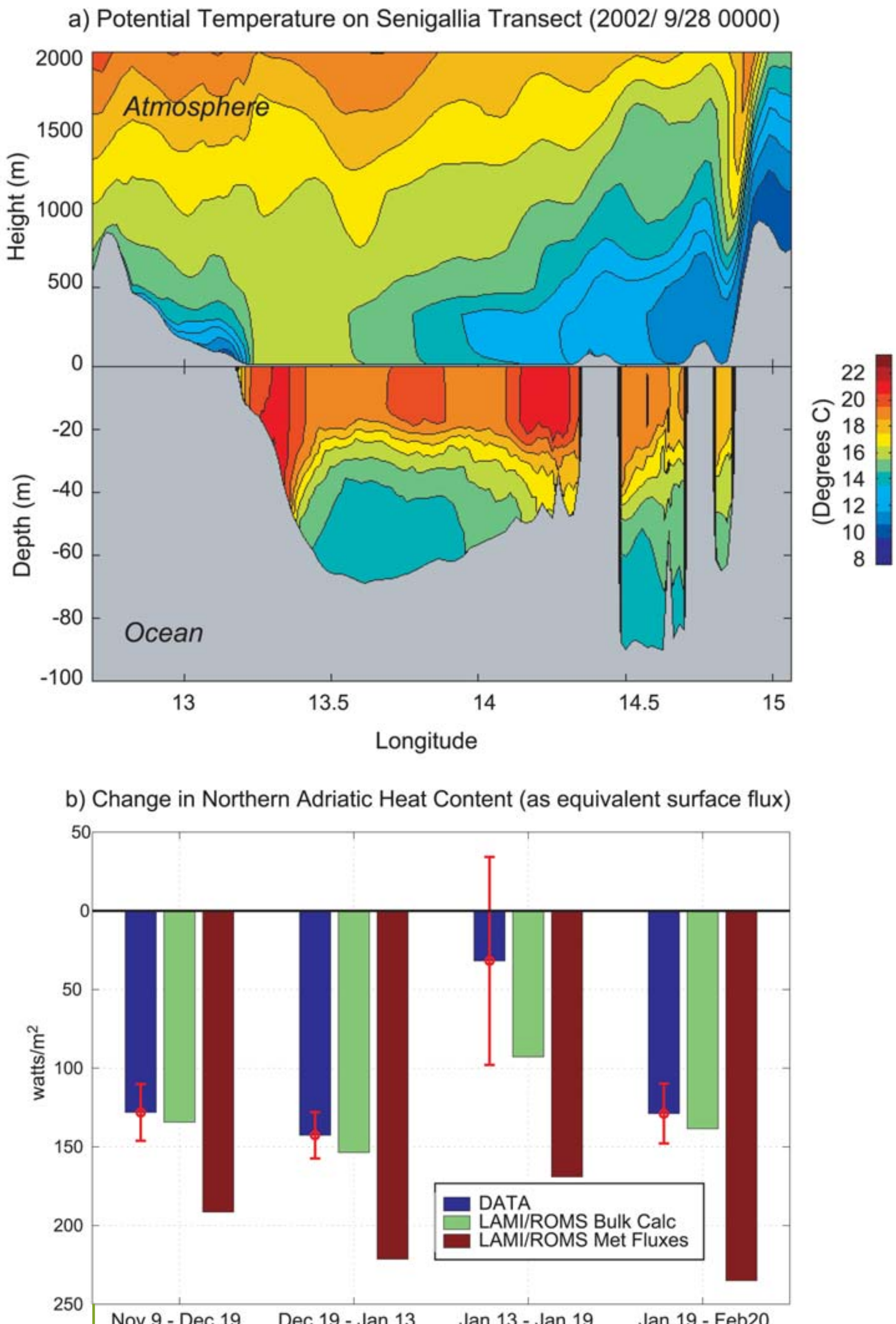


Figure 3. (a) As cold Bora winds cross the Adriatic, they flow over surface waters that are ~10 degrees warmer. This induces vigorous air-sea exchange as the atmosphere extracts heat from the ocean. The vertical contour plot shows COAMPS/NCOM two-way coupled potential temperature at the beginning of a Bora. (b) Bulk heat transfer rates calculated by ROMS fall within error bounds around fluxes estimated from satellite and *in situ* temperature data, but LAMI algorithms overpredict rate of heat transfer.

