Two-Way Air–Sea Coupling: A Study of the Adriatic

JULIE PULLEN AND JAMES D. DOYLE

Marine Meteorology Division, Naval Research Laboratory, Monterey, California

RICHARD P. SIGNELL

NATO Undersea Research Centre, La Spezia, Italy

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ABSTRACT

High-resolution numerical simulations of the Adriatic Sea using the Navy Coastal Ocean Model (NCOM) and Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) were conducted to examine the impact of the coupling strategy (one versus two way) on the ocean and atmosphere model skill, and to elucidate dynamical aspects of the coupled response. Simulations for 23 September–23 October 2002 utilized 2- and 4-km resolution grids for the ocean and atmosphere, respectively. During a strong wind and sea surface cooling event, cold water fringed the west and north coasts in the two-way coupled simulation (where the atmosphere interacted with SST generated by the ocean model) and attenuated by approximately 20% of the cross-basin extension of bora-driven upward heat fluxes relative to the one-way coupled simulation (where the atmosphere model was not influenced by the ocean model). An assessment of model results using remotely sensed and in situ measurements of ocean temperature along with overwater and coastal wind observations showed enhanced skill in the two-way coupled model. In particular, the two-way coupled model produced spatially complex SSTs after the cooling event that compared more favorably (using mean bias and rms error) with satellite multichannel SST (MCSST) and had a stabilizing effect on the atmosphere. As a consequence, mean mixing was suppressed by over 20% in the atmospheric boundary layer and more realistic mean 10-m wind speeds were produced during the monthlong two-way coupled simulation.

1. Introduction

Global climate simulations (e.g., Ma et al. 1996) as well as hurricane simulations (Li et al. 2002) typically employ relatively coarse-resolution (20–200 km) coupled air–sea models with varying levels of physical approximations, and often out of necessity focus on regions with limited observations. In this study, we conduct realistic coastal mesoscale high-resolution (<5 km) air–sea coupled model simulations that dynamically represent the feedback of finescale SST structure to the atmosphere, and we draw on observations of comparable resolution to evaluate model performance.

The impact of local SST gradients on the overlying atmosphere has been documented in ship-based observations for over 20 years. Sweet et al. (1981) recorded the acceleration of near-surface winds over warm water in the Gulf Stream region due to the destabilization of the marine atmospheric boundary layer (ABL). Other field campaigns in the Atlantic [the Frontal Air–Sea Interaction Experiment (FASINEX) and the Joint Air–Sea Interaction experiment (JASIN)] measured how mesoscale SST gradients affected ABL depth and vertical coupling throughout the boundary layer (Weller 1991; Pollard 1978).

Recent scatterometer data have afforded an unprecedented global view of how the atmosphere adjusts to the ocean on scales greater than 25 km (Chelton et al. 2004; Xie 2004). Incident surface winds decelerate in the eastern equatorial Pacific above the cold pool waters (Hayes et al. 1989; Chelton et al. 2001). Similar effects have been observed in the Arabian Sea (Vecchi et al. 2004) and remotely sensed in the Southern Ocean, Kuroshio, and Gulf Stream regions (O'Neill et al. 2003; Nonaka and Xie 2003; Park and Cornillon 2002).

Corresponding author address: Dr. Julie Pullen, Marine Meteorology Division, Naval Research Laboratory, 7 Grace Hopper Ave., Monterey, CA 93943.
E-mail: pullen@nrlmry.navy.mil

Internal boundary layers (IBLs) typically develop as air moves across a discontinuity in surface properties (Garratt 1990). The dynamical response of the ABL to small-scale temporal and spatial variations in sea surface temperature has been investigated in detailed process-oriented modeling studies. Using a 1D framework, Koracin and Rogers (1990) simulated stable IBL formation as air encountered a 2°C colder ocean front. As the IBL developed, turbulent exchanges between the cloud layer and the surface became decoupled and surface stress was reduced by 45%.

The recent high-resolution 3D modeling studies of Song et al. (2004), using a temporally fixed and simple SST, were designed to aid the selection of a boundary layer parameterization to reproduce atmospheric soundings from the FASINEX observational program. They found a 20% decrease in surface wind speed as the air moved across a 2°C cooler (10 km wide) ocean temperature front. The reduced wind speed was due to the formation of a stable IBL.

The air–sea interaction studies surveyed above have been largely limited to observations in open-ocean settings and to models invoking idealized or quasi-idealized assumptions. The ongoing Coastal Boundary Layers/Air–Sea Transfer (CBLAST) field and modeling campaign is yielding important insight into complex coastal air–sea interaction processes. Vickers and Mahrt (2004) analyzed 10-m aircraft flight data and discovered that for a 1°–2°C increase of SST, mean wind speed increased by 6% (with minimal observational spread). SST decreases of 1°–2°C led to wind speed reductions of approximately 4%, but there was more spread in wind speed response due to increased sampling errors in stable conditions. Preliminary simulations of the conditions at the CBLAST study site off the east coast of the United States motivated the incorporation of an improved surface flux parameterization in the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS[1]; Wang et al. 2002), which we utilize in the coupled simulations presented here.

The Adriatic Sea is well suited to coastal air–sea interaction studies because strong northeasterly "bora" winds occur frequently and induce large upward heat fluxes from the shallow waters of the northern Adriatic (Smith 1987). The circulation of the northern Adriatic (Fig. 1) consists of the southeastward-flowing west Adriatic Current (WAC) and the opposed east Adriatic Current (EAC). The WAC, EAC, and cyclonic gyres in the southern Adriatic are persistent year-round. Po

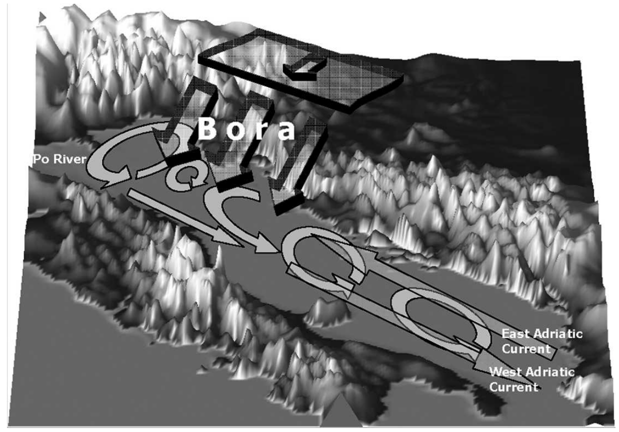

FIG. 1. Representation of major northern Adriatic near-surface circulation features in the ocean and atmosphere during bora events. The southern Adriatic features pictured are present in all seasons. The schematic draws on results from Poulain (2001) and Orlic et al. (1994).

River water is transported down the Adriatic in the WAC in times of low outflow (Barale et al. 1986). Cool water from the eastern side of the Adriatic around the Croatian Islands crosses the basin just below the Istrian Peninsula and joins the WAC, which is a cold, swift current. A pronounced "Istrian front" separates the warmer waters to the south from the cold waters of the northern Adriatic, especially in wintertime.

Isolated evidence from observations and previous modeling studies (Orlic et al. 1994; Paklar et al. 2001) suggested that a gyre circulation dominated the far northern Adriatic in winter. Pullen et al. (2003) used EOFs to document the intrinsic pattern of ocean response to bora forcing over several months, which is driven by the wind stress curl (Orlic et al. 1994). In the dominant mode, a cyclone stirs waters along the north coast, while a smaller anticyclonic cell circulates the waters off the Istrian Peninsula, as shown in Fig. 1. Water entering the Adriatic at the mouth of the Po River is entrained into the cyclonic gyre in the northern Adriatic (Paklar et al. 2001), particularly when discharge rates are high. In addition to the Po River water, there are several smaller rivers along the northern Adriatic coast that contribute to runoff.

Fall is typically a transition season when stratified waters are vertically mixed through the repeated experience of bora episodes. The combined effects of river runoff, upward heat flux, and wind-induced currents create a cold band of water along the northern and western Adriatic as the energetic bora season gets under way. Subsequently, the wintertime currents in the northern Adriatic become predominantly barotropic (Zavatarelli et al. 2002).

[1] COAMPS is a registered trademark of the Naval Research Laboratory.

In an idealized 2D study of bora winds, Enger and Grisogono (1998) evaluated the influence of relatively higher or lower uniform ocean temperature on the bora's descent in the lee of the mountains out over the sea. They found that a constant warmer ocean temperature (relative to land) promoted bora extension out over the Adriatic because the buoyancy flux sustained the supercritical flow in the bora mountain wave; however, the maximum wind speed was unaffected. Though their work was illuminating in terms of the response of the atmospheric bora structure to gross land–sea temperature differences, it did not address the influence of spatial variations of SST on atmospheric flow.

In high-resolution studies of the Adriatic using the Navy Coastal Ocean Model (NCOM; 2-km resolution) forced by COAMPS (4- and 36-km resolution), Pullen et al. (2003) documented the emergence of realistic finescale bora features with enhanced atmospheric model resolution. Velocity measurements in the ocean and atmosphere were compared with model fields from a 125-day simulation. The superior atmospheric forecasts produced by the 4-km nest relative to the 36-km nest also improved the skill of the ocean model in generating wind-forced currents when evaluated against Acoustic Doppler Current Profiler (ADCP) observations.

Motivated by the goal of assessing the impact of a dynamically evolving ocean on the overlying atmosphere, we build on our prior studies in the Adriatic by extending the modeling system to include two-way coupling (i.e., the atmosphere model interacts fully with the ocean model). Our approach differs from prior coupled simulations of the Adriatic. In Loglisci et al. (2004), the ocean model was initialized with climatology, which created challenges in comparing the 2-day-long simulations with ocean temperature measurements. In addition, Loglisci et al. (2004) did not investigate the impact of air–sea coupling on the atmosphere.

The focus of our research is on evaluating the impact of two-way coupling relative to one-way coupling, and on exploring the nature of the mutual adjustment in the ocean and atmosphere that is afforded by the two-way coupling. The paper first describes the modeling system extensions in section 2, and then in section 3 details how the coupled ocean and atmosphere evolve during a bora. Results of month-long one- and two-way coupled simulations are compared with observations in section 4, and contrasted with each other in section 5. The discussion and conclusions are contained in section 6.

2. Model configuration

The simulations described here for the time period 20 September–23 October 2002 use a similar model configuration to Pullen et al. (2003). The 4-km-resolution inner nest of the triply nested COAMPS domain, however, is allowed to interact with the SSTs generated by the 2-km-resolution ocean model, NCOM, as detailed below. In addition, while the previous simulations used the Louis et al. (1981) surface flux parameterization, these simulations use an "enhanced Louis" scheme, which produces more realistic heat fluxes, especially in unstable atmospheric regimes (Wang et al. 2002).

As explained in Pullen et al. (2003), NCOM utilizes 50 vertical levels (36 of which are sigma levels) with enhanced resolution in the surface and bottom boundary layers. The ocean model domain covers the whole Adriatic and is aligned along the axis of the basin. The innermost COAMPS domain consists of 30 terrain-following vertical levels and a horizontal grid that extends from 39.6° to 47.3°N and from 10.4° to 20.6°E.

