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February 2003 marine atmospheric conditions and the bora over the northern Adriatic

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[1] A winter oceanographic field experiment provided an opportunity to examine the atmospheric marine conditions over the northern Adriatic. Mean February winds are from a northeasterly direction over most of the Adriatic and a more northerly direction along the western coast. Wind speeds are fastest in jets over the NE coast during bora events and weakest in the mid-northwestern Adriatic. Diurnal air temperature cycles are smallest on the NE coast and largest in the midwestern Adriatic. The maximum sea-air difference is +10°C on the eastern coast and near zero on the midwestern Adriatic. Boras are northeasterly (from) wind events that sweep off Croatia and Slovenia, bringing slightly colder and drier air over the northern Adriatic. The main bora season is December to March. Winter 2002–2003 was normal for bora events. Synoptic-scale temporal variations are correlated over the northern Adriatic. Fastest Bora winds and highest wind stress over the northern Adriatic is concentrated in four topographically controlled jets. The strongest is the Senj Jet, while the Trieste Jet extends across the entire northern Adriatic. Between each two jets is a weak wind zone. The greatest mean net heat loss is in bora jets in the NE Adriatic, where it was −438 W m^{-2} and is weakest in the midwestern northern Adriatic, where it was near zero. Wind stress is concentrated over the NE half of Adriatic in four bora jets, while wind stress is weak in the NW Adriatic. There is significant variation in wind stress mean and standard deviation structure over the northern Adriatic with each bora event.

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1. Introduction

[2] Winter cold air pushing out across warmer continents is usually a vigorous meteorological event. The energy and dynamics are dramatically enhanced when cold, continental air pushes off the east coast of a continent and across a relatively warm, open ocean, guaranteeing a strong, unstable boundary layer, great heat losses and large wind stresses [*SethuRaman et al.*, 1986; *Bajić* 1987; *Renfrew and Moore*, 1999; *Dorman et al.*, 2000]. A northern Mediterranean Sea example is that of air flowing off Croatia and across the Adriatic Sea to Italy. While this has attracted interest, no comprehensive examination has been made of the measurements to characterize the meteorological conditions over the Adriatic and quantify the surface forcing.

[3] Meteorological conditions above the Adriatic are dominated by three weather types: unperturbed weather, sirocco-related weather, or bora-related weather [*Penzar et al.*, 2001]. Unperturbed situations, which account for about half of the days and prevail in the warmer part of the year. The sirocco is a SE wind, which brings warm, humid air to the Adriatic area. The bora, on the other hand, blows from the NE quadrant and brings cold and dry air to the Adriatic. The bora occurs more frequently in winter and in the northern Adriatic, and often coincides with the clear-sky

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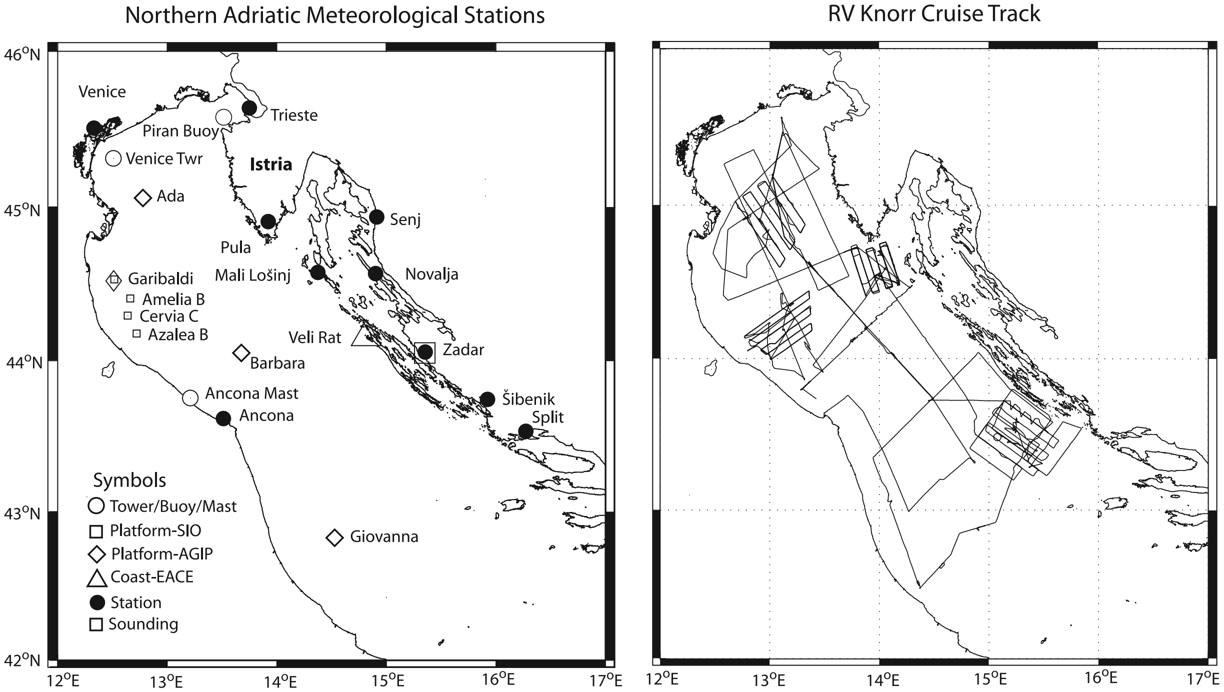

Figure 1. Geographical map of northern Adriatic Sea with (left) meteorological stations and (right) RV *Knorr* cruise track from 31 January to 24 February 2003.

conditions. The relationships between the large-scale synoptic setting and the wind fields over the northern Adriatic have been investigated by *Pandžić and Likso* [2005].

[4] Of the three weather types, the bora has interested investigators most often [i.e., *Defant*, 1951; *Yoshino*, 1976]. *Lukšić* [1975] showed that for Senj, the station where the bora usually attains the greatest speeds, the wintertime bora typically lasts 1 day but may in some cases extend over more than 10 days, and that the maximum speeds may surpass 40 m s^{-1}.

[5] Radiosonde measurements have showed that the height of the bora layer usually does not surpass 2500 m and the speed may increase with height [*Grober*, 1948; *Poje*, 1962]. Aircraft observations of the bora revealed that the upstream height of the bora layer varied from 2200 and 3600 m, that the incoming air descended over the mountains, and that winds aloft were from all directions [*Smith*,1987].

[6] Two-dimensional numerical modeling of the bora flow strongly supported internal hydraulic theory for the dynamic basis of the cross-mountain flow [*Klemp and Durran*, 1987]. In the case of weak upstream flow it was found that the factor contributing most to the development of pronounced lee slope winds is wave overturning which occurs beneath the inversion layer [*Jurčec and Glasnović*, 1991]. Evidence has been found both against [*Ivančan-Picek and Tutiš*, 1996] and for simple hydraulic theory [e.g., *Bajić*, 1991; *Vučetić*, 1993]. *Lazić and Tošić* [1998] used real data simulation to investigate the influence of mountain height on bora trajectories. Two recent modeling and observational studies provide insights into the bora structures, the role of waves and the alternating surface jets and wakes along the Croatian coast [*Gohm and Mayr*, 2005; *Jiang and Doyle*, 2005].