mum modeled waves reached 5 m (significant wave height) in open waters of the northeast Adriatic during a Scirocco that inundated Venice lagoon with the sixth highest aqua alta (storm surge) in the last 60 years (more information available at Centro Previsioni e segnalazioni Maree, Comune di Venezia; http://www.comune.venezia.it/maree/). Bora events were remarkable for their spatial structure (Figure 4). Comparisons of SWAN model hindcasts with Italian buoy records indicate the model captures most of the features in the records of wave height. Modeled near-bottom

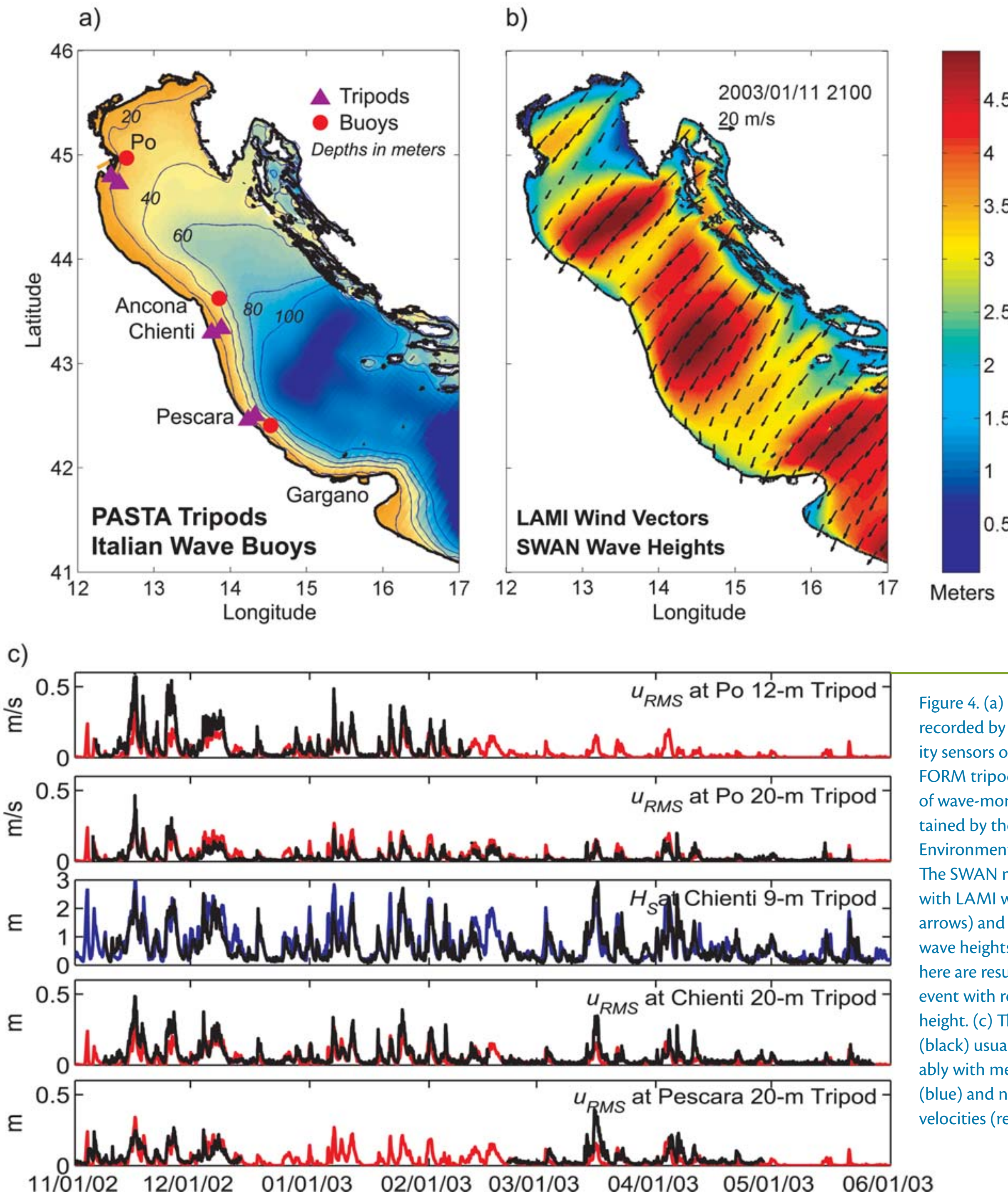


Figure 4. (a) Wave data were recorded by pressure and velocity sensors on the EuroSTRATAFORM tripods, and by a network of wave-monitoring buoys maintained by the Italian Agency for Environmental Protection. (b) The SWAN model was forced with LAMI wind fields (black arrows) and produced fields of wave heights. The colors shown here are results for a January Bora event with red = 5 m significant height. (c) The model results (black) usually compare favorably with measured wave heights (blue) and near-bottom orbital velocities (red).