We chose the SST analysis that COAMPS routinely uses in operational and research applications as the bottom boundary for the one-way coupled simulation (Chen et al. 2003). It is, for instance, the SST utilized in the atmospheric reanalyses presented in Pullen et al. (2003). This product is sensitive to satellite data availability, cloud cover, and spatial correlation scales used in the data processing.

At a 12-h frequency, the atmospheric COAMPS reanalysis assimilates quality-controlled data from radiosondes, surface stations, aircraft, and satellites using a 3D multivariate optimum interpolation (MVOI) incremental update procedure (Hodur 1997; our Fig. 2a). The COAMPS system produces 6-h forecasts, at the start of which the atmospheric model receives an updated SST analyzed using an optimum interpolation (OI) of satellite observations (one way coupled) or an ocean model–evolved SST (two way coupled). The two-way coupled SST is bilinearly interpolated from the 2-km ocean grid to the 4-km atmosphere grid. Analyzed SSTs are inserted in regions of the Mediterranean that are covered by the COAMPS nest but not by the NCOM domain. The boundary conditions for COAMPS are derived from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model.

The 2-km-resolution ocean model, NCOM (Martin 2000), is forced directly with bilinearly interpolated hourly momentum and heat fluxes from one- and two-way coupled COAMPS. The one- and two-way coupled atmospheric fluxes diverge because of the different SST fields they receive. In the two-way coupled simulation, the feedback with the ocean model modulates the fluxes.

River discharge from 22 sources throughout the Adriatic (including the Po River) is introduced as additional forcing in these simulations. Po River discharge

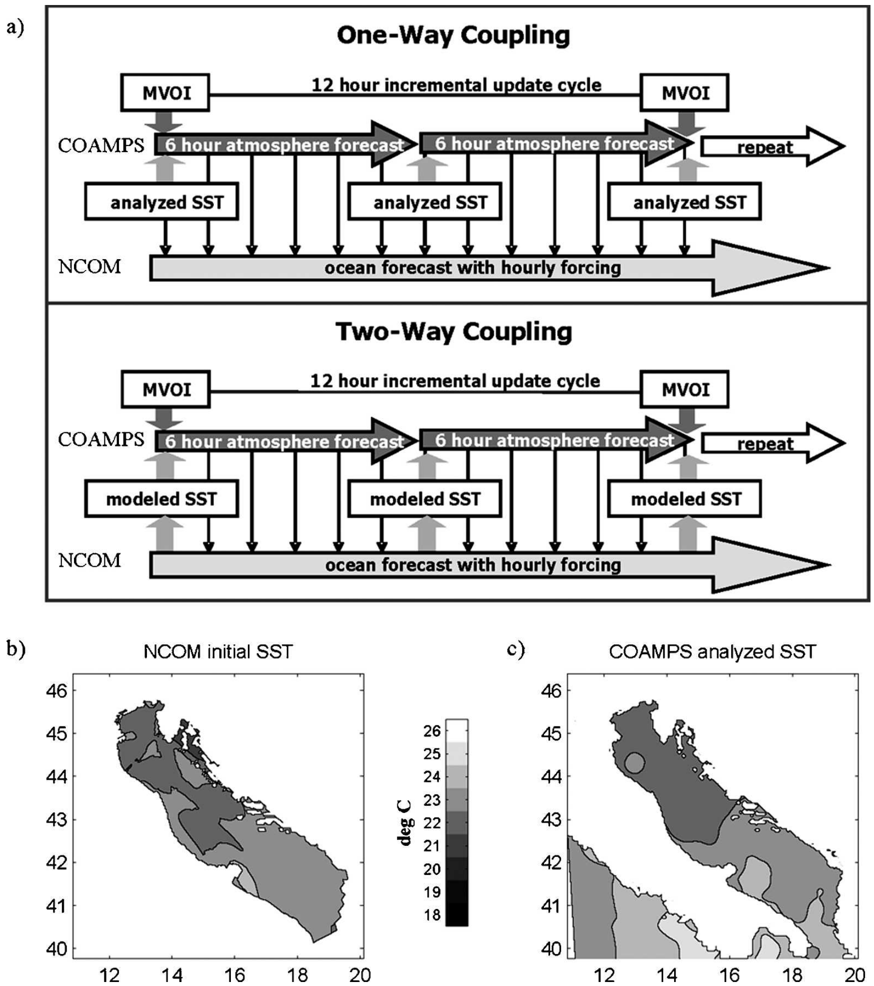

FIG. 2. (a) Schematic drawing of coupling procedure. (b) SST for 0600 UTC 20 Sep 2002 from an OI of CTD casts, used in the two-way coupled simulation. The full 3D *T*/*S* fields were used to initialize NCOM. (c) COAMPS-analyzed SST from an OI of satellite observations valid during the 0600 UTC 20 Sep 2002 update cycle, used at the start of the one-way coupled simulation.

can differ by several degrees Celsius from the ambient water. The river temperature is held constant at the monthly climatological value. For October, the Po River temperature was 20°C. Early in the simulation the river water was cooler than ambient water, while later the river runoff became warmer than the adjacent waters. During the month of this simulation, Po River discharge was fairly uniform with a mean (standard deviation) of 1467 (315) $m^3\,s^{-1}$. The discharge closely matched the climatological annual average of 1547 $m^3\,s^{-1}$ (Raicich 1994). The peak discharge of 2240 $m^3\,s^{-1}$ occurred on 14 October.

To initialize the ocean model, an OI was performed on numerous conductivity–temperature–depth (CTD) casts in the Adriatic to generate 3D temperature and salinity fields valid for 20 September 2002. [The CTD data is from the coincident North Atlantic Treaty Organisation (NATO) Undersea Research Centre R/V *Alliance* and the University of Ancona R/V *Dallaporta* cruises.] The ocean velocity fields were spun up using a diagnostic model simulation forced by winds from the prior 5 days, in order to permit the currents to adjust to the initial temperature and salinity (*T*/*S*) fields. At the initialization time, the surface temperature from the analyzed in situ data (used to initialize NCOM) was in reasonable agreement with the SST from analyzed satellite observations used as a bottom boundary by one-way coupled COAMPS (Figs. 2b,c). So the initial surface temperature in the ocean model used in the two-way coupled simulation did not differ appreciably from the SST utilized by the one-way coupled atmospheric model at the start of the simulation. Apart from the OI that generated the initial ocean state, data assimilation was turned off in the ocean model simulations.

Our one- and two-way coupled simulations were run for over 30 days, but we focus on the time period from 23 September to 23 October in the analysis. The simulations contain several pronounced bora events, including one on 29 September 2002 that is examined in the next section.

3. Coupled ocean–atmosphere bora response

A snapshot from the two-way coupled model illustrates the basic understanding of the bora structure that has emerged from observations and modeling studies (Jiang and Doyle 2005; Grubisic 2004; Smith 1987; our Fig. 3a). Bora events are generated by synoptic pressure systems interacting with orography. During a bora event, cold northeasterly winds flow over the Dinaric Alps and result in large-amplitude gravity waves and wave breaking along the western slopes near the Adriatic shore. The strongest winds are found in the lee of mountain gaps, where wave breaking is minimized and bora "jets" are orographically accelerated. The gap in topography on the mainland, to the northeast of the Croatian Islands (between the 1000-m contour lines), accelerates flow across Kvarner Bay. There is also a wind speed maximum over the southern Gulf of Trieste in the lee of Postojna Pass. The highest terrain forces larger-amplitude waves that overturn and break, thereby inducing a downstream "wake" of low-speed winds such as is found off of the Istrian Peninsula. The jets and wakes are organized in bands perpendicular to the axis of the Adriatic and possess a characteristic width of less than 25 km (Grubisic 2004).

The rapidly moving air in the bora flow is typically 10°C colder than the sea, creating unstable atmospheric conditions. The near-surface air warms in the fast-moving winds through air–sea interaction processes as it transits the basin in contact with the warmer sea temperatures. An additional factor in the two-way coupled air–sea interaction is the circulation of the waters in the northern Adriatic (Fig. 3b). The counterclockwise cell serves to transport warm waters from the area adjacent to the Istrian Peninsula northward and westward, thereby exposing the bora jet to comparatively warmer water over time. However, the time scale for ocean advection is longer than the time of transit of an air parcel. We will return to the influence of the ocean circulation in section 5.

The ABL depth over the ocean is approximately 1 km, in agreement with Grubisic (2004; our Fig. 3c). Above the bora flow, the unstable convective marine ABL is capped by a temperature inversion. In the ocean, large upward heat flux leads to a 10–20-m-deep surface mixed layer as evidenced by the vertical temperature contours.

Elevated heat flux in the northern Adriatic follows a distinct spatial pattern due to the high winds in the bora jets in both the one- and two-way coupled simulations (Fig. 4). Enhanced bora-forced heat fluxes extend across the basin in the one-way coupled simulation, while heat fluxes are attenuated midbasin in the two-way coupled simulation. Locally, the latent and sensible heat fluxes in the northernmost bora jet drop by 19% and 22%, respectively, on the west side of the Adriatic. The mutual adjustment of the air and ocean temperature controls the amount of heat that can be removed from the ocean in the two-way coupled simulation, leading to generally smaller upward heat fluxes. One-way coupled latent heat flux exceeds two-way coupled latent heat flux by 10%, while one-way coupled sensible heat flux exceeds two-way coupled sensible heat flux by 12%, using a spatial mean over the domain shown. Mean latent heat fluxes are approximately 70% greater than sensible heat fluxes in both experiments.

Differences in surface heat flux are related to variations in SST (Table 1a). A (National Oceanic and Atmospheric Administration) *NOAA-16* multichannel SST (MCSST) postbora image from 1 October reveals the complex structure in the observed surface distribution of temperature (Fig. 5a). Contemporaneous near-surface CTD casts (shown with solid-colored circles) provide independent ground truthing and agree well with the satellite-derived temperatures.

The analyzed SST (which uses large correlation scales due to a lack of data at finescales) does not retain the tight spatial structure, and fails to display the cold regions concentrated behind the Croatian Islands and along the northern and western Adriatic coasts (Fig. 5b). Overall, the mean temperature in the analyzed field is too warm.

In the span of 11 days since initialization (Figs. 2b,c), the modeled SST has undergone dramatic changes. In our configuration, heat fluxes for the one-way coupled simulation are computed using the analyzed SST. When applied to the ocean model using one-way coupling, these heat fluxes lead to an SST field that is too cold (Fig. 5d). However, in the two-way coupled simulation the atmospheric model interacts with the modeled SST, leading to reduced upward heat flux relative to the one-way coupled simulation (as seen previously in Fig. 4) and, consequently, a more realistic SST as measured by the mean bias (MB) and rmse (Fig. 5c; Table 1b).