[7] *Polli* [1956] showed that the bora strength is reduced by about 30% when blowing across the Adriatic, from

Table 1. Major Stations[a]

	Position	Elevation, m	Variables	Type	Agency
Ancona Mast	43.75 N 13.21E	8	W,D,Ta,Ts,H[b],Rs[c]	Mast	ISMAR-CNR
Amelia-B	44.4073 12.6623	37	W,D,Ta,Ts,H,P,Rs,Rl	Platform	SIO
Azalea-B	44.17N 12.72E	29	W,D,Ta,Ts,H,P,Rs,Rl	Platform	SIO
Cervia-C	44.29N 12.63E	23	W,D,Ta,Ts,H,P,Rs,Rl	Platform	SIO
Garibaldi-C	44.53N 12.51E	37	W,D,Ta,Ts,H,P,Rs,Rl	Platform	SIO
Mali Lošinj	44 32N 14.28E	53	W,D,Ta,H	Coastal Stn	Croatia
Piran Buoy	45.55N 13.55E	5	W	Buoy	MBS-NIB
Veli Rat	44.15N 14.25E	49	W,D,Ta,Ts,H,P,Rs	Coastal Stn	EACE
Venice	45.31N 12.51N	20	W,D,Ta[d],Ts,H,P,Rs[d]	Tower	ISMAR-CNR
Zadar	44.10 N 15.36 E	79	W,D, Soundings	Airport	Croatia

[a] W, wind speed; D, direction; Ta, temperature of air; Ts, temperature of sea; H, humidity; P, pressure; Rs, shortwave radiation; Solar, Rl, long wave radiation; SIO, Scripps Institution of Oceanography.

[b] Taken at airport.

[c] Taken in harbor.

[d] Taken in Venice city lagoon.

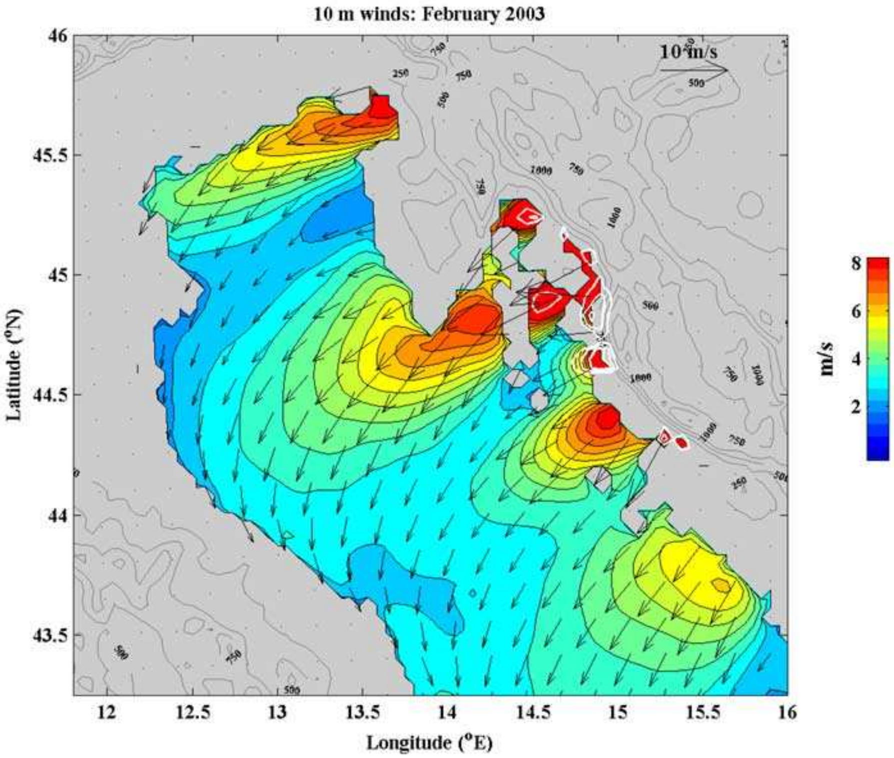

Figure 2. February 2003 COAMPS mean 10-m winds. Arrows point down wind.

Trieste to Venice. *Orlić et al.* [1986, 1994] determined the bora profile along the east Adriatic coast, with maxima close to Trieste, Senj, Šibenik, and Makarska, and minima in between. The along-basin bora profile resulting from climatological data was confirmed and somewhat refined by recent satellite [*Zecchetto and Cappa*, 2001] and aircraft [*Grubišić*, 2004] measurements. The MM5 atmospheric mesoscale model-simulated bora wind fields with a hori-

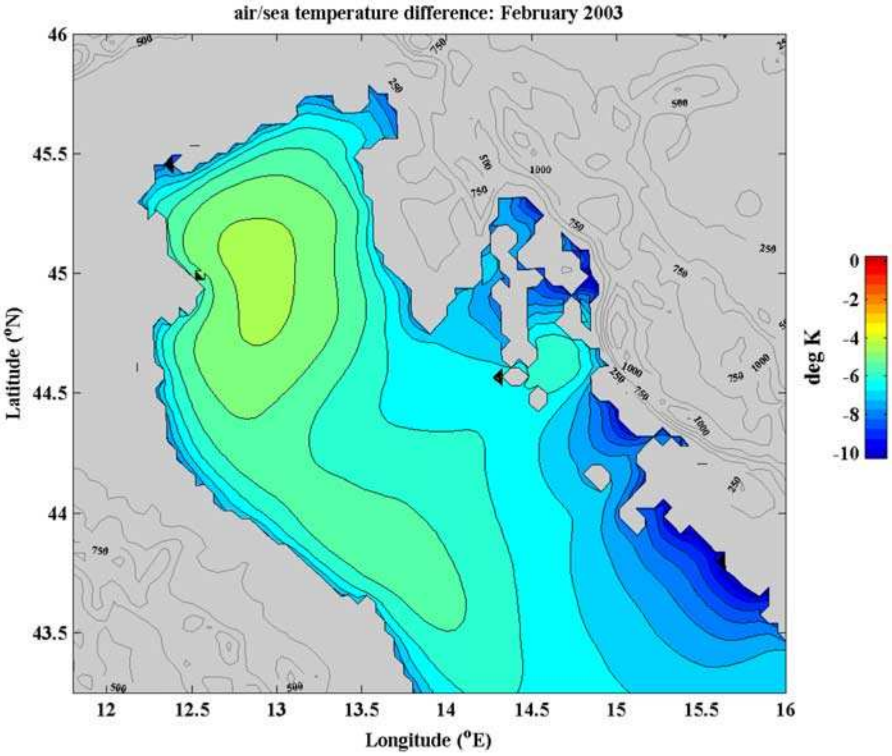

Figure 3. February 2003 COAMPS mean air minus sea temperature.