wave orbital velocities also agree fairly well with PASTA tripod measurements, but there are some intriguing differences during some events (Figure 4) that may be related to incorrect wind forcing or problems with swell dissipation in SWAN (see Rodgers et al., 2003).

Circulation, Sediment-Transport, and Stratigraphy Models

Modeled circulation in the Adriatic agreed well with the extensive data collected in 2002 to 2003. The mean flow, driven by winds and buoyancy input, matches circulation described by earlier drifter studies (Poulain, 2001) and recent modeling efforts (e.g., Pullen et al., 2003). Detailed comparison during Bora events (Figure 5) indicates that the model captures complex circulation patterns. Modeled transport in the WACC was compared with estimates made from

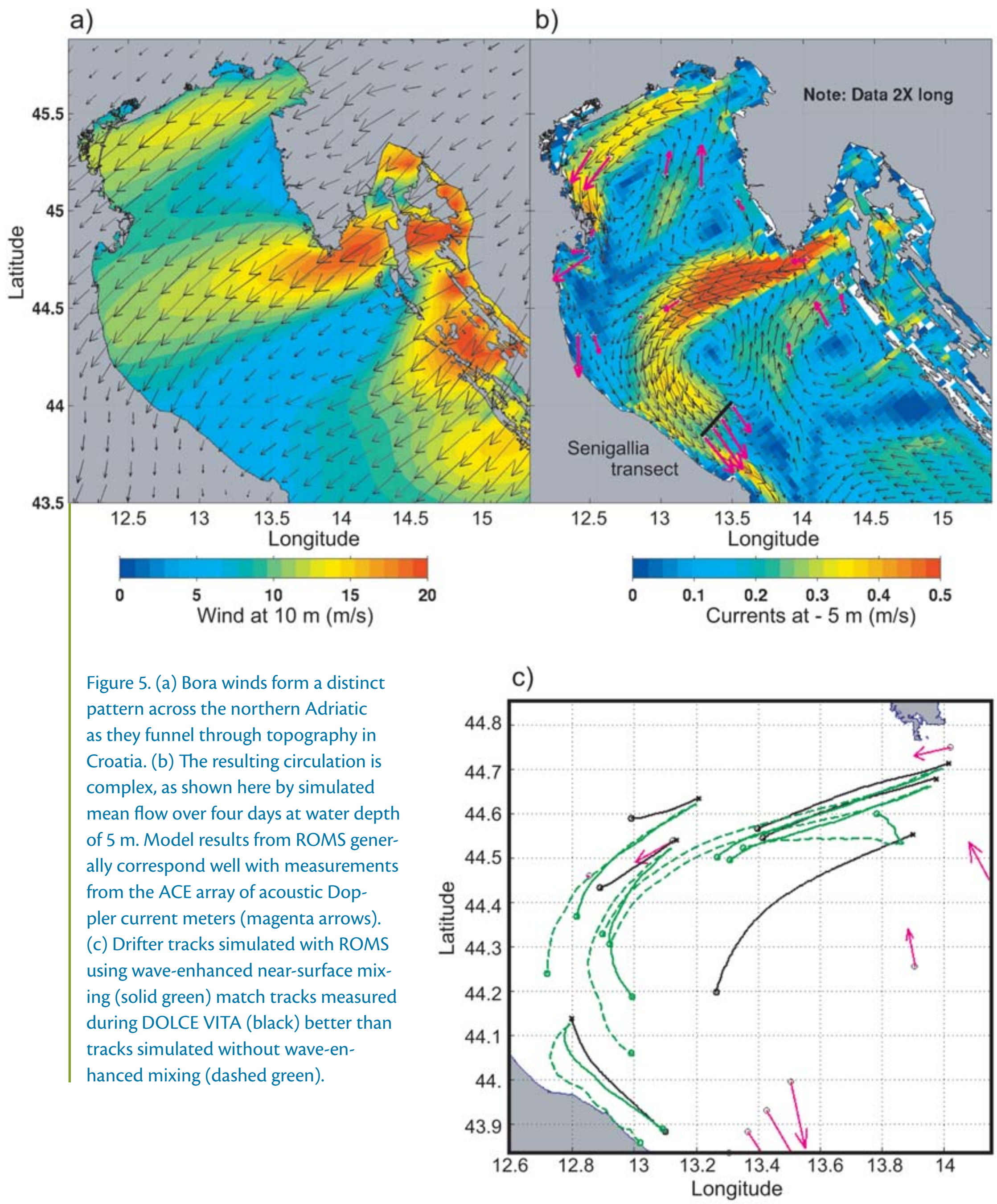


Figure 5. (a) Bora winds form a distinct pattern across the northern Adriatic as they funnel through topography in Croatia. (b) The resulting circulation is complex, as shown here by simulated mean flow over four days at water depth of 5 m. Model results from ROMS generally correspond well with measurements from the ACE array of acoustic Doppler current meters (magenta arrows). (c) Drifter tracks simulated with ROMS using wave-enhanced near-surface mixing (solid green) match tracks measured during DOLCE VITA (black) better than tracks simulated without wave-enhanced mixing (dashed green).

four acoustic Doppler current profiles (ADCPs) off Senigallia (Figure 6). The timing of modeled transport events agreed closely with observations, but the peaks of the events were underestimated. Overall, the modeled mean transport was about 20% lower than the mean inferred from measurements on this transect. Sediment transport is strongly nonlinear, however, and the impact of errors in circulation during specific events is under investigation.