At the Acqua Alta observing platform (location shown in Fig. 3a), the intensity of distinct cold bora wind events pulses in the lower ABL over a 6-day period (Fig. 6a). The ocean is progressively cooled by trans-

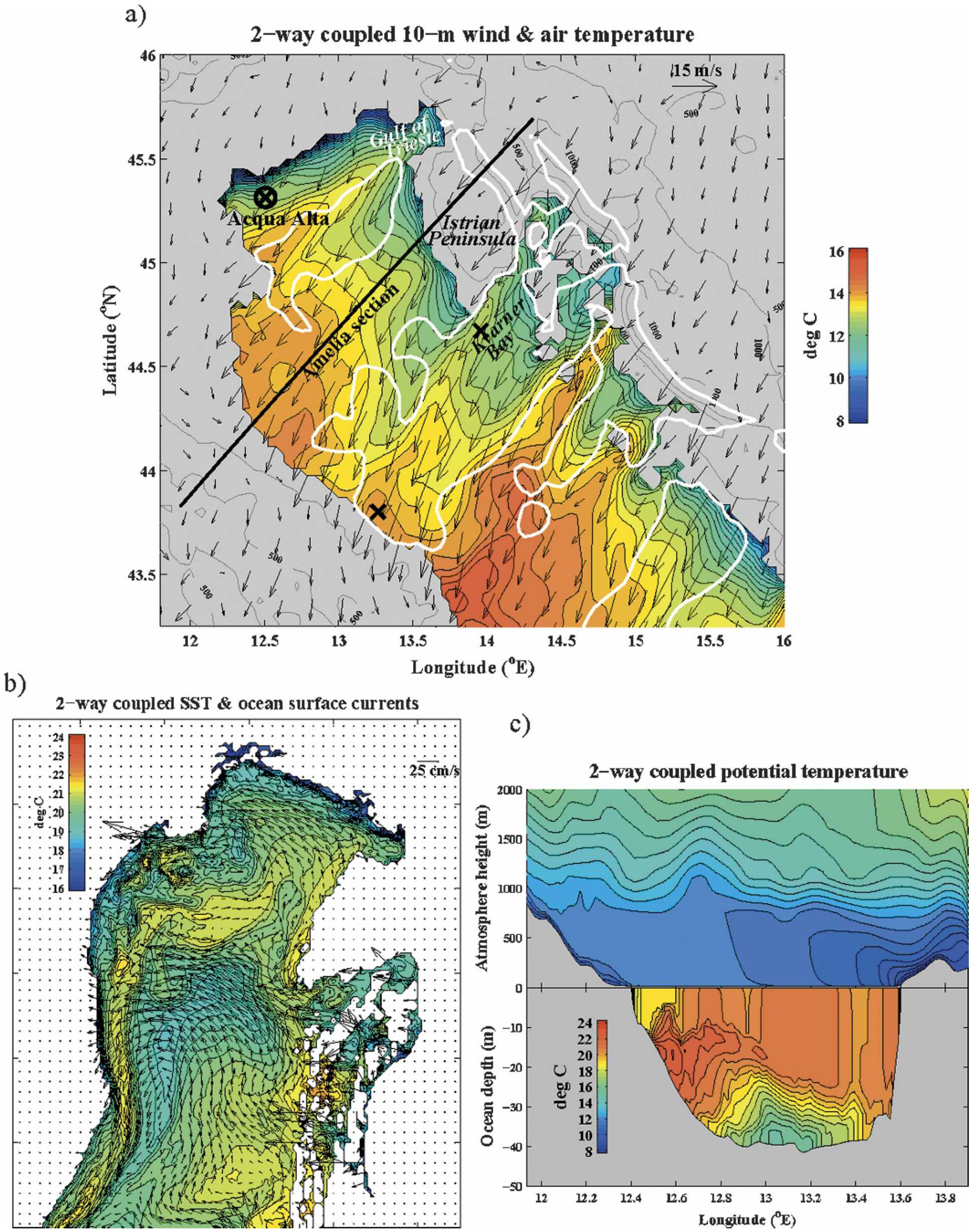

FIG. 3. (a) The 10-m wind velocity arrows at every fourth grid cell and color-contoured 10-m air temperature on 0600 UTC 29 Sep 2002 for the two-way coupled simulation. A wind speed of 10 m s^{-1} is contoured in white. Topographic isobaths of 100, 500, 1000, 1500, and 2000 m are shown. (b) SST on 0600 UTC 29 Sep 2002 and surface currents averaged over 24 h (from 1200 UTC 28 Sep to 1200 UTC 29 Sep) shown at every third grid cell. (c) Cross section of two-way coupled ocean and atmosphere potential temperature through the Amelia section on 0600 UTC 29 Sep 2002.

ferring heat to the atmosphere. Compared to the one-way coupled simulation, the two-way coupled ocean is warmer, while the two-way coupled atmosphere is cooler (as denoted by the areas outside of the solid white "zero difference" contour). The short period when the two-way coupled ocean simulation is cooler than the one-way coupled ocean simulation relates to a mismatch between the models in the position of the tem-

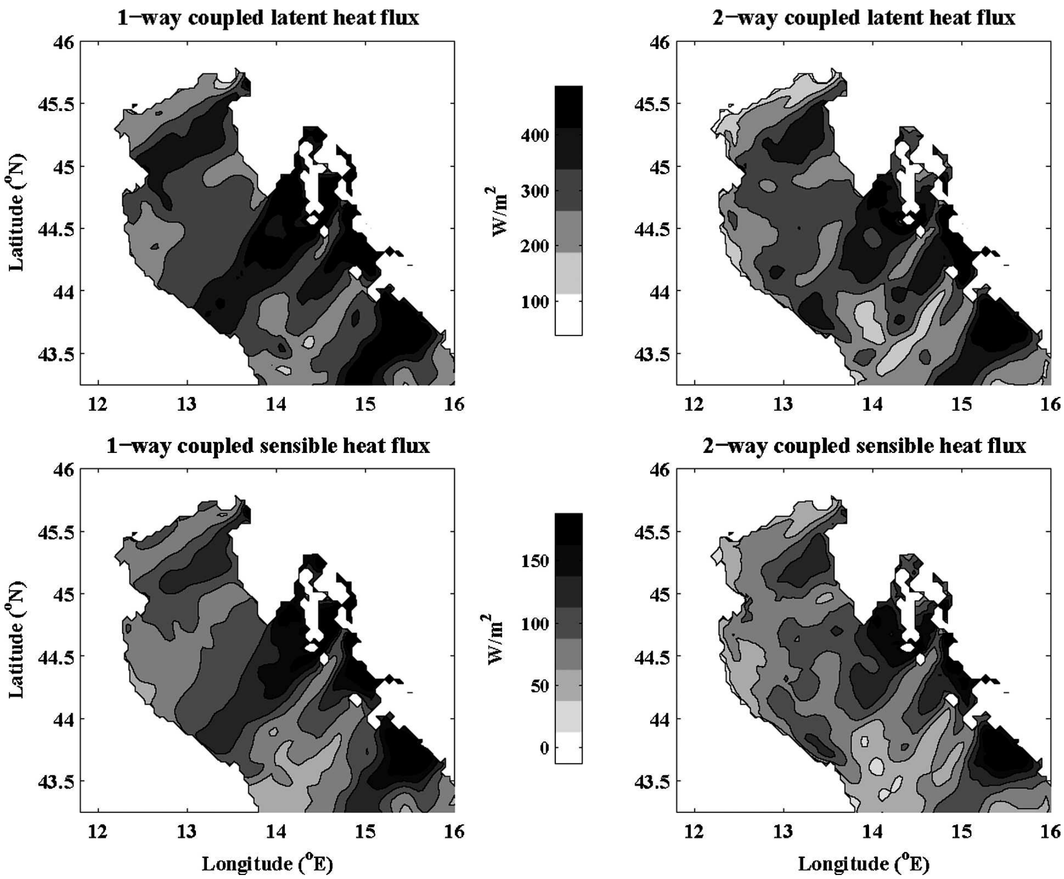

FIG. 4. Maps of surface heat flux in the northern Adriatic during the bora on 0600 UTC 29 Sep 2002.

perature front in the northern Adriatic. Overall, during these bora episodes at this shallow (20 m deep) site, the two-way coupled ocean loses 15% less heat to the atmosphere compared to the one-way coupled simulation.

At Acqua Alta, the bora jets induce elevated mixing in the lower ABL as depicted by the gradient Richardson number (using virtual potential temperature) in the two-way coupled simulation (Fig. 6b). Two-way coupled values of the gradient Richardson number are increased relative to the one-way coupled simulation, as denoted by the overall positive difference values away from the white contours. Therefore, there is increased stability (although unstable conditions persist) of the two-way coupled simulation over the one-way coupled simulation.

During the bora event, the atmospheric stability is modified through contact with the SSTs that contain detailed smaller-scale structure. In the two-way coupled simulation, the gradient Richardson number along the Amelia section (location shown in Fig. 3a) is increased in the lower ~100 m of the boundary layer compared to the one-way coupled simulation (Figs. 7a,b). The less unstable atmosphere in the two-way coupled simulation is most evident in the regions near the coast. In both simulations there is a sharp transition in the boundary layer adjacent to both coasts as the convective marine ABL abuts the stable nocturnal overland ABL at this early morning hour.

During the bora, the most unstable 30-m Richardson numbers extend off of the Istrian Peninsula and along the north coast (Figs. 7c,d). The most unstable air is situated in the gaps between the bora jets (shown in Fig. 3a). (In this region the air, though unstable, is more stable in the two-way coupled simulation relative to the one-way coupled simulation.) Presumably the heat extraction in the high-speed bands of the bora ameliorates the air–sea temperature difference and causes the air to

TABLE 1a. SST statistics for the bora on 1 Oct 2002. *N* is the number of points. The observations are *NOAA-16* MCSST.