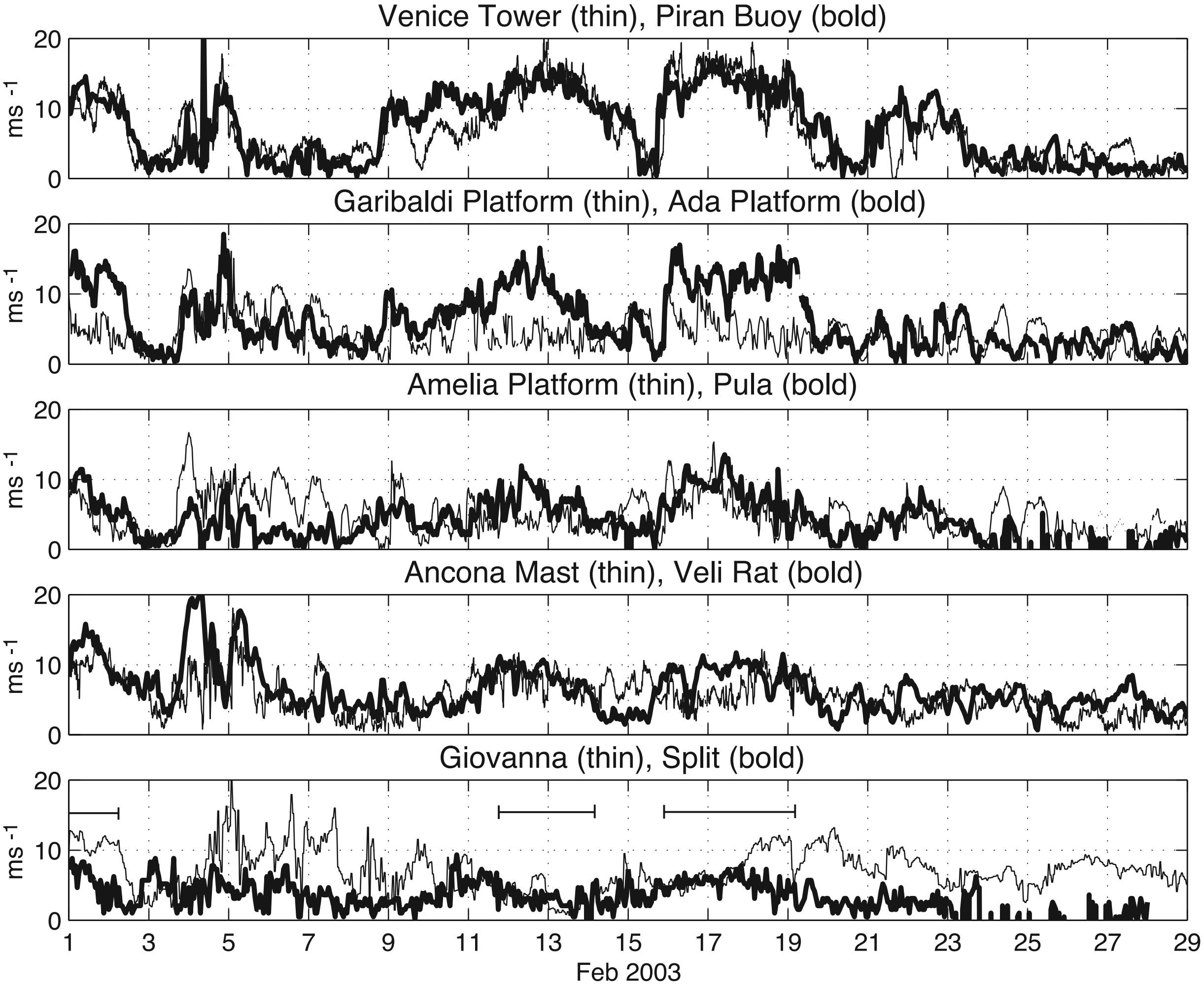

Figure 4. February 2003 hourly wind speeds at selected cross-Adriatic station pairs. Winds are adjusted to a normalized height of 10 m assuming a neutral atmosphere. Boras defined by Zadar winds are indicated by the horizontal bars in the fifth panel.

zontal resolution of 10 km were realistic enough to successfully force an oceanographic model [*Beg Paklar et al.*, 2005].

[8] Another important characteristic of the bora is its gustiness. It was shown that at Senj the gusts are less pronounced than those at Trieste during long-lasting bora episodes [*Bajić*, 1989]. Gusts occur at periods of 3–11 min [*Petkovšek*, 1982, 1987]. When the high-rate measurements were extended over two months it was found that the gusts could appear, disappear, and reappear inside a single bora episode [*Belušić et al.*, 2004].

[9] The feedback of the sea on the atmosphere has received little attention. In a rare study *Enger and Grisogono* [1998] showed that the greater the temperature of the sea with

Table 2. Veli Rat February 2003 Meteorological and Flux Statistics

	Mean	Standard Deviation	Minimum	Maximum
Air T,[a] °C	6.1	2.4	1.5	13.8
RH,[a] %	49	11	25	80
SST,[b] °C	11.8	0.5	10.8	13.4
SST-AirT,[b] °C	5.8	2.5	0.2	10.4
Speed,[a] m s^{-1}	6.5	3.4	0.7	20.2
Q_{SW},[a] W m^{-2}	166	252	0	847
Q_{LW},[b] W m^{-2}	−127	4	−139	−119
Q_{SEN},[b] W m^{2}	−64	40	−147	−1
Q_{LAT},[b] W m^{-2}	−214	71	−375	−64
Q_{NET},[b] W m^{2}	−215	307	−638	537
Stress,[a] N m^{2}	0.071	0.062	0.002	0.275

[a] Time: 1–28 February 2003.
[b] Time: 9.5–28 February 2003.

Table 3. Ancona Mast February 2003 Meteorological and Flux Statistics

	Mean	Standard Deviation	Minimum	Maximum
Air T, °C	4.8	2.0	0.3	12.8
RH,[a] %	68	14	31	93
SST, °C	7.2	0.7	5.5	9.1
SST-AirT, °C	2.4	1.9	−4.0	7.3
Speed, m s^{-1}	5.6	2.7	0.7	16.0
Q_{SW},[b] W m^{-2}	100	131	0	547
Q_{LW}, W m^{-2}	−89	4	−102	−79
Q_{SEN}, W m^{-2}	−24	20	−97	50
Q_{LAT}, W m^{-2}	−66	33	−170	0
Q_{NET}, W m^{-2}	−76	141	−351	418
Stress, Pa	0.071	0.068	0	0.617

[a] RH taken at airport.
[b] Short wave taken at harbor building.

Table 4. Venice Tower February 2003 Meteorological and Flux Statistics[a]

	Mean	Standard Deviation	Minimum	Maximum
Air T*,[b] °C	3.8	2.4	−1.0	10.4
RH, %	57	13	31	91
SST, °C	4.7	1.6	0.9	9.5
SST-AirT, °C	1.2*	1.1*	−2.2*	4.5*
Speed, m s^{-1}	6.8	4.6	0	18.4
Q_{SW},[b] W m^{-2}	124	182	0	571
Q_{LW}, W m^{-2}	−92	4	−101	−82
Q_{SEN}, W m^{-2}	−12	15	−83	17
Q_{LAT}, W m^{-2}	−66	40	−198	0
Q_{NET}, W m^{-2}	−50	197	−373	466
Stress, Pa	0.110	0.150	0.000	0.714

[a] Time: 1–25.4 February 2003.

[b] Air temperature and short wave taken at Venice city lagoon.

Table 6. Garibaldi-C Platform February 2003 Meteorological and Flux Statistics[a]

	Mean	Standard Deviation	Minimum	Maximum
Air T, °C	9.0	1.3	6.3	13.6
RH, %	61	14	33	98
SST, [b] °C	8.2	0.4	6.8	9.0
SST-AirT, °C	−0.8	1.4	−6.0	2.1
Speed, m s^{-1}	3.0	2.1	0	10.6
Q_{SW}, W m^{-2}	110	166	0	544
Q_{LW}, W m^{-2}	−90	5	−102	−78
Q_{SEN}, W m^{-2}	1	3	−9	13
Q_{LAT}, W m^{-2}	−19	23	−95	1
Q_{NET}, W m^{-2}	2	170	−184	452
Stress, Pa	0.013	0.024	0	0.153

[a] Time: 2003 Feb 9–28.

[b] SST taken at platform Cervia-C.

respect to that of the land, the larger the bora fetch over the sea. *Pullen et al.* [2006] found that ocean feedback significantly improved an atmospheric model performance.

[10] This paper reports on the meteorological results of an international oceanographic program that took place over the northern Adriatic Sea during the winter of 2002–2003. During this program, special surface measurements were made at Italian gas platforms and by an instrumented research vessel that supplemented ongoing measurements at an instrumented meteorological tower, mast, buoy and beach coastal stations as well as operational airport stations. Special atmospheric soundings were also taken at a Croatian coastal airport (Figure 1).

2. Data Description

[11] Several stations were used to examine the meteorology at representative locations in the northern Adriatic (Figure 1 and Table 1). A Slovenian MBS-NIB meteorological buoy was anchored on the southern side of the Gulf of Trieste off Piran. The over water station on the NW coast is the ISMAR-CNR Institute Venice tower located 16 km off the main inlet leading to Venice. However, the shortwave radiation and the air temperature for Venice come from a site in the Venice lagoon. The over water station on the western coast is the ISMAR-CNR Ancona Section meteorological mast positioned 2 km offshore near Ancona, Italy (Senigallia Station). Shortwave radiation was measured at a building in Ancona Harbor, and the humidity was taken at the Ancona airport close by. EACE took the Veli Rat meteorological data. More distant from shore, but in the midwestern Adriatic, were the Scripps Institution of Oceanography instrumented Italian AGIP gas platforms of Amelia-B, Azalea-B, Cervia-C and Garibaldi-C. The Cervia-C sea surface temperature was used for the one that failed at Garibaldi-C. Anemometer heights were adjusted to 10 m for all wind stress, and heat flux calculations as described by *Fairall et al.* [2003]. The R/V *Knorr* made 10-min averaged meteorological measurements over the northern Adriatic from 31 January to 24 February 2003 (Figure 1, right).