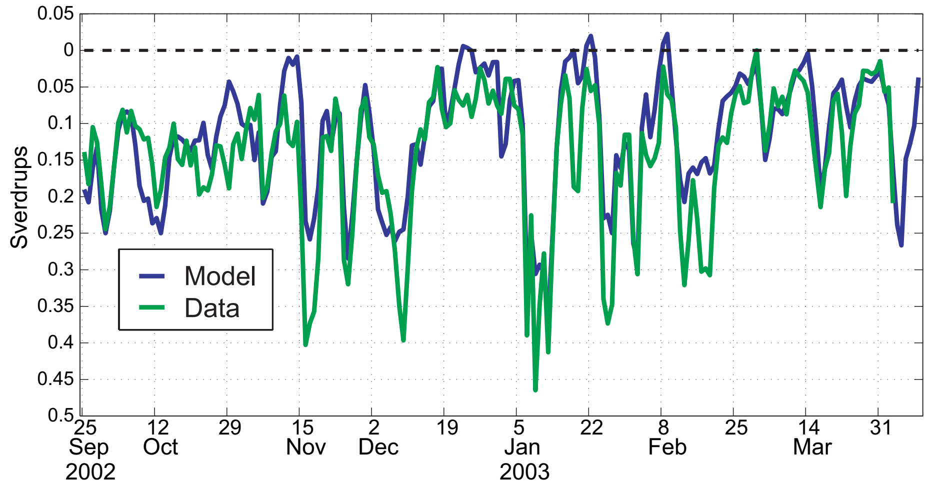


Figure 6. The western Adriatic current causes southward water transport along the Italian coast. Model results (blue) match the timing and often the magnitude of transport estimated from an array of four acoustic Doppler current profiles on a transect near Senigallia (see Figure 5b).

Model simulations of river-supplied sediment naturally indicated that rapid-settling material tends to accumulate near the river mouths (particularly the Po), and that unflocculated material is transported farther along the coast and accumulates in elongated deposits near the shelf edge (Figure 7). The depositional pattern produced by a model simulation for winter 2002 to 2003 mimics aspects of the long-term depositional pattern observed in Holocene stratigraphy. Specifically, deposition on the Po delta, near the Apennine river mouths, and near the shelf edge north of the Gargano promontory occurs where late Holocene deposits are thickest. Typical results from the HSM-3D model showed depositional patterns that indicate alongshore transport produces coalescing clinoforms off the Apennine rivers. Larger-scale features that develop over millennia are predicted with the CST model (Pratson et al., this issue). The encouraging agreement suggests that the linked system of models incorporate the key mechanisms for transport and delivery of sediment from shelf environments to depocenters located farther south in deeper water. Work is ongoing to investigate the sensitivity of these patterns to winds, settling velocity, variations in erosion formulae, and other parameters. These sensitivity studies will help us understand the weak links in the overall modeling system.