	N	Mean (°C)	Std dev (°C)
Observed	39 217	20.06	1.19
Analyzed	37 214	20.80	0.21
One-way coupled	37 319	19.48	1.26
Two-way coupled	37 319	19.81	0.88

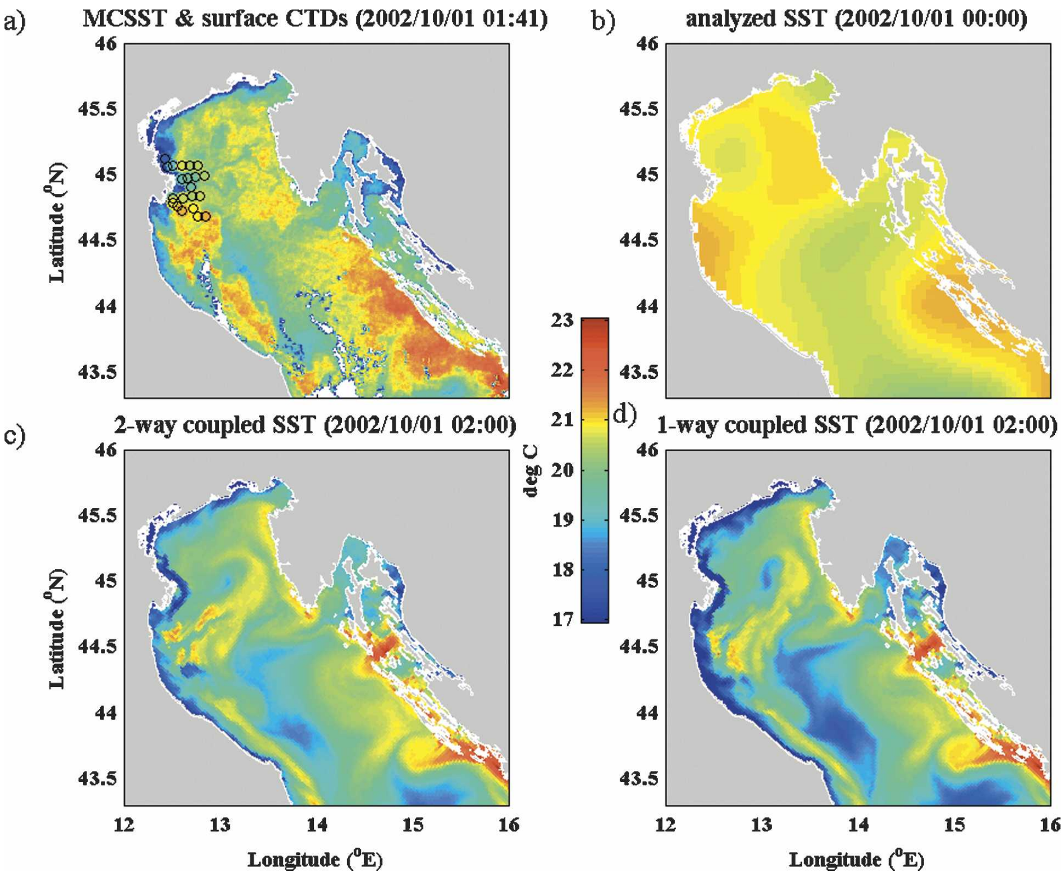

FIG. 5. Postbora maps of SST in the northern Adriatic on 1 Oct 2002. (a) Remotely sensed SST is shown in color contours, while in situ near-surface CTDs are shown with solid-colored circles. (b) Analyzed, (c) two-way, and (d) one-way coupled SST.

be relatively stable compared to the more convective regions where the winds are weaker and the air–sea temperature difference is larger.

Additionally, during a bora event, the wind speeds decrease across the Adriatic. For instance, on 29 September, mean two-way coupled wind speeds (over 9 h, from 0100 to 0900 UTC) were reduced by 10% from 12.34 to 11.08 m s^{-1} between Kvarner Bay and the west Adriatic (marked with black crosses in Fig. 3a). This phenomenon will be examined in more detail in the final section.

4. Comparison with month-long wind and ocean temperature observations

The Italian national oil and gas company, AGIP, has instrumented several gas platforms in the northern Adriatic with meteorological stations. An airport meteorological station at Rimini augments the meteorological data. The heights of the station are as follows: Acqua Alta, 21 m; Amelia, 25 m; Azalea-B, 29 m; and Rimini, 10 m. Model fields were extracted at the nearest horizontal grid point, and vertically interpolated from the 10- and 30-m sigma levels. Forecast hours 1–6 of COAMPS hourly wind velocity along with NCOM hourly SST were utilized in the comparisons presented below.

Mean two-way coupled winds for the time period 23 September–23 October 2002 at the four stations were quite spatially variable (Fig. 8a). Mean winds at Acqua Alta were from the northeast, while mean winds at the other stations were weaker and from the west or northwest. Cold water framed the Adriatic on the north and

TABLE 1b. Same as in Table 1a, but relative to satellite measurements. Here N excludes points not common to both fields (i.e., cloud contaminated or overland.) CC is the correlation coefficient.

	N	MB (°C)	Rmse (°C)	CC
Analyzed	35 977	0.59	1.16	0.23
One-way coupled	36 295	−0.69	1.22	0.60
Two-way coupled	36 295	−0.38	0.97	0.57

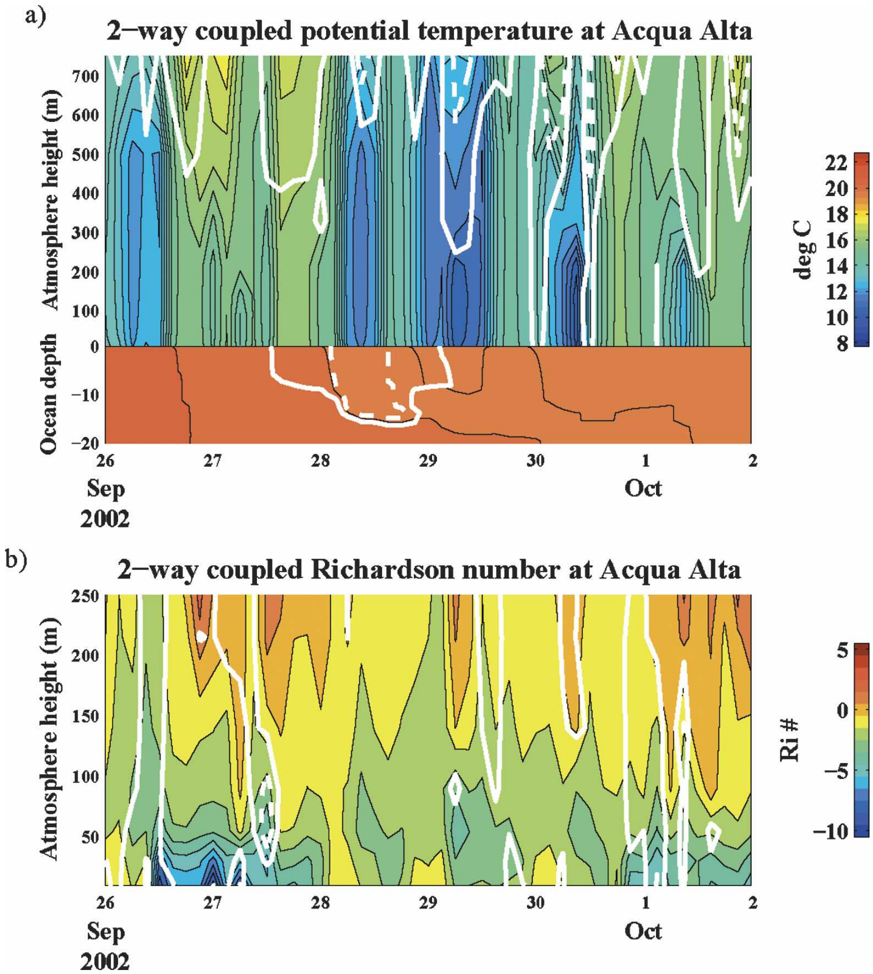

FIG. 6. Evolution of the ocean and atmosphere boundary layers during the bora event at the Acqua Alta station (shown with a circled cross in Fig. 3a). The solid white contours represent the zero contour of two-way minus one-way coupled values (i.e., a difference measure). (a) The dashed white contour represents a difference of 0.5°C in the atmosphere and −0.25°C in the ocean. (b) Same as in (a), but for a difference of −1°C in the atmosphere.

west coasts. The time evolution of hourly near-surface temperature at Acqua Alta was better approximated by the two-way coupled model where MB (rmse) two-way coupled error statistics were −0.06 (0.49)°C while MB (rmse) one-way coupled error statistics were −0.62 (1.05)°C.

Measured wind speeds were strongest at Acqua Alta while at Rimini they were weakest (Table 2a). Modeled (one- and two-way coupled) mean wind speeds were greatest at Azalea-B and smallest at Rimini. Wind speeds fluctuated the most at Acqua Alta and the least at Rimini in the observations and models. The standard deviations from the one-way coupled model exceeded the two-way coupled values at all stations except Rimini. At the three overwater stations, the one-way coupled standard deviations agreed better with the observations. Two-way coupled mean 10-m wind speeds at all stations were lower than the corresponding one-way coupled mean wind speeds. And the mean biases of the two-way coupled model were consistently smaller than those of the one-way coupled model at all stations (Table 2b). That is, the smaller mean wind speeds predicted by the two-way coupled model accorded better with the observations. The two-way coupling occasioned the greatest reduction in MB at Acqua Alta and Azalea-B, while the smallest reduction in MB was found at Rimini. The two-way coupled rmse was slightly lower for Amelia, but the remaining stations had similar error levels for one- and two-way coupling. The correlation coefficients were largest at Acqua Alta (0.7) and were comparable for the one- and two-way coupled simulations at all the stations.

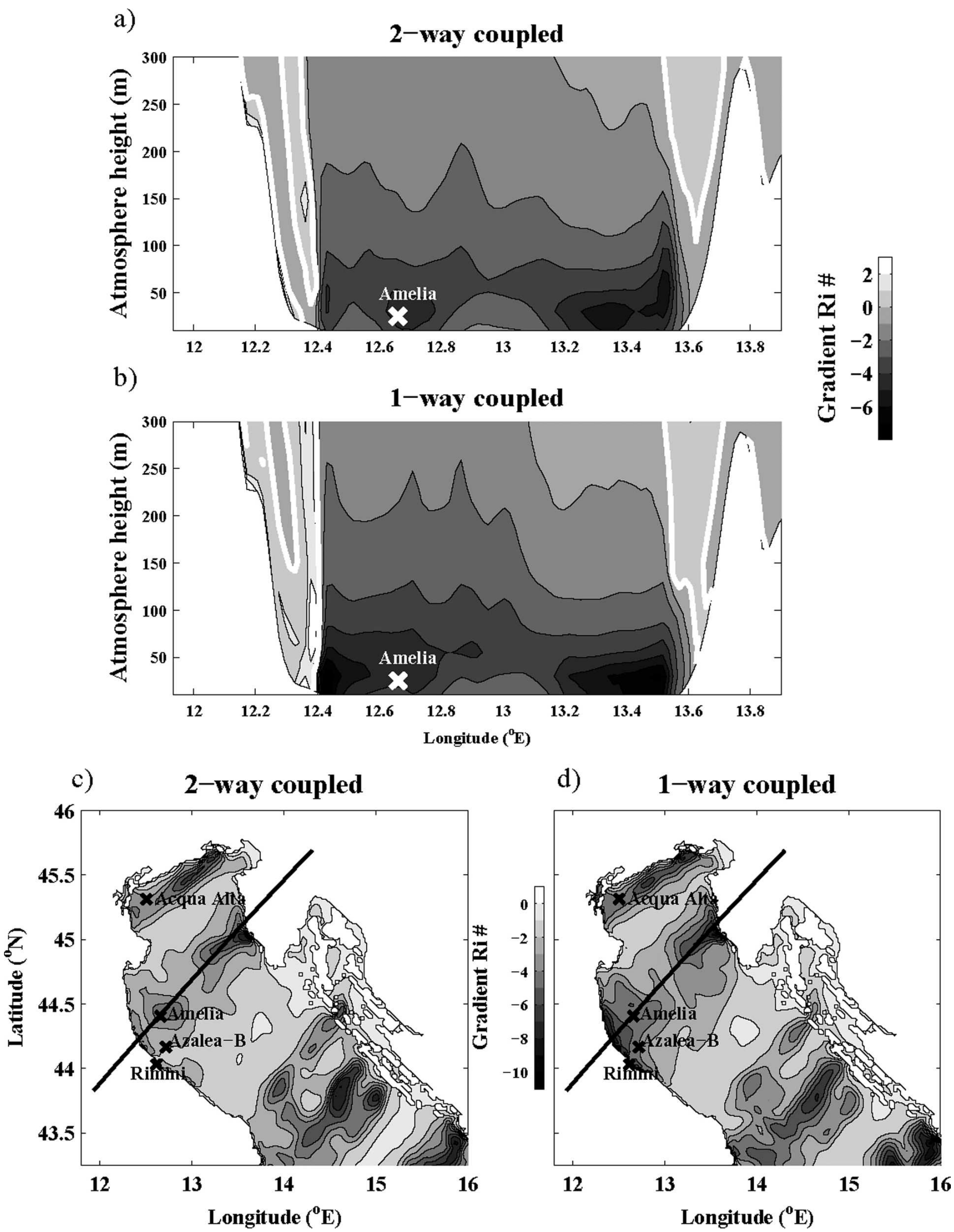

FIG. 7. (a), (b) Gradient Richardson number through the Amelia section marked in Fig. 3a during the bora on 0600 UTC 29 Sep 2002. The 0.5 contour level is drawn in white. (c), (d) Same as in (a), (b), but for a height of 30 m. The maximum contour level is 0.5. The figure is marked with the sites of the meteorological stations used in the model evaluation in section 4.