[12] Atmospheric soundings were taken twice a day at the Zadar airport, which is on a low coastal plain at the western foot of the Croatian coastal mountains. The Croatian Meteorological Service used a Vaisala system with a balloon-lifted, GPS-based sonde to make twice-a-day soundings.

[13] The atmospheric portion of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) [*Hodur*, 1997], which is the operational and research mesoscale modeling system of the U.S. Navy, is applied in a reanalysis and forecast mode in order to obtain an analysis of the surface conditions in the Adriatic. The COAMPS atmospheric model is a finite difference approximation to the fully compressible, nonhydrostatic equations. Physical parameterizations are used to represent surface fluxes, boundary layer, radiation, and moist processes including microphysical quantities [see *Hodur*, 1997]. The domain configuration for these reanalysis simulations contains three horizontally nested grid meshes with horizontal grid increments on the computational meshes of 36 km, 12 km, and 4 km, respectively. The 4-km resolution grid mesh

Table 5. Azalea-B Platform February 2003 Meteorological and Flux Statistics[a]

	Mean	Standard Deviation	Minimum	Maximum
Air T, °C	8.9	1.2	5.8	12.0
RH, %	64	12	38	95
SST, °C	8.1	0.5	6.3	9.0
SST-AirT, °C	−0.8	1.3	−4.3	3.1
Speed, m s^{-1}	5.4	2.9	0.1	13.0
Q_{SW}, W m^{-2}	137	183	0	646
Q_{LW}, W m^{-2}	−89	4	−99	−77
Q_{SEN}, W m^{-2}	2	6	−36	20
Q_{LAT}, W m^{-2}	−31	30	−115	1
Q_{NET}, W m^{-2}	19	189	−190	549
Stress, Pa	0.042	0.052	0	0.243

[a] Time: 9–28 February 2003.

Table 7a. R/V *Knorr* 31 January to 24 February 2003 Meteorological and Flux Statistics[a]

	Mean	Standard Deviation	Minimum	Maximum
Air T, °C	5.1	2.1	0	12.1
RH, %	54	14	0	91
SST, °C	11.3	2.4	0	14.4
SST-AirT, °C	6.1	2.9	−1.7	14.3
U, m s^{-1}	−0.7	6.6	−22.3	20.2
V, m s^{-1}	−0.5	6.5	−17.5	25.1
Speed, m s^{-1}	8.1	4.4	0	24.1
Q_{SW}, W m^{-2}	100	162	0	683
Q_{LW}, W m^{-2}	−85	13	−109	−44
Q_{SEN}, W m^{-2}	−83	62	−361	33
Q_{LAT}, W m^{-2}	−170	193	−557	−4
Q_{NET}, W m^{-2}	−238	237	−969	482
Stress, Pa	0.168	0.194	0	1.590

[a] Time: 31 January 2003 1800 through 24 February 2003 1116, 23.7 days.

Table 7b. R/V *Knorr* 11–14 Feruary 2003 Meteorological and Flux Statistics

	Mean	Standard Deviation	Minimum	Maximum
Air T, °C	3.5	1.4	0.8	6.7
RH, %	58	4	44	68
SST, °C	11.9	1.2	9.4	14.1
SST-Air T, °C	8.3	1.2	5.2	11.0
U, m s^{-1}	−1.2	8.8	−17.5	24.1
V, m s^{-1}	−5.7	8.8	−22.3	20.2
Speed, m s^{-1}	12.9	4.7	0.5	24.1
Q_{SW}, W m^{-2}	98	150	0	633
Q_{LW}, W m^{-2}	−69	5	−106	−80
Q_{SEN}, W m^{-2}	−172	58	−361	−18
Q_{LAT}, W m^{-2}	−272	82	−507	−40
Q_{NET}, W m^{-2}	−438	228	−969	265
Stress, Pa	0.397	0.272	0	1.458

is centered over the Adriatic Sea. The model is configured with 30 vertical levels on a nonuniform vertical grid consisting of an increment of 10 m at the lowest level. COAMPS uses a surface flux parametrization by *Louis et al.* [1981]. Additional details of the COAMPS reanalysis and forecasts are given by *Pullen et al.* [2003].

[14] The COAMPS Adriatic reanalysis and forecast simulations have been extensively evaluated. *Pullen et al.* [2003] compared wind velocity measurements at several coastal stations with the 36 km and 4 km resolution nested fields for 28 January to 4 June 2001. The researchers found that the 4-km resolution fields were superior in resolving the detailed structure of the bora jets, in matching observed velocity statistics, and in more faithfully reproducing the observed depth-dependent ocean velocity structure when used to drive a realistic 3D ocean model. Measured/modeled correlations of 10-m wind velocity were over 0.85. *Pullen et al.* [2006] extended that study to include the effects of two-way coupling between the ocean and atmosphere models for a month-long simulation in fall 2002. Velocity measurements at three overwater stations were compared with modeled fields. Overall, mean bias levels were approximately 0.5 m s^{-1}; these values were reduced by half using two-way coupling. In addition, the SST mean bias and root-