SEDIMENT-TRANSPORT MECHANISMS

Measurements and model simulations of winter conditions in the Adriatic showed that near the mouth of the Po River, rapid accumulation after floods produces ephemeral deposits of sediment that are subsequently remobilized by waves to form density flows. This was observed on three occasions in 2002 to 2003, and these fluid-mud flows moved sediment from ephemeral shallow-water deposits beneath the river plume to deeper water. These results lead us to believe that fluid mud processes may control the geometry of deltaic deposits; EuroSTRATAFORM researchers are developing models to calculate the resulting depth profiles.

The mechanisms that move Po River sediment hundreds of kilometers to depocenters off the Gargano promontory must be associated with a larger-scale phenomena like the western Adriatic coastal current. The WACC is partially buoyancy driven, a forcing that increases during floods when suspended-sediment supply is highest. Observations and models demonstrate that Po water flows around the Gargano Promontory, but because the sediment aggregates and settles rapidly, it is unlikely that much remains in suspension for the entire journey. It appears that Po sediments must travel southward in a series of episodic transport events, and that wave-induced resuspension is important in these hops (Wang and Pinardi, 2002).

Bora winds generate large waves in the western Adriatic and enhance flow in the WACC, so it is reasonable to expect that correlated wave resuspension and stronger-than-average southward flow in the WACC combine to generate southward sediment flux. However, our data and