5. Air–sea interaction patterns

Modeled 3D potential temperature and velocity were saved every 3 h, whereas forecast hours 3 and 6 were used in the subsequent statistics. For surface fields such as heat fluxes, hourly fields were saved, and forecast hours 1–6 are utilized here. Statistics are presented for the 23 September–23 October 2002 time period.

The difference of mean potential temperature between the two simulations (two-way coupled minus

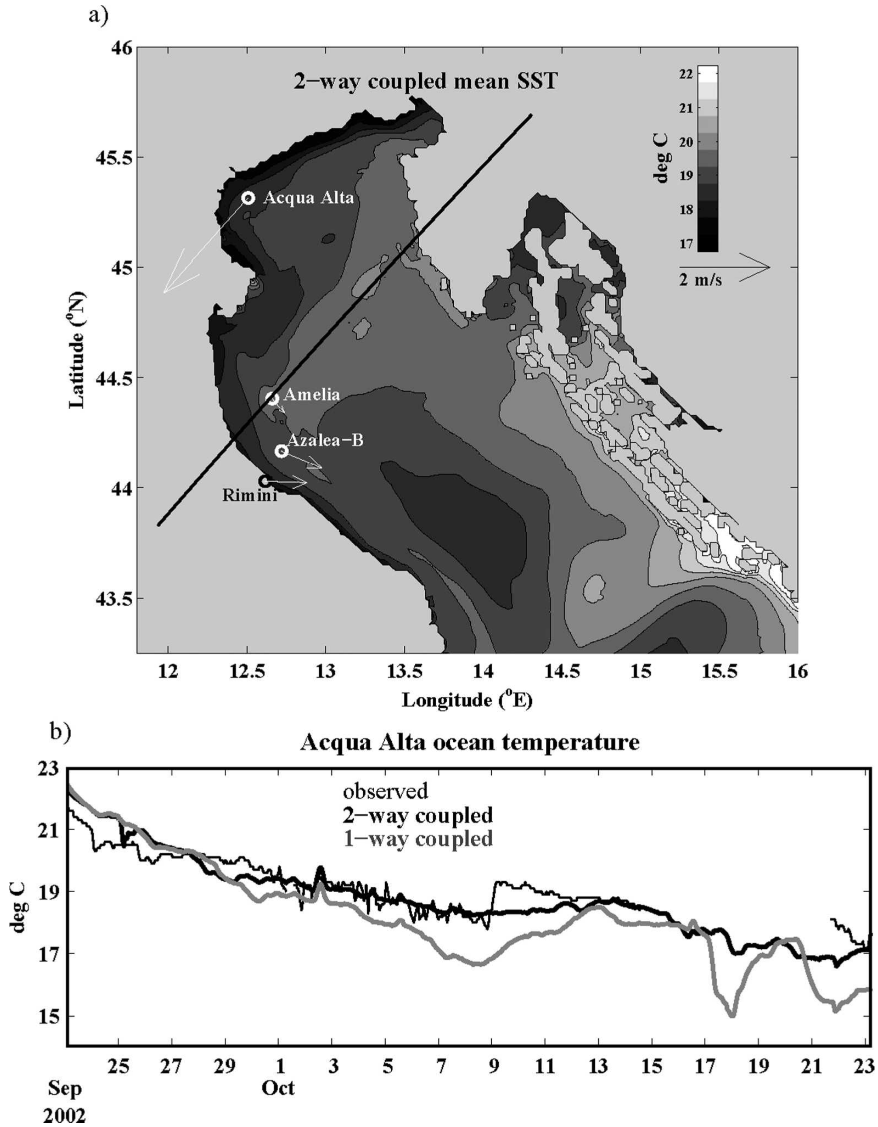

FIG. 8. (a) Mean two-way coupled SST for 23 Sep–23 Oct 2002. Mean two-way coupled wind velocity arrows at the meteorological station heights are shown overlaid. (b) Observed and modeled near-surface ocean temperature at Acqua Alta. (There is an approximately 6-day gap in the observed record.)

one-way coupled) reveals the region of influence of the two-way coupling on the ocean and atmosphere (Fig. 9). Because modeled ocean temperatures were colder on the western side of the Adriatic, the two-way coupled model did not extract as much heat there as did the one-way coupled simulation. Differences of mean heat flux reveal that less heat was removed from the western and northern Adriatic in the two-way coupled simulation—by over 30 W m^{-2} latent and 10 W m^{-2} sensible (Fig. 10). Hence, the two-way coupled ocean was over 1.5°C warmer than the one-way coupled ocean in a narrow band next to the coast in the upper 10 m of the water column (Fig. 9a).

The lower approximately 500 m of the atmosphere was about 0.5°C cooler in the two-way coupled simulation relative to the one-way coupled simulation. This is due to the dynamic adjustment introduced by the two-way feedback, as discussed earlier. The spatial map of 10-m air temperature differences shows that the two-way coupled simulation was cooler along the far northern coast, the western Adriatic around Rimini, and the central basin, roughly corresponding to the location of coldest mean SST (Fig. 9b).

The mean 30-m Richardson number for the two-way coupled simulation shows an area of most unstable air extending off the Istrian Peninsula, between the main

TABLE 2a. Wind speed statistics from 23 Sep to 23 Oct 2002. Observations are from the AGIP gas platform meteorological stations.

	N	Mean (m s^{-1})	Std dev (m s^{-1})
Acqua Alta observed	726	5.36	3.76
One-way coupled	726	5.59	3.27
Two-way coupled	726	5.35	3.13
Amelia observed	722	4.76	3.21
One-way coupled	722	5.44	2.93
Two-way coupled	722	5.32	2.85
Rimini observed	723	2.65	2.05
One-way coupled	723	2.76	1.21
Two-way coupled	723	2.68	1.25
Azalea-B observed	655	5.05	2.94
One-way coupled	655	5.74	2.76
Two-way coupled	655	5.51	2.67

bora jets (Fig. 11a). The standard deviation of the gradient Richardson number for the two-way coupled monthlong simulation was greatest in a narrow band along the west coast of the Adriatic. Diurnal coastal fluctuations associated with excursions of stable nocturnal overland air out across the ocean are likely a dominant source for this variability. The two-way coupled simulation produced air that was more stable relative to the one-way coupled simulation in the coastal regions of the northern and western Adriatic (Fig. 11b).

Mean statistics at Acqua Alta for the month-long simulation show that the two-way coupled simulation had cooler temperatures in the lower ABL as well as smaller wind speeds relative to the one-way coupled simulation (Fig. 12). Below 215 m, the mean wind speed differences were greater than 0.25 m s^{-1}. Above approximately 700 m, the differences between the mean fields were negligible. Both simulations produced a well-mixed ABL, as indicated by potential temperature

TABLE 2b. Comparison wind speed statistics from 23 Sep to 23 Oct 2002. Data sources are the same as in Table 2a.

	MB (m s^{-1})	Rmse (m s^{-1})	CC
Acqua Alta	−0.23	2.81	0.69
One-way coupled	0.01	2.82	0.68
Two-way coupled			
Amelia	−0.67	3.20	0.48
One-way coupled	−0.56	3.12	0.49
Two-way coupled			
Rimini	−0.11	1.87	0.44
One-way coupled	−0.04	1.86	0.45
Two-way coupled			
Azalea-B	−0.69	2.97	0.49
One-way coupled	−0.46	2.98	0.45
Two-way coupled			

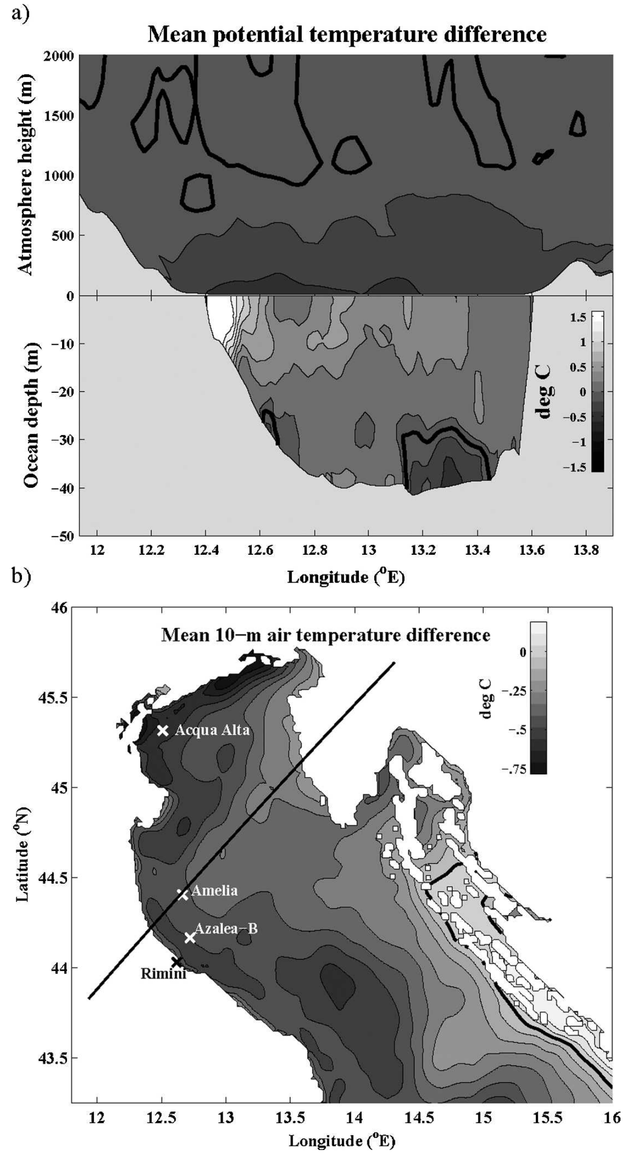

FIG. 9. (a) Difference of mean potential temperature (two-way minus one-way coupled) for the time period 23 Sep–23 Oct 2002. (b) Same as in (a), but for 10-m air temperature. The zero contour is drawn with a thick black line in both (a) and (b).

profiles. But there was elevated mean turbulent kinetic energy (TKE) and more vertical coherence (from zero-lagged correlations of 500-m TKE with other heights) in the lower portion of the ABL for the one-way coupled simulation compared to the two-way coupled experiment. That is, the two-way coupled model developed a reduced (by 23% between 140- and 215-m heights) mean TKE and a less vertically coupled boundary layer—the responses are consistent with the stabilizing role played by cooler SSTs in the two-way coupled model.