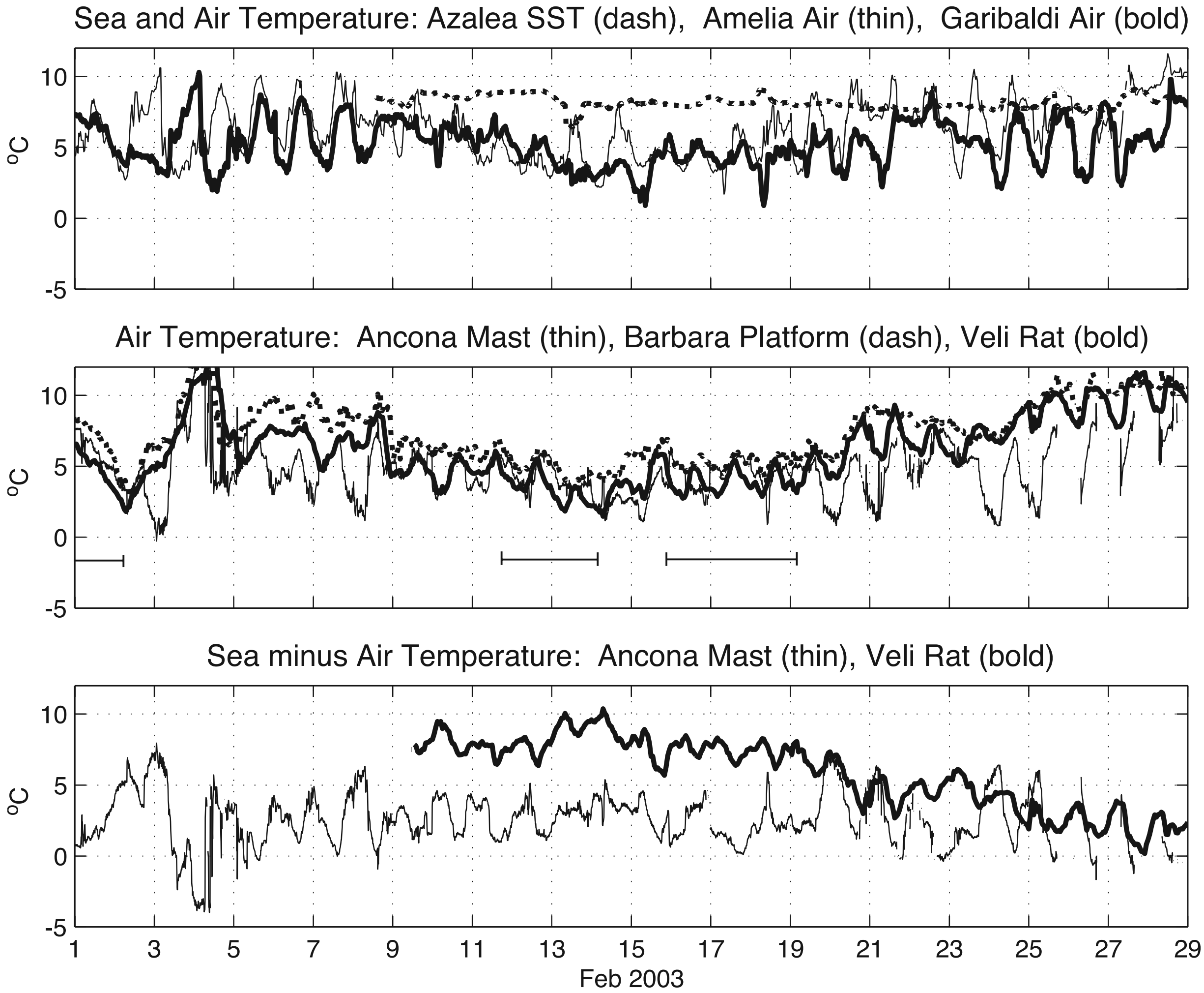

Figure 5. (top) February 2003 hourly air temperature and sea temperature at midwestern Adriatic platforms. (middle) Air temperatures at mid-Adriatic stations of Ancona, Amelia, and Veli Rat. (bottom) Sea minus air temperature at mid-Adriatic stations of Ancona and Veli Rat. Boras defined by Zadar winds are indicated by the horizontal bars in Figure 5 (middle).

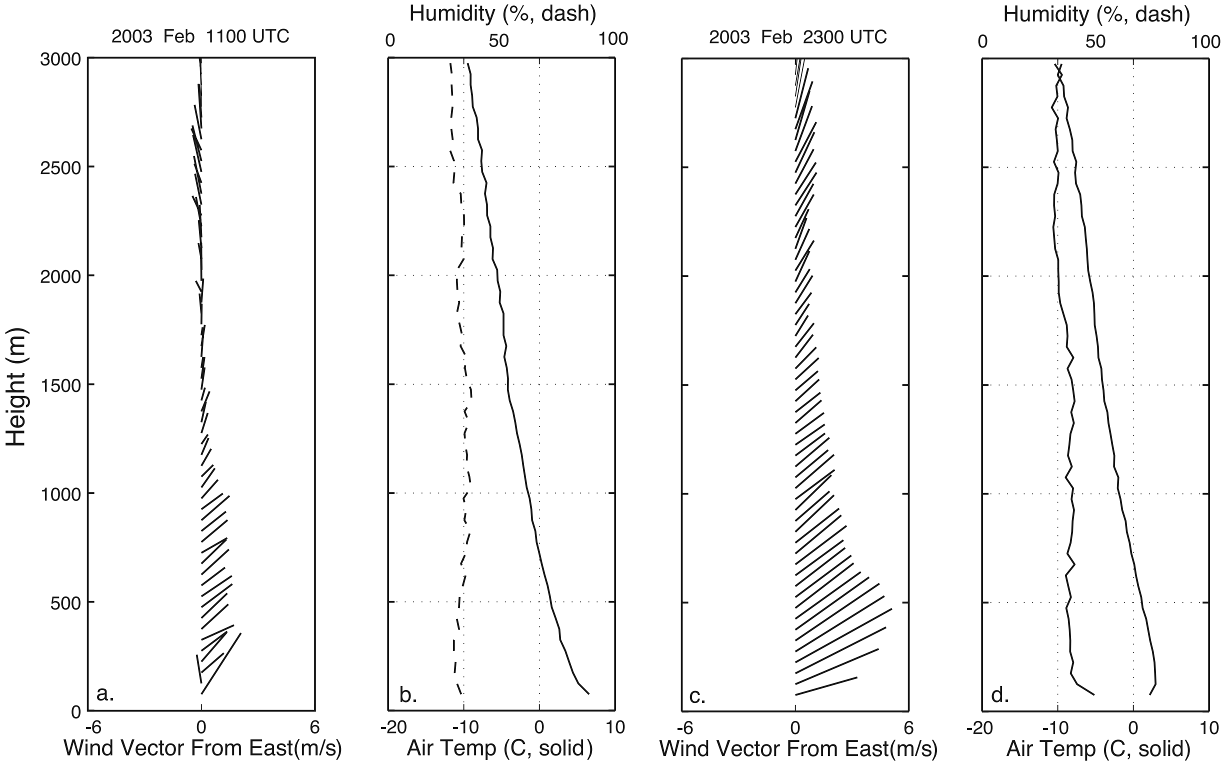

Figure 6. Zadar mean February 2003 sounding for (a and b) 1100 UTC and (c and d) 2300 UTC. Wind vectors start from 0 speed at elevation taken and point upwind similar to a compass. Wind speed is vector length scaled by horizontal axis. Data are averaged at 50-m intervals.

mean-square error (RMSE) statistics were reduced by over 0.5°C using two-way coupling. Moreover, *Jiang and Doyle* [2005] found good agreement of COAMPS 1-km simulations with aircraft winds and TKE measured during a bora in November 1999.

3. February 2003 Conditions Over the Northern Adriatic

3.1. Sea Surface

[15] The mean February 2003 surface conditions over water are represented by the COAMPS mesoscale model simulations that have the advantage of uniformly covering the northern Adriatic (Figure 2). The 10-m winds are from the NE over most of the Adriatic, with the direction turning to be from the N or even NNW close to the Italian coast, due to partial blocking by the Italian mountains. Alternating, topographically forced bora high-speed wind jets and weak wind wakes are positioned along the eastern Adriatic coast. The jets are at Trieste, Senj (the strongest), Novalja, and Šibenik. For each jet, the highest over water speeds are at the coast. Only the Trieste Jet reaches across the entire Adriatic. Between each jet is a weak wind wake and the largest area wake extends westward from the Istria peninsula.

[16] The air temperature over water is warmest in the central and southern Adriatic, grading to the colder northern coast (not shown). The absolute coldest air temperatures are on the edge of the northern coast extending from Venice to Trieste and the inner Croatian coast around Senj. The sea surface temperature also grades from warmest in the south to colder in the north (not shown). The exception to this trend is in the large pool of cold water in the northwestern end of the Adriatic as the water of the cold Po River pushes in and turns cyclonically. That is also an area where dense water is generated during severe winters [*Vilibić and Supić*, 2005], being also observed in winter 2003 [*Lee et al.*, 2005]. The COAMPS February mean air temperature minus sea temperature is always negative, as the air is colder (Figure 3). The largest difference approaches −10° C along the central Croatian coast and inner passages where the fastest, coolest air first comes off land over the relatively warm Adriatic. This shifts to the smallest difference of − 4° C over the cold pool in the NW central Adriatic at 45° N 13° W.

[17] The horizontal wind structures of the COAMPS analyses are generally consistent with those measured at the fixed stations and the research vessel. The location, structure and values of the wind jets and weaker wakes on the NE half of the Adriatic are supported by the measurements available. However, the COAMPS February mean sea minus air temperatures are overestimated by a few degrees in the NE coast and underestimated by a few degrees in the mid-central NW Adriatic where measured values hover around zero. Part of the differences may be because the COAMPS sea surface temperature analysis is derived from a smooth version of the satellite-derived sea surface temperature that misrepresents some of the more subtle processes nearshore. In addition, the Po River thermal structure is generally not in the COAMPS analysis,