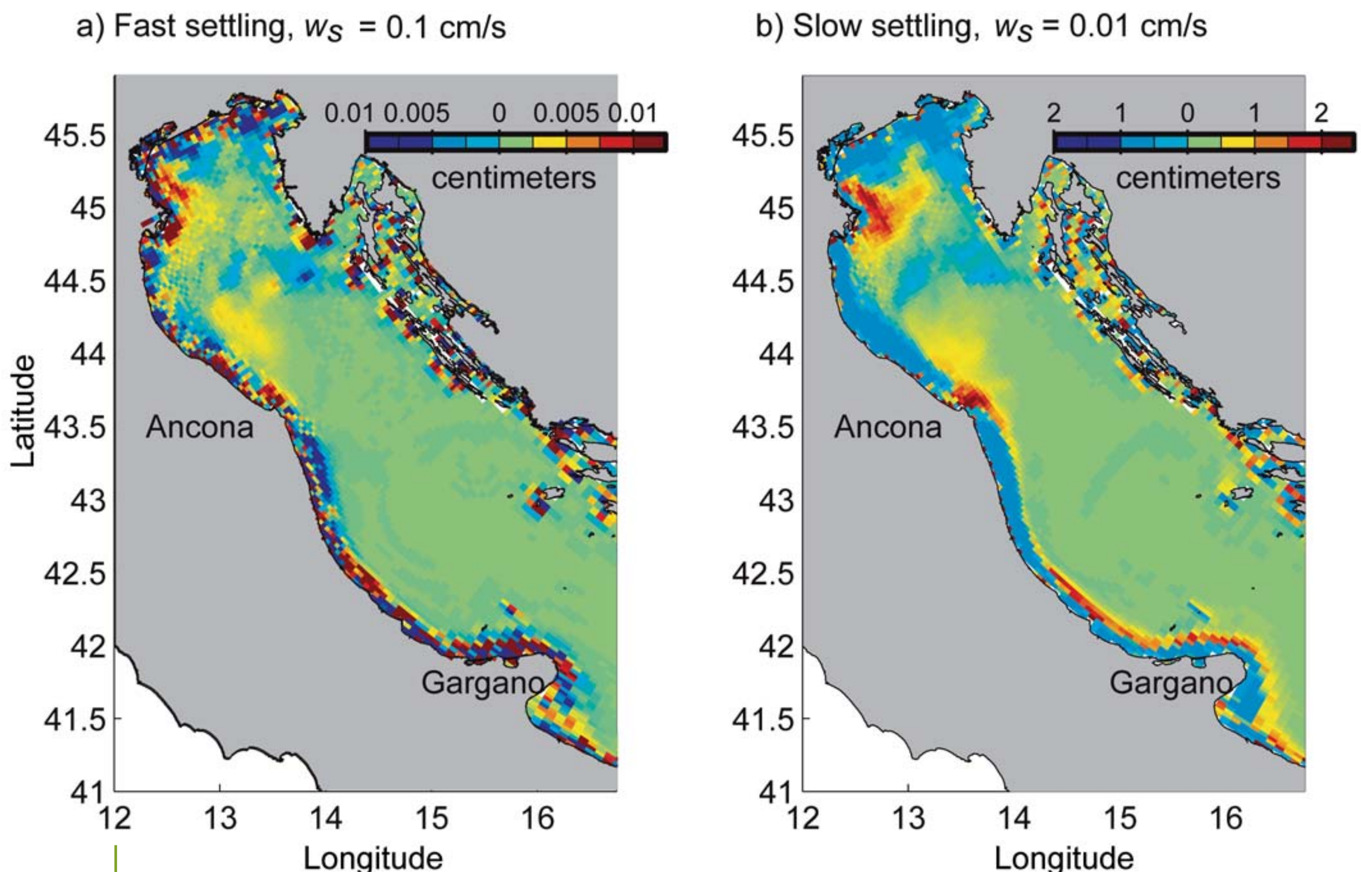


Figure 7. (a) Results of sediment-transport simulations for nine months (November 2002 – May 2003) reveal patterns of deposition for (a) fast-settling aggregates (1 mm/s) and (b) slow-settling particles (0.1 mm/s) supplied by rivers. The depositional patterns are dominated by local deposition of material from the Po River in the northern Adriatic and by southward dispersal of Apennine sediment along much of the Italian coast. Deposition is enhanced north of Ancona and the Gargano promontory, similar to the pattern seen in the Holocene thicknesses.

model results show only a weak correlation between wave height and southward flow velocity in the WACC on the Chienti transect. The best correlation between WACC flow at Chienti and modeled wind is with wind near Trieste, nearly 200 km from the Chienti transect. This is evidence that wind-driven circulation in the northern Adriatic has a very large scale, and that waves are not necessarily collocated with Bora-enhanced southward flow. The model indicates that Scirocco winds can generate large waves that resuspend sediment without reversing flow in the WACC, suggesting that southward transport is likely to prevail regardless of the timing or mechanisms for resuspension.

The system of models we have applied to the Adriatic Sea incorporates processes at scales ranging from hours and kilometers up to millennia and basin dimensions. Large collaborative field efforts such as those in the Adriatic Sea during 2002 to 2003 are the only viable way to obtain enough synoptic data on waves, currents, and sediment to evaluate such complex models. Although research is ongoing to assess the skill of these models, results from the simulations are already helping us gain a better understanding of the mechanisms that form deposits on the margins of epicontinental seas.

ACKNOWLEDGEMENTS

LAMI products were generously provided by T. Col. Gianni Daddario, Ufficio Generale per la Meteorologia, Rome through our colleagues at ARPA Emilia Romagna. Po River discharge was provided by Alessandro Allodi of the Ufficio Idrografico del Magistrato per il Po (Parma). Support for the EuroSTRATAFORM PASTA experiment, ACE, and Naval Research Laboratory participants was provided by the Office of Naval Research. ACE was a joint research project between Naval Research Laboratory and NATO SACLANTC. COAMPS™ is a trademark of the Naval Research Laboratory. COAMPS simulations were supported by the U. S. Department of Defense MSRC. We thank Mike Kuzmic at Rudjer Boskovic Institute and Mirko Orlic at University of Zagreb for WISE and EACE data; Nadia Pinardi at INGV and University of Bologna for ADRICOSM (supported by the Italian Ministry for Environment) data; Andrea Ogston (University of Washington, Seattle) and Pere Puig (Institut de Ciències del Mar, Barcelona) for PASTA tripod data; Aaron Bever at Virginia Institute of Marine Sciences for his contribution to ROMS runs and figures; and Jim Robb, Brad Butman, and Rob Thieler, all at the U. S. Geological Survey, for helpful comments.

REFERENCES

Booij, N., R.C. Ris, and L.H. Holthuijsen. 1999. A third-generation wave model for coastal regions. Part I: Model description and validation. *Journal of Geophysical Research* 104(C4):7649-7666.

Cattaneo A., A. Correggiari, L. Langone, and F. Trincardi. 2003. The late-Holocene Gargano subaqueous delta, Adriatic shelf: Sediment pathways and supply fluctuations. *Marine Geology* 193:61-91.

Cavaleri, L. 1999. The oceanographic tower Acqua Alta: More than a quarter of a century of activity. *Il Nuovo Cimento* 22C(1):1-111.