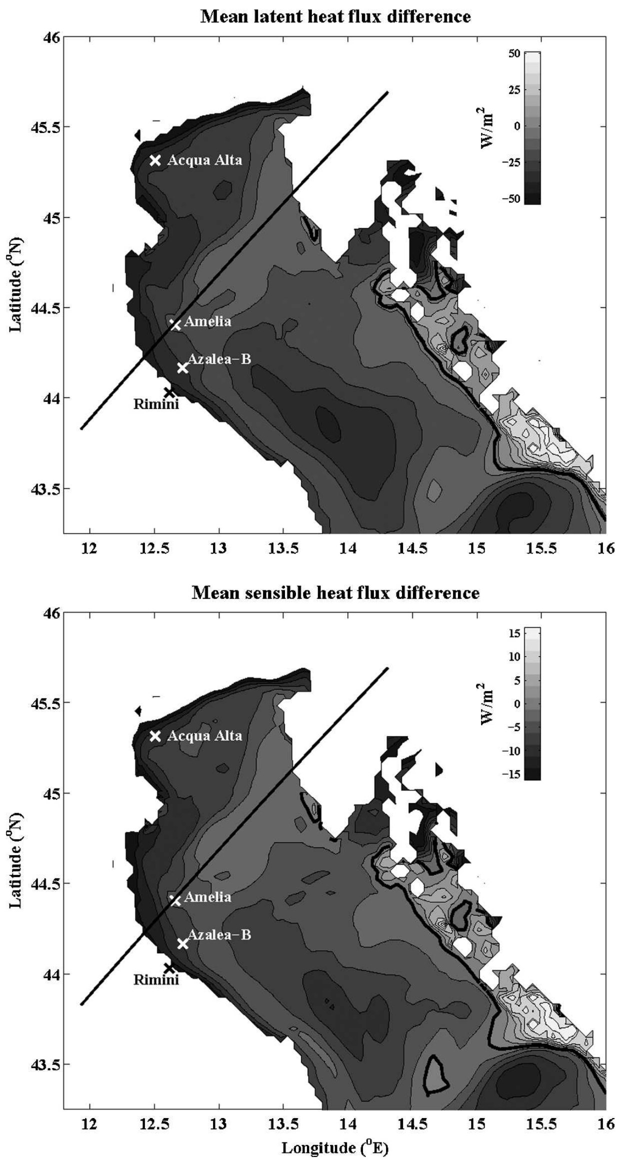

FIG. 10. Same as in Fig. 9, but for heat fluxes.

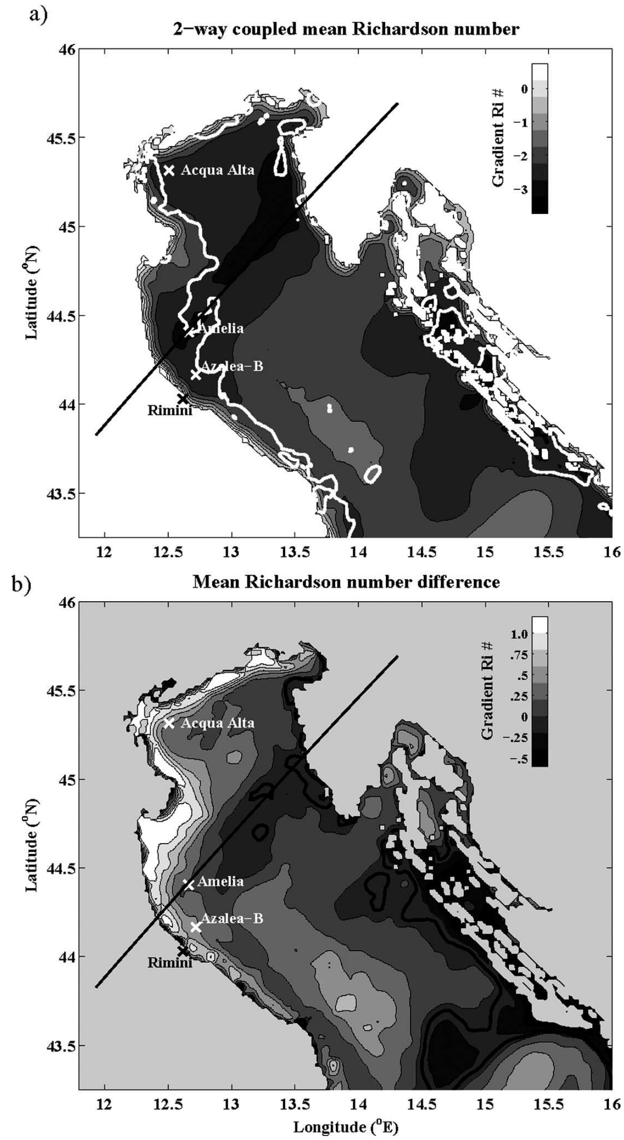

FIG. 11. (a) Mean 30-m two-way coupled Richardson number for 23 Sep–23 Oct 2002, with the 2.0 std dev contour drawn in white. (b) Difference of mean 30-m Richardson number (two-way minus one-way coupled). The zero line is contoured in thick black.

Situating the month-long two-way coupled mean wind velocity at the stations (Fig. 8a) within the context of the regional atmospheric circulation, we see that the magnitudes of mean wind velocity (gray shaded in Fig. 13a) were greatest in the bora jets. The wind fluctuations were not as large in the Gulf of Trieste jet compared with the Kvarner Bay jet, which exceeded 7 m s^{-1}. (This feature was also noted in the winter and spring simulations of Pullen et al. 2003.) The Acqua Alta station sampled a bora regime, whereas the other stations were located in weaker northwesterly and westerly coastal flows. Mean winds were generally cyclonic over the basin, with a strong contribution from the southeasterly sirocco winds. In the area of the largest air–sea temperature difference immediately adjacent to the Istrian Peninsula (Fig. 13b), there was a large positive divergence in the mean wind stress (Fig. 13c). Similarly, mean winds were accelerated off the west coast of the Adriatic, north of Rimini. Elsewhere, negative divergence dominated the region, indicative of slowing winds over much of the basin. However, the small-scale spatial complexity of the divergence field is striking. For example, over the Gulf of Trieste, mean winds were northeasterly (bora oriented) and had anomalously large negative stress divergence.

Shifting focus from the mean fields, we close this

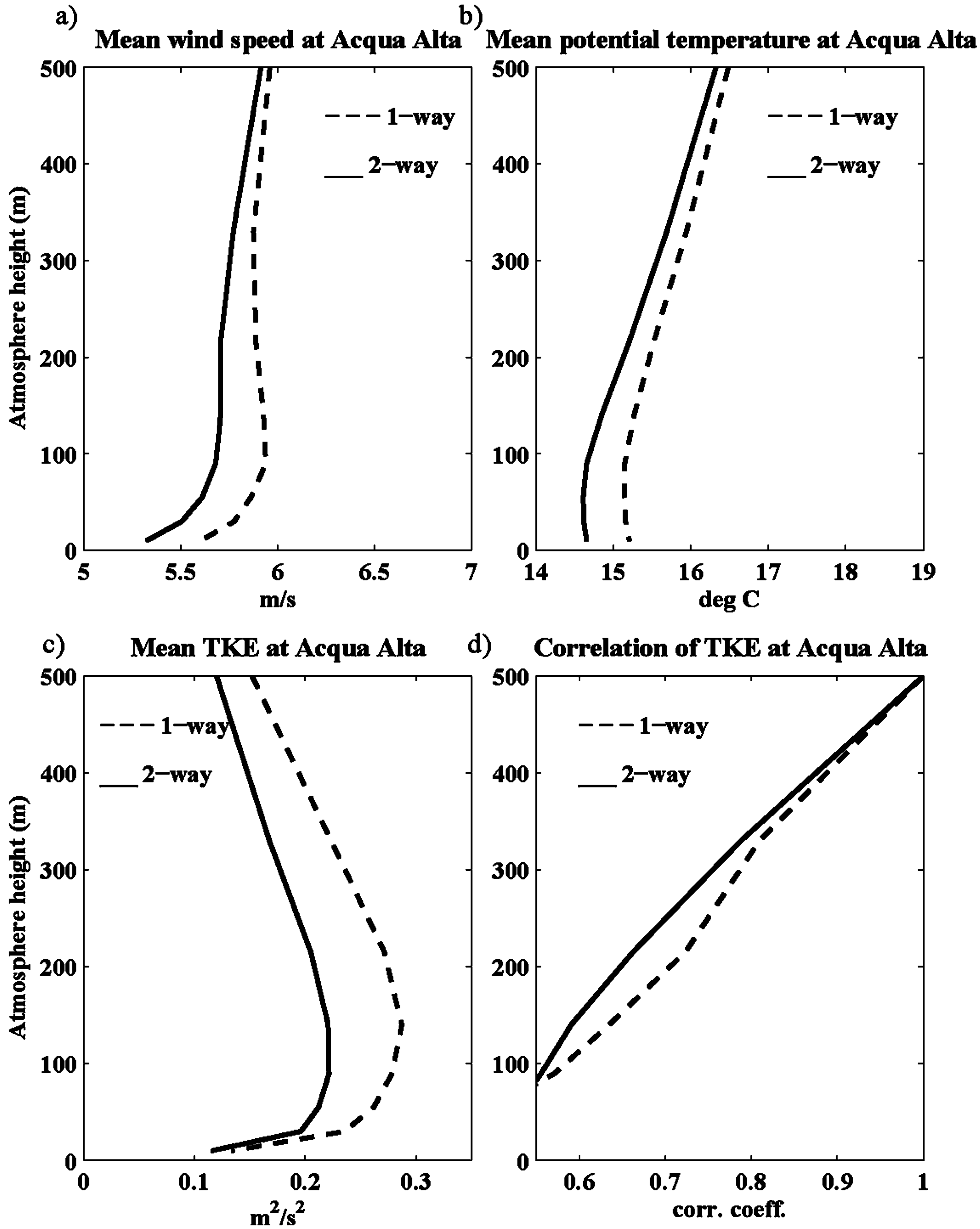

FIG. 12. (a) Mean wind speed, (b) mean potential temperature, (c) mean TKE, and (d) zero-lagged correlations of 500-m TKE with lower heights, from 23 Sep to 23 Oct 2002 at Acqua Alta for the one- and two-way coupled simulations.