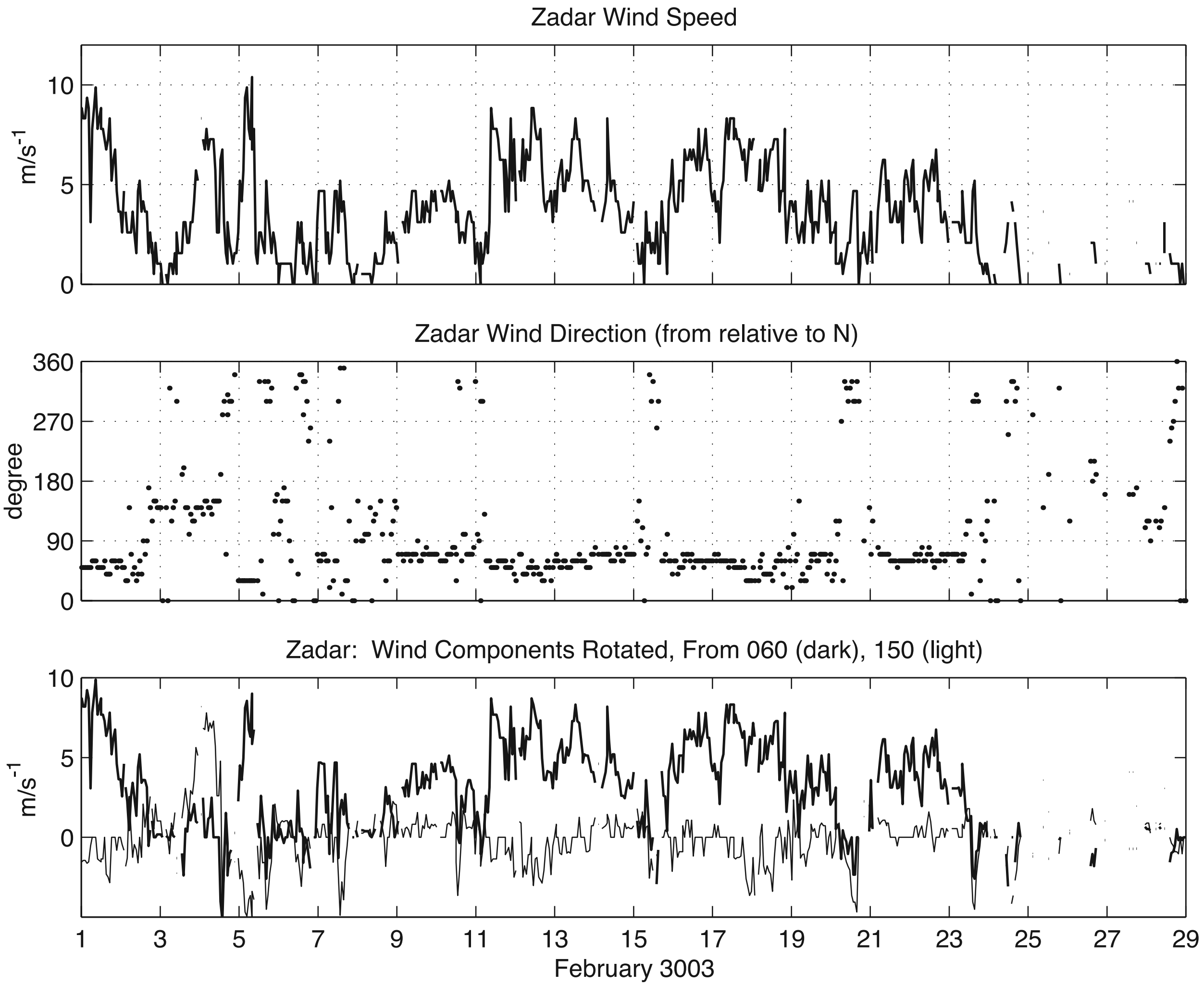

Figure 7. (top) Zadar hourly surface winds for February 2003. (middle) Wind direction and (bottom) positive wind components are from.

Table 8. Bora Events Determined by the Zadar Wind Component From 060 > 2.6 m s^{-1} Lasting 24 hours or Longer[a]

Start				End				Duration, hours	Average Speed, m s^{-1}	Maximum Speed, Ms^{-1}	Average AT, °C	Minimum At, °C	Number
Year	Month	Day	Hour	Year	Month	Day	Hour						
02	11	5	9	02	11	6	18	33	4.5	6.6	8.3	4	1^b
02	11	30	21	02	12	2	1	28	4.3	8.2	11.0	8	2
02	12	4	3	02	12	9	23	140	5.8	11.2	8.6	1	$3a^b$
02	12	18	12	02	12	19	8	20	4.2	7.6	5.5	2	$3b^b$
03	1	11	2	03	1	12	23	45	5.9	9.2	1.0	−2	4^b
03	1	23	22	03	1	27	6	80	6.7	12.7	8.0	4	5^b
03	1	31	14	03	2	2	6	40	5.6	9.7	3.0	−2	6^b
03	2	4	22	03	2	5	21	23	4.4	10.3	4.4	1	short
03	2	11	7	03	2	14	4	69	5.6	8.7	2.0	−3	7^b
03	2	15	21	03	2	19	5	80	5.6	8.2	2.1	−2	8^b
03	2	21	19	03	2	22	16	21	4.7	6.7	5.4	3	short
03	3	3	20	03	3	5	8	36	2.7	5.6	9.1	4	9^b
03	3	13	18	03	3	14	11	17	3.4	4.6	5.8	1	$10a^b$
03	3	14	18	03	3	17	0	54	6.4	12.2	5.9	2	$10b^b$
03	4	3	17	03	4	8	3	106	4.7	8.8	7.8	−3	11^b
03	4	14	0	03	4	18	19	115	4.7	9.2	16.0	5	
03	5	15	8	03	5	16	8	24	3.5	5.1	18.8	11	
03	5	21	4	03	5	22	21	41	3.6	8.2	16.9	11	
03	5	28	23	03	5	30	3	28	3.2	5.1	24.8	22	

[a] Events with mean air temperature near or less than 10° C, approximately the Adriatic sea surface temperature, are numbered. Events are counted as a and b if there was a significant dip in the wind speed between them but might otherwise be considered as the same continuous event.

[b] Mean air temperature of event <10° C, about SST of Adriatic.

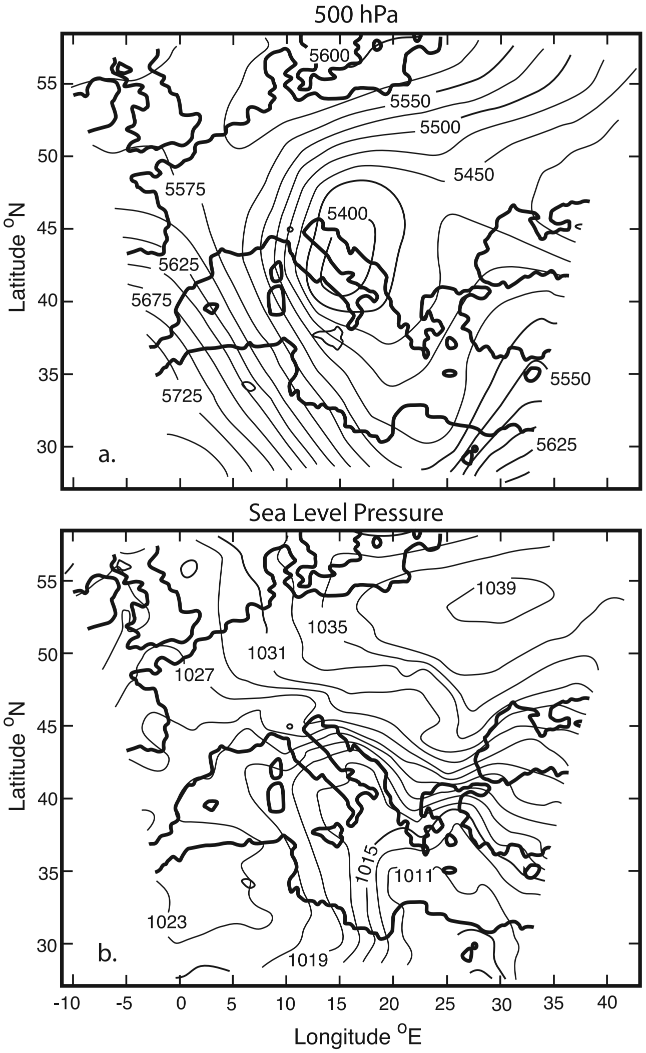

Figure 8. (a) The 500 hPa and (b) sea level pressure COAMPS nest 1 (36 km) analysis at 0000 UTC 12 February 2003 during the strongest portion of the 11–14 February bora.

although this is believed not to play a major factor in the dynamics during this period.