Cowell, P.J., M.J.F. Stive, A.W. Niedoroda, D.J.P. Swift, M. Buijsman, R.J. Nicholls, P.S. Roy, G. Kaminsky, J. Cleveringa, C.W. Reed, P.L. deBoer, M. Capobianco, and H.J. deVriend. In press. The coastal-tract: aggregated modeling of low-order coastal change. *Journal of Coastal Research*.

Cushman-Roisin B., M. Gacic, P.-M. Poulain, and A. Artegiani. 2001. *Physical Oceanography of the Adriatic Sea; Past, Present, and Future*. Kluwer Academic Publishers, 304 pp.

Fox, J.M., P.S. Hill, T.G. Milligan, and A. Boldrin. 2004. Flocculation and sedimentation on the Po River Delta. *Marine Geology* 203:95-107.

Fox , J.M., P.S. Hill, T.G. Milligan, A.S. Ogston, and A. Boldrin. In press. Floc fraction in the waters of the Po River prodelta. *Continental Shelf Research*.

Grant W.D., and O.S. Madsen. 1979. Combined wave and current interaction with a rough bottom. *Journal of Geophysical Research* 84(C4):1797-1808.

Hodur, R.M., and J.D. Doyle. 1999. The coupled ocean/atmosphere mesoscale model prediction system (COAMPS). Pp. 125-155 in *Coastal Ocean Prediction*, C.N.K. Mooers, ed. Coastal and Estuarine Studies 56. American Geophysical Union.

Orlic M., M. Kuzmic, and M. Pasaric. 1994. Response of the Adriatic Sea to the bora and sirocco forcing. *Continental Shelf Research* 14(1):91-116.

Poulain, P.-M. 2001. Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999. *Journal of Marine Systems* 29(1-4):3-32.

Pullen, J., J.D. Doyle, R. Hodur, A. Ogston, J.W. Book, H. Perkins, and R. Signell. 2003. Coupled ocean-atmosphere nested modeling of the Adriatic Sea during winter and spring 2001. *Journal of Geophysical Research* 108(C10):3320. doi: 10.1029/2003JC001780.

Rogers, W.E., P.A. Hwang, and D.W. Wang. 2003. Investigation of wave growth and decay in the SWAN model: Three regional-scale applications. *Journal of Physical Oceanography* 33(2):366-389.

Signell, R.P., S. Carniel, L. Cavaleri, J. Chiggiato, J.D. Doyle, J. Pullen, and M. Sclavo. In press. Assessment of wind quality for oceanographic modelling in semi-enclosed basins. *Journal of Marine Systems.*

Sommerfield, C.K., and C.A. Nittrouer. 1999. Modern accumulation rates and a sediment budget for the Eel River shelf, USA: A flood-dominated depositional environment. *Marine Geology* 154(1-4):227-241.

Steppeler, J., G. Doms, U. Schattler, H.W. Bitzer, A. Gassmann, U. Damrath, G. Gregoric. 2003. Meso-gamma scale forecasts using nonhydrostatic model LM. *Meteorology and Atmospheric Physics* 82:75-96. doi: 10.1007/s00703-001-0592-9.

Swift, D.J.P., D.B. Duane, and O.H. Pilkey. 1972. *Shelf Sediment Transport: Process and Pattern*. Dowden, Hutchinson and Ross, Stroudburg, Pennsylvania, 656 pp.

Syvitski, J.P.M., M.D. Morehead, and M. Nicholson. 1998. HYDROTREND: A climate-driven hydrologic-transport model for predicting discharge and sediment loads to lakes or oceans. *Computers & Geosciences* 24(1):51-68.

Traykovski P., W.R. Geyer, J.D. Irish, and J.F. Lynch. 2000. The role of wave-induced density-driven fluid mud flows for cross-shelf transport on the Eel River continental shelf. *Continental Shelf Research* 20:2113-2140.

Wang X. H. and N. Pinardi. 2002. Modeling the dynamics of sediment transport and resuspension in the northern Adriatic Sea. *Journal of Geophysical Research*, 107(C12):3225. doi:10.1029/2001JC001303.

Wheatcroft, R.A., and J.C. Borgeld. 2000. Oceanic flood deposits on the northern California shelf: large-scale distribution and small-scale physical properties. *Continental Shelf Research* 20:2163-2190.