section with an investigation of the fluctuating fields. The two-way coupled principal SST EOF accounts for the majority of the total and local variance and shows the imprint of the ocean circulation patterns (Fig. 14b). The cyclonic gyre in the far northern Adriatic moves relatively warmer waters northward and westward, wrapping around a core of cold water. And the anticyclonic gyre off the Istrian Peninsula transports warmer water southward. The Istrian front separating warmer from colder water is also apparent. None of these finescale features evolve in the analyzed principal SST EOF, which also contains the major portion of total and

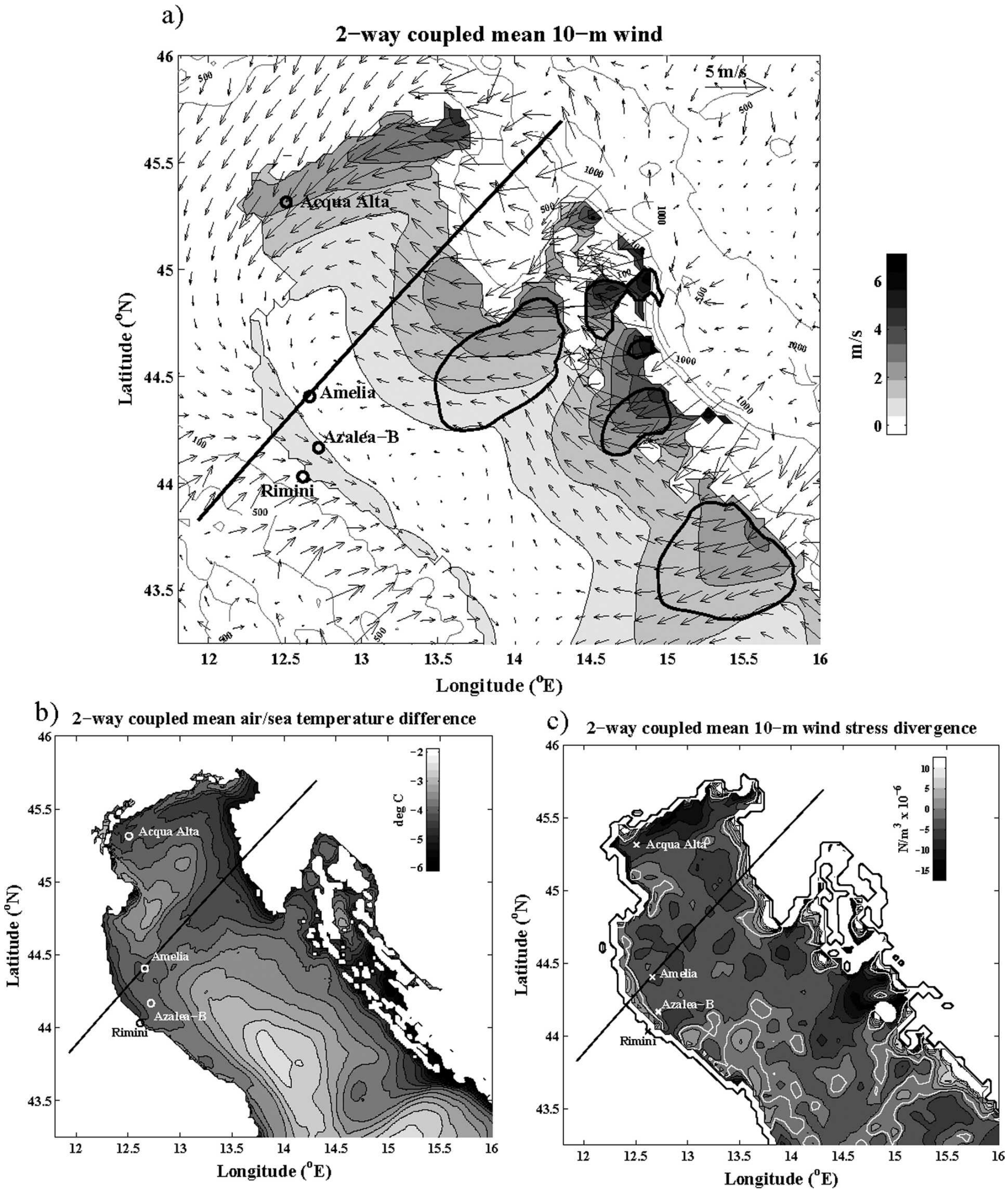

FIG. 13. Statistics from the two-way coupled simulation for the time period 23 Sep–23 Oct 2002. (a) The 10-m mean wind velocity arrows are at every third grid cell, with the vector amplitude shaded gray. The 7 m s^{-1} rms vector amplitude is contoured with a thick black line. (b) The 10-m mean air temperature minus mean SST. (c) Mean wind stress divergence with the zero contour shown in white.

local variance (Fig. 14a). However, the amplitude time series of both fields show the same slow, steady cooling during the course of the month (Fig. 14c). Incidentally, Po River discharge events exceeding the climatological annual average (times are shaded gray in Fig. 14c) do not appear to influence the primary mode of two-way coupled SST variability during the month.

Finally, zero-lagged 10-m air temperature correlations at Amelia and points elsewhere indicate that the two-way coupled simulation possesses shorter correlation length scales than the one-way coupled simulation (Figs. 14d,e). Model-derived correlation scales are often used in data assimilation. It is clear that these scales can be sensitive to SST feedback. In particular, the detailed two-way coupled SST represented in the EOF map serves to reduce the horizontal coherence of the

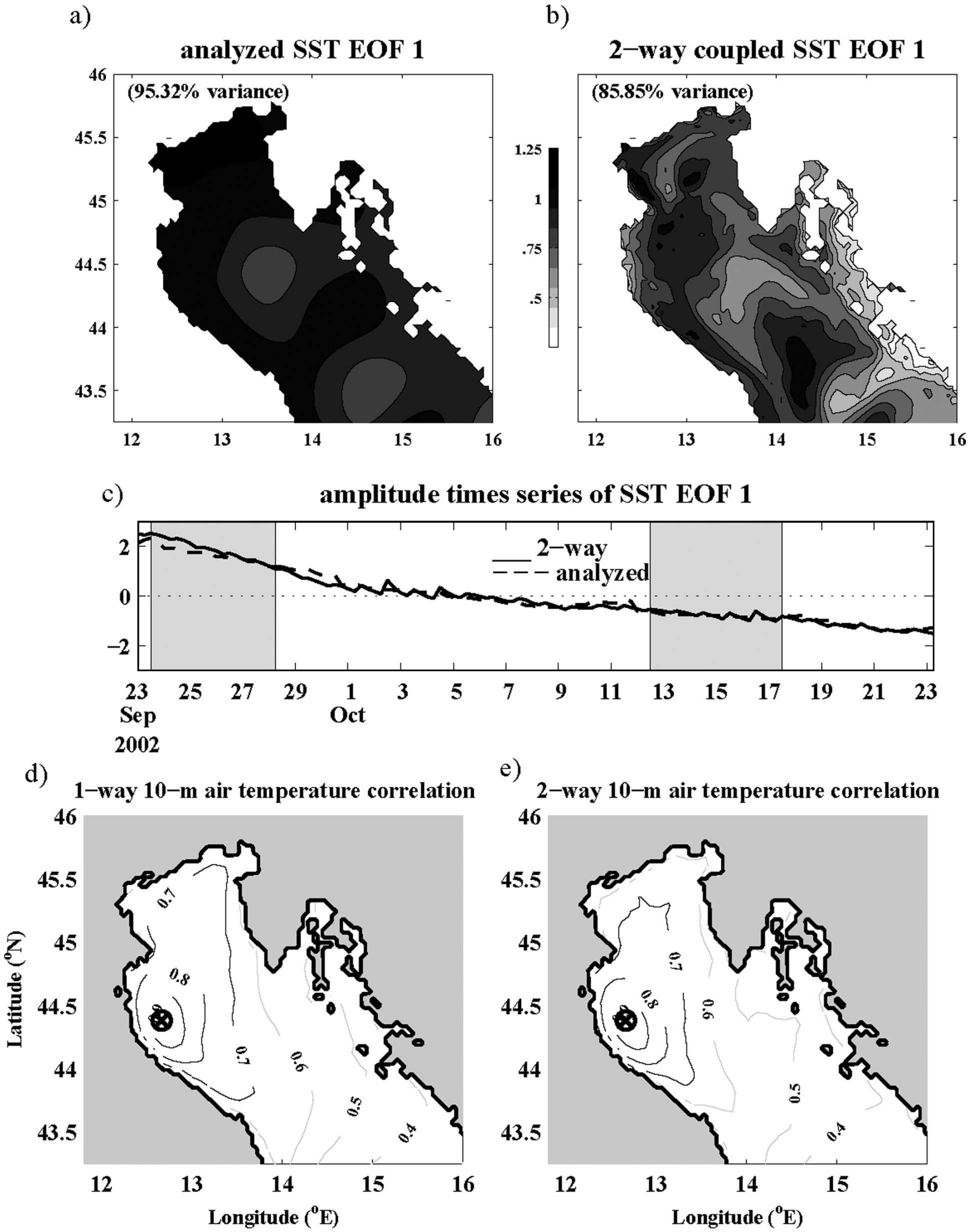

FIG. 14. (a), (b) SST EOF 1. (c) Associated amplitude time series for the month-long simulations. The shaded regions of the time series plot delineate when the Po River discharge exceeded the climatological average of 1547 $m^3 s^{-1}$. (d), (e) Zero-lagged correlation of 10-m Amelia air temperature with 10-m air temperature elsewhere in the domain computed at every second cell on the 4-km COAMPS grid. Correlation coefficients >0.6 are drawn in black.

two-way coupled air temperature at Amelia (as well as the other stations).

6. Discussion and conclusions

Vigorous air–sea exchange occurs routinely in the atmospheric and oceanic boundary layers of the shallow northern Adriatic during bora events. The region often exhibits an unstable ABL due to cool air moving over comparatively warmer seas.

A main goal of this work was to quantify and examine the impact of two-way coupled high-resolution coastal ocean temperatures on the overlying air properties. This necessitated verification that the two-way coupled SST generated during the course of the model simulation was realistic and that the observed SST spatial structure was reproduced well. We established the superior predictive skill of the two-way coupled SST via MB and rmse scores using satellite and in situ measurements of ocean temperature. Indeed, for the satellite data comparison, MB was reduced by 45% while rmse was reduced by 26% using two-way coupling. For the in situ data, ocean temperature MB was reduced by 90% with rmse reduced by 53% over one-way coupling. In absolute terms, this represented a reduction in MB and rmse of over 0.5°C.

As surface heat loss is a dominant term in the heat budget of the northern Adriatic (R. P. Signell et al. 2005, unpublished manuscript), it is important that the ocean and atmosphere be interactively coupled to more accurately simulate heat fluxes, as demonstrated by the two-way coupled model skill in matching the observed SST. (The quality of meteorological heat fluxes was evaluated here in terms of their ability to generate realistic SSTs when used to directly force an ocean model. It is more common in ocean modeling to modify meteorological model-derived heat fluxes using a separate bulk formula to partially overcome the perils of a one-way coupled system.)