3.2. Surface Stations

[18] The near sea surface wind structure has great variation over the Adriatic while being correlated in time. As shown in the previous section, the fastest winds are near the NE Adriatic coast in the topographically formed jets. The Trieste Jet's wind speeds measured by the Piran meteorological buoy in the Gulf of Trieste were up to 19 m s^{-1} (Figure 4, first panel). The Trieste Jet's Piran buoy measured wind speeds are undiminished downwind at Venice tower (Figure 1, left) for any of the three February 2003 boras (1 February, 11–14 February, 15–19 February). This jet structure sweeping across the entire northern Adriatic is also captured by RADARSAT, as will be noted in section 5.2. This result is in conflict with *Polli* [1956], who found that wind jets are reduced by about 30% when blowing from Trieste to Venice but did not have the benefit of fixed station, over water measurements. Some of the Trieste Jet flow turns to the south and expands while weakening in speed, resulting in peak values of 12–15 m s^{-1} at the Ada platform (Figure 4, second panel). The other jets do not extend as far across the Adriatic. Meteorological statistics for representative stations are shown in Tables 2–7b.

[19] Away from the northern coast, the speeds decelerate more rapidly across the Adriatic. The weakest winds in the northern Adriatic are south of 45.5°N, west of 13.5°E, and away from the Italian coast. There are only weaker winds at the Garibaldi platform (Figure 4, second panel) or at Amelia (Figure 4, third panel). Wind speeds and components at the SIO-equipped platforms in this area have moderate correlations between 50% (most distant) to 75% (closest).

[20] Wind events reach similar maximum speeds (near 10 m s^{-1}) at the mid-Adriatic station triangle characterized by the Pula, Veli Rat, and Ancona mast stations. Of course, these stations are outside of the Senj and Novalja jets (Figure 2). Nevertheless, outside of the jets, the bora wind events are correlated, and there is a significant wind speed increase at stations nominally in wake zones such as Veli Rat, Mali Lošinj, or even Zadar.

[21] South of Ancona, the surface conditions are represented by the Giovanna platform in the west and Split in the east (Figure 4, fifth panel) where the variations have a different character as this area is affected by other synoptic

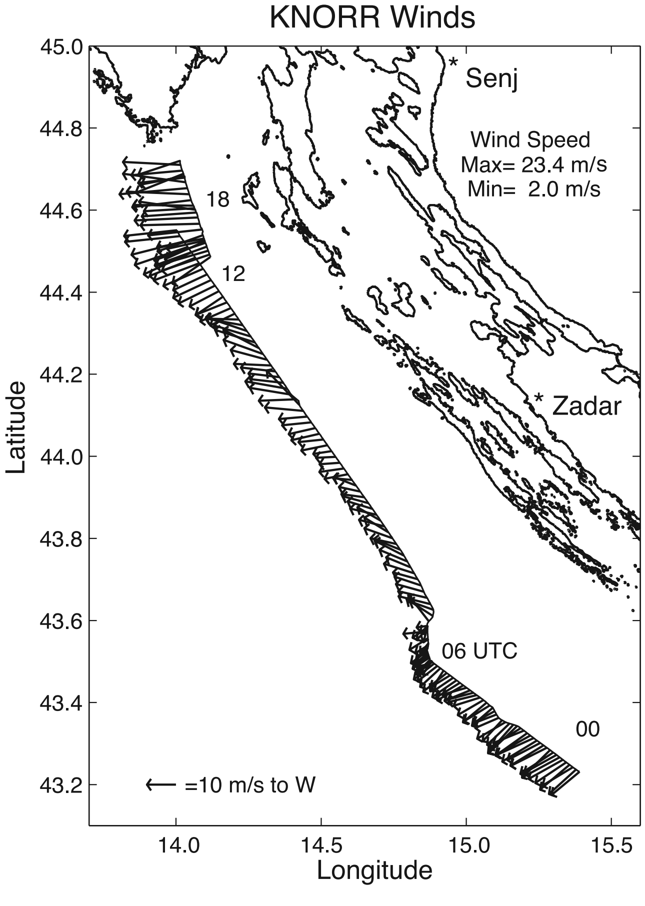

Figure 9. Winds measured by R/V *Knorr* 0130–1847 UTC on 11 February 2003. Arrows flow with the wind, with tail at the measurement position. Numbers designate the time of the ship position in UTC.

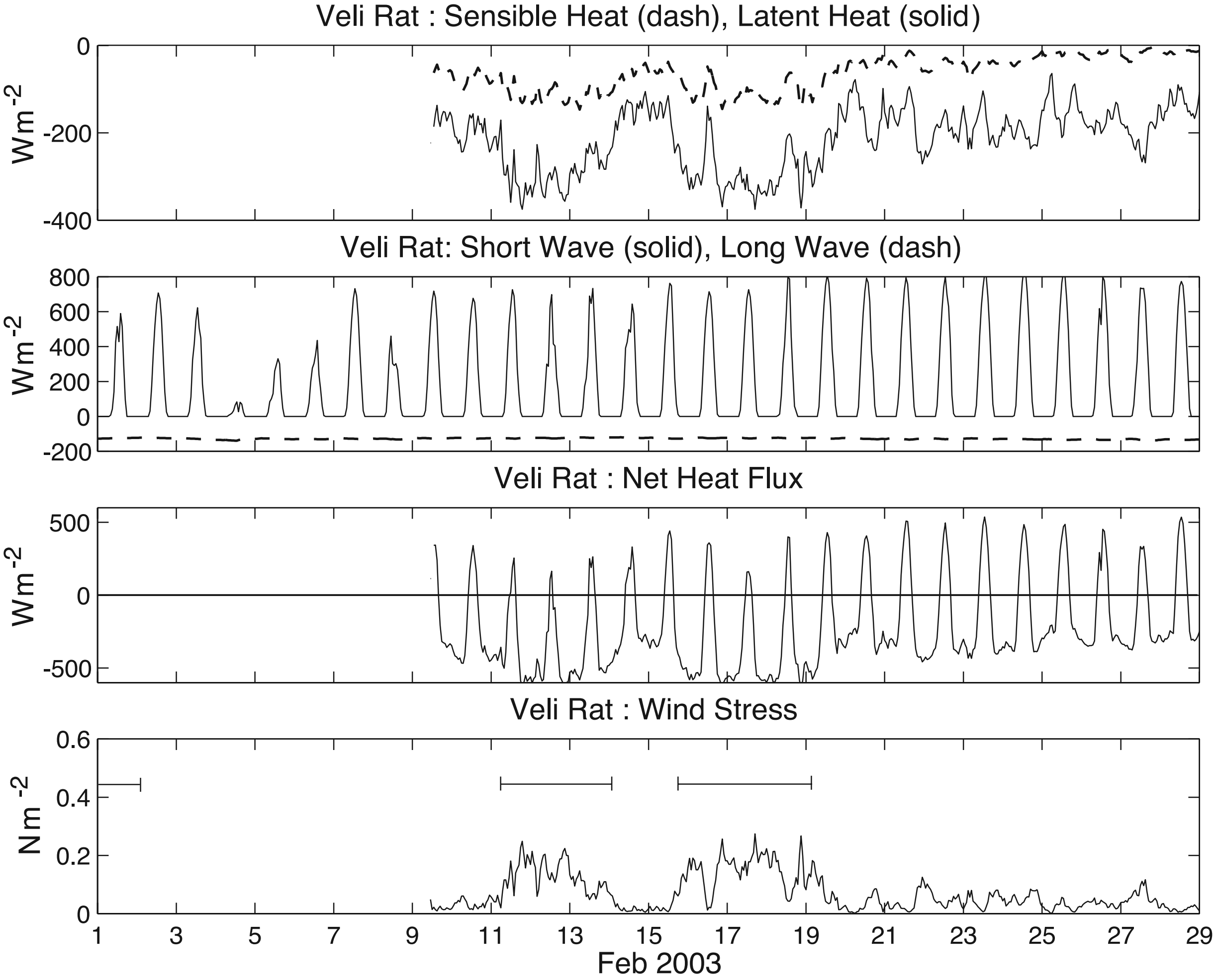

Figure 10. Veli Rat February 2003 heat fluxes and wind stress. Boras defined by Zadar winds are indicated by the horizontal bars in the fourth panel.

factors. Giovanna experiences much stronger events on 6–8 February and 18–22 February than that experienced by the stations more to the north. Split only has a weak shadow of the 11–14 February and the 15–19 February boras and even weaker winds than at the midwestern platforms.

[22] The air temperature has a clear diurnal cycle at all stations, and trends over several days are well correlated at all stations (Figure 5, middle). The smallest diurnal temperature cycles are on the NE coast as at Veli Rat or measured by the *Knorr* in the Senj Jet on11–14 February (not shown). Larger diurnal temperature variations are experienced by Ancona on the west coast. However, the greatest afternoon peaking temperature is at the platforms from Garibaldi to Azalea in the midwestern Adriatic platforms (Figure 5, top, Amelia and Garibaldi air temperature).

[23] The sea minus air temperature difference is important to the characterization of sea surface fluxes and boundary layer turbulence. This temperature difference approaches an extreme +8°C to +10°C on the NE Adriatic coast at Veli Rat during the 11–14 February bora when cool air moves over relatively warm ocean surface water. The sea minus air difference decreases as the air moves across the Adriatic, so that the difference is reduced to +2°C to +4/6°C on the western coast at Ancona. The very lowest sea minus air difference is around zero at the midwestern Adriatic platforms (Azalea SST is in Figure 5, bottom, for reference).

[24] The humidity values and variations at Veli Rat are generally similar to those at Venice and Amelia-B (not shown). Diurnal variations dominate all of the measured records and values are near midvalues and without extremes. With this noisy background of large diurnal variations in humidity and air temperature, it is hard to detect smaller synoptic-scale trends or bora events in the humidity that are statistically resolvable with longer-record land stations.

[25] Another sampling of the sea surface conditions over the northern Adriatic was taken by the *Knorr* between 31 January and 24 February 2003. As all but a few hours were in February, and the observations were rather evenly distributed over the northern Adriatic (Figure 1, right), this represents a quasi-mean of the February 2003 conditions over all of the northern Adriatic. The *Knorr* reported the fastest winds and extremes, as

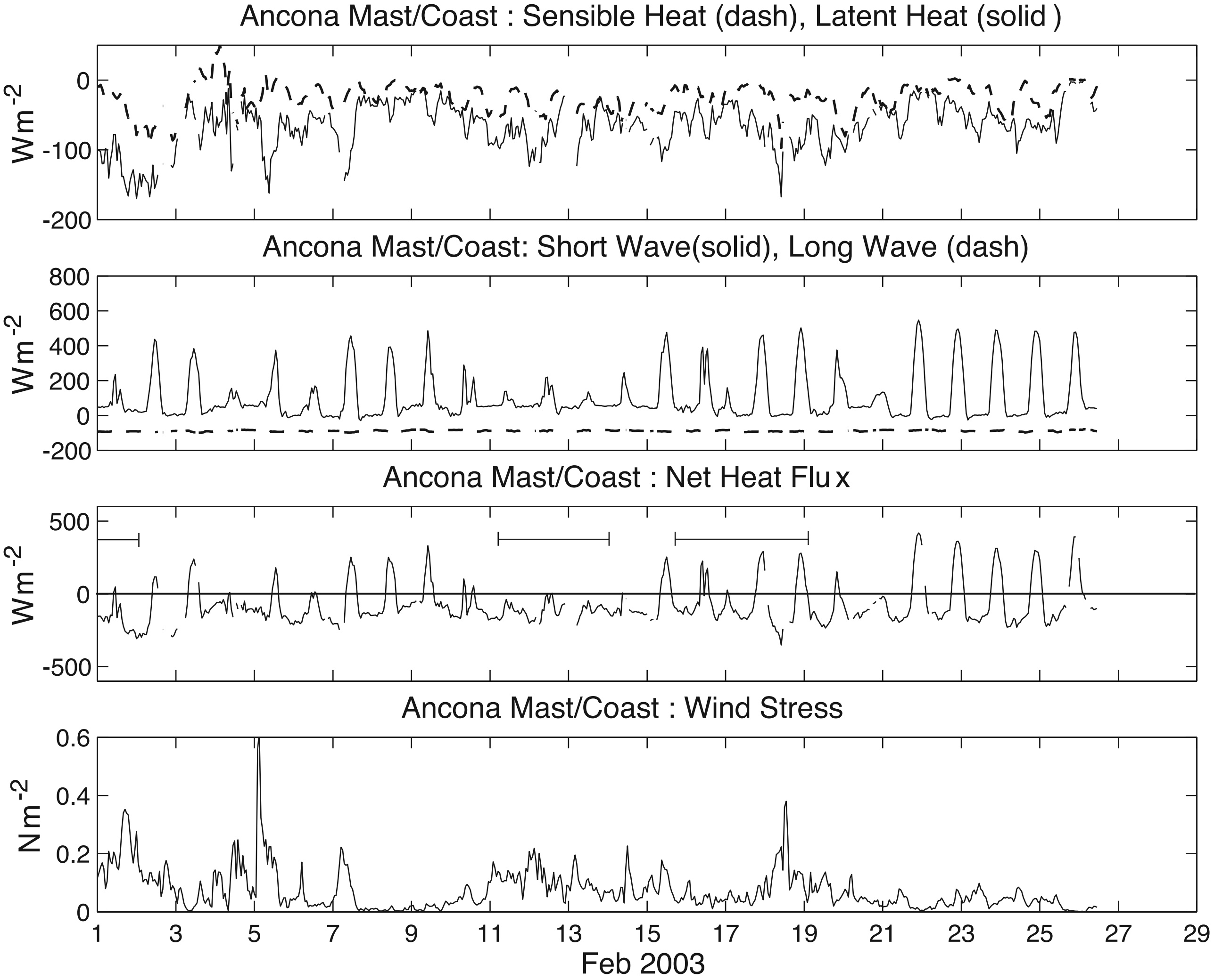

Figure 11. Ancona mast February 2003 heat fluxes and wind stress. Boras defined by Zadar winds are indicated by the horizontal bars in the third panel.

well as the largest mean sea minus air temperature that occurred in the Senj Jet (Tables 7a and 7b).

3.3. Zadar Sounding

[26] As noted earlier, upper air soundings were taken twice a day near 1100 UTC and 2300 UTC at the Zadar airport. The mean 50-m averaged 1100 UTC and the 2300 UTC February soundings both have maximum winds from the NE below 1200 m (Figure 6). The surface jet was most sharply peaked at 2300 UTC at 200-m elevation and more broadly peaked at 1100 UTC, suggesting that diurnal heating plays a significant role in the boundary layer stability and local circulation. Of note is that there was no air temperature inversion and that the lapse rate was that of stable, weakly descending air.

[27] Above the surface, the bora winds at Zadar were dominantly from 045° (not shown). The fastest speeds were below 1200 m during higher-speed wind events, with multiple speed maxima in the range of 10–14 m s^{-1}. The wind speeds were substantially weaker between 1200 m and 2000 m elevations. For each of the three surface-defined February wind events, there was a distinct wind jet above the surface but below 1200 m.

4. Defining the Bora

[28] An objective method was needed to define when a bora was occurring. Examination of available data suggested that the definition of a bora be based upon the surface winds at a station along the low, NE Adriatic coast between Trieste and Split with a complete record of hourly observations for 2002–2003. Zadar was found to be one of the few stations to meet these criteria and had the advantage that it was available in digital form and was reported to the international weather data network. Bora wind events occurred systematically at the Zadar airport and were coincident with all bora events at other Croatian meteorological sites on the western lee slopes, including weak wind zones. All boras lasting longer than 24 hours start and end within a few hours of each other. However, maximum wind speeds at Zadar were weaker than at wind jet locations such as Senj. The mean February winds at Zadar were from 060° (Figure 7). A bora wind was considered to exist at Zadar