We found that mean wind speeds at four stations (three overwater and one coastal) in the northern Adriatic were systematically lower in the two-way coupled simulation relative to the one-way coupled simulation. The two-way coupled mean wind speeds were always closer to observed values and produced a 53% average reduction in MB for the four stations. The stations sampled different mean wind regimes, with the Acqua Alta tower being located in the bora path while Amelia was situated in weaker northwesterly flow, and Azalea-B experienced coastal offshore wind excursions. Rimini, the land station, was positioned near a convergent front. In absolute terms, at the overwater stations there was a reduction of MB by approximately 0.2 m s^{-1}. As a percentage of the observed value, the mean wind speeds at Azalea-B and Acqua Alta were reduced by about 5% (from 114% to 109% and 104% to 100%, respectively) using two-way coupling. The mean two-way coupled cross-basin SST gradient was approximately 1°–2°C, although winds were not always incident across the front. A 5% reduction of 10-m wind speed falls within the range measured by Vickers and Mahrt (2004) across 1°–2°C cooler temperature fronts.

The synoptically driven bora is sensitive to orography and imposes horizontal and temporal scales over which heat is transferred from the ocean to the atmosphere. There is a mutual adjustment at work in the feedback between the ocean and atmosphere. In the bora jets, air–sea temperature differences are diminished as the strong winds transit the basin. The interaction of the air with comparatively cooler ocean temperatures on the west and north coasts reduced the local upward heat flux by approximately 20% in the two-way coupled simulation relative to the one-way coupled simulation. In those regions, the two-way coupled SST had a relatively stabilizing effect by reducing mixing in the overlying atmosphere, slowing the winds, and muting their variability. Although mean SST gradients were more diffuse than the instantaneous fields, this effect was apparent both during bora events and in the month-long mean and suggests the importance of air–sea interaction in shaping both episodic and long-term dynamics. In addition, the principal component analyses of SSTs and the correlations using atmospheric temperature and TKE (statistics where the mean is removed) highlight the role of two-way coupling in modifying fluctuating fields.

The results of the one-way coupled simulation are dependent upon the quality of the analyzed SST fields. As higher-resolution satellite products become available, the fidelity of the analyzed fields should improve. The simulations presented here were conducted in reanalysis mode where the data window for including satellite SST information in the analysis was symmetric (including past and future times). In forecast mode, analyzed fields are weighted toward the past and have no information about the evolution of the field into the future. So the one-way coupled model in the forecast mode would display reduced skill compared to the reanalysis mode. Even assuming that a "perfect" SST could be acquired from an analysis, real additional benefits would accrue with two-way coupling because the mutual air–sea exchange processes have an important impact on the dynamics of the coupled system. Given sufficiently skillful ocean and atmosphere models, this coupled effect would have a positive impact on forecast skill. In addition, this coupled effect would likely be enhanced by allowing more frequent exchange of information between the ocean and atmosphere models.

Our simulations were conducted for the fall, when the ocean was stratified. In the wintertime, the ocean is well mixed because of the repeated experience of bora and other strong synoptic-scale events and is also uniformly colder north of the Istrian Peninsula, leading to a stronger Istrian front. The effect of realistic SSTs on the bora winds is likely to be different during this time of year and is currently under investigation using the coupled system.

The bulk of the statistics computed here involved month-long means and fields from a multiday bora event. It is expected that the investigation of air–sea interaction processes operative at shorter time scales (such as coastal sea breezes) would allow further discrimination between one- and two-way coupled simulations. Also, situations where the marine ABL undergoes an ocean-induced stability change (e.g., from unstable to stable) will leave a pronounced mark on the air properties. Such a case occurred during a bora event in January 2003 as cold winds encountered even colder SSTs along the west coast of the Adriatic and is the subject of our ongoing, 3D, high-resolution coupled ocean–atmosphere studies.

In many areas of the world, sharp coastal gradients in SST are ubiquitous features. They are associated, in particular, with upwelling and downwelling fronts, river runoff, and local ocean circulation patterns. These features render the coastal ocean dynamically complex in space and time and can alter the overlying atmosphere in discernible ways, as documented here. To fully account for these effects requires the deployment of high-resolution coupled modeling systems to resolve the small scales adjacent to the coast and to close the feedback loop between the ocean and atmosphere.

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REFERENCES

Barale, V., C. R. McClain, and P. Malanotte-Rizzoli, 1986: Space and time variability of the surface color field in the northern Adriatic Sea. *J. Geophys. Res.,* **91,** 12 957–12 974.

Chelton, D. B., and Coauthors, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical Pacific. *J. Climate,* **14,** 1479–1498.

——, M. G. Schlax, M. H. Freilich, and R. F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds. *Science,* **303,** 978–983.

Chen, S., and Coauthors, 2003: COAMPS version 3 model description. Naval Research Laboratory Publication NRL/PU/7500-03-448, Marine Meteorology Division, Monterey, CA, 143 pp.

Enger, L., and B. Grisogono, 1998: The response of bora-type flow to sea surface temperature. *Quart. J. Roy. Meteor. Soc.,* **124,** 1227–1244.

Garratt, J. R., 1990: The internal boundary layer—A review. *Bound.-Layer Meteor.,* **50,** 171–203.

Grubisic, V., 2004: Bora-driven potential vorticity banners over the Adriatic. *Quart. J. Roy. Meteor. Soc.,* **130,** 2571–2603.

Hayes, S. P., M. J. McPhaden, and J. M. Wallace, 1989: The influence of sea surface temperature on surface wind in the eastern equatorial Pacific: Weekly to monthly variability. *J. Climate,* **2,** 1500–1506.

Hodur, R. M., 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). *Mon. Wea. Rev.,* **125,** 1414–1430.

Jiang, Q., and J. D. Doyle, 2005: Wave breaking induced surface wakes and jets observed during a bora event. *Geophys. Res. Lett.*, **32,** L17807, doi:10.1029/2005GL022398.

Koracin, D., and D. Rogers, 1990: Numerical simulations of the response of the marine atmosphere to ocean forcing. *J. Atmos. Sci.,* **47,** 592–611.

Li, Y., H. Xue, and J. M. Bane, 2002: Air–sea interactions during the passage of a winter storm over the Gulf Stream: A three-dimensional coupled atmosphere–ocean model study. *J. Geophys. Res.,* **107,** 3200, doi:10.1029/2001JC001161.

Loglisci, N., and Coauthors, 2004: Development of an atmosphere–ocean coupled model and its application over the Adriatic Sea during a severe weather event of Bora wind. *J. Geophys. Res.,* **109,** D01102, doi:10.1029/2003JD003956.

Louis, J.-F., M. Tiedtke, and J.-F. Geleyn, 1981: A short history of the PBL parameterisation at ECMWF. *Proc. Workshop on Planetary Boundary Layer Parameterisation,* Reading, United Kingdom, ECMWF, 59–80.

Ma, C.-C., C. R. Mechoso, A. W. Roberton, and A. Arakawa, 1996: Peruvian stratus clouds and the tropical Pacific circulation—A coupled ocean–atmosphere GCM study. *J. Climate,* **9,** 1635–1645.

Martin, P. J., 2000: A description of the Navy Coastal Ocean Model version 1.0. Naval Research Laboratory Rep. NRL/FR/7322-00-9962, Stennis Space Center, MS, 42 pp.

Nonaka, M., and S.-P. Xie, 2003: Covariations of sea surface temperature and wind over the Kuroshio and its extension: Evidence for ocean-to-atmosphere feedback. *J. Climate,* **16,** 1404–1413.

O'Neill, L. W., D. B. Chelton, and S. K. Esbensen, 2003: Observations of SST-induced perturbations of the wind stress field over the Southern Ocean on seasonal time scales. *J. Climate,* **16,** 2340–2354.

Orlic, M., M. Kuzmic, and Z. Pasaric, 1994: Response of the Adriatic Sea to the bora and sirocco forcing. *Cont. Shelf Res.,* **14,** 91–116.

Paklar, G. B., V. Isakov, D. Koracin, V. Kourafalou, and M. Orlic, 2001: A case study of bora-driven flow and density changes on the Adriatic Shelf (January 1987). *Cont. Shelf Res.,* **21,** 1751–1783.

Park, K.-A., and P. C. Cornillon, 2002: Stability-induced modification of sea surface winds over Gulf Stream rings. *Geophys. Res. Lett.,* **29,** 2211, doi:10.1029/2001GL014236.

Pollard, R. T., 1978: The joint air–sea interaction experiment—JASIN. *Bull. Amer. Meteor. Soc.,* **59,** 1310–1318.

Poulain, P.-M., 2001: Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999. *J. Mar. Syst.,* **29,** 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. *J. Geophys. Res.,* **108,** 3320, doi:10.1029/2003JC001780.

Raicich, F., 1994: Note on the flow rates of the Adriatic rivers. CNR Istituto Sperimentale Talassografico Tech. Rep. RF 02/94, Trieste, Italy, 8 pp.

Smith, R. B., 1987: Aerial observations of the Yugoslavian bora. *J. Atmos. Sci.,* **44,** 269–297.

Song, Q., T. Hara, P. Cornillon, and C. Friehe, 2004: A comparison between observations and MM5 simulations of the marine atmospheric boundary layer across a temperature front. *J. Atmos. Oceanic Technol.,* **21,** 170–178.

Sweet, W. R., R. Fett, J. Kerling, and P. LaViolette, 1981: Air–sea interaction effects in the lower troposphere across the north wall of the Gulf Stream. *Mon. Wea. Rev.,* **109,** 1042–1052.

Vecchi, G. A., S.-P. Xie, and A. S. Fischer, 2004: Ocean–atmosphere covariability in the western Arabian Sea. *J. Climate,* **17,** 1213–1224.

Vickers, D., and L. Mahrt, 2004: Atmospheric response to sea-surface temperature variability. Preprints, *13th Conf. on Interactions of the Sea and Atmosphere,* Portland, ME, Amer. Meteor. Soc., CD-ROM, 2.9.

Wang, S., Q. Wang, and J. Doyle, 2002: Some improvements to Louis surface flux parameterization. Preprints, *15th Symp. on Boundary Layers and Turbulence,* Wageningen, Netherlands, Amer. Meteor. Soc., 547–550.

Weller, R. A., 1991: Overview of the Frontal Air-Sea Interaction Experiment (FASINEX): A study of air–sea interaction in a region of strong oceanic gradients. *J. Geophys. Res.,* **96** (C5), 8501–8516.

Xie, S.-P., 2004: Satellite observations of cool ocean–atmosphere interaction. *Bull. Amer. Meteor. Soc.,* **85,** 195–208.

Zavatarelli, M., N. Pinardi, V. H. Kourafalou, and A. Maggiore, 2002: Diagnostic and prognostic model studies of the Adriatic Sea general circulation: Seasonal variability. *J. Geophys. Res.,* **107,** 3004, doi:10.1029/2000JC000210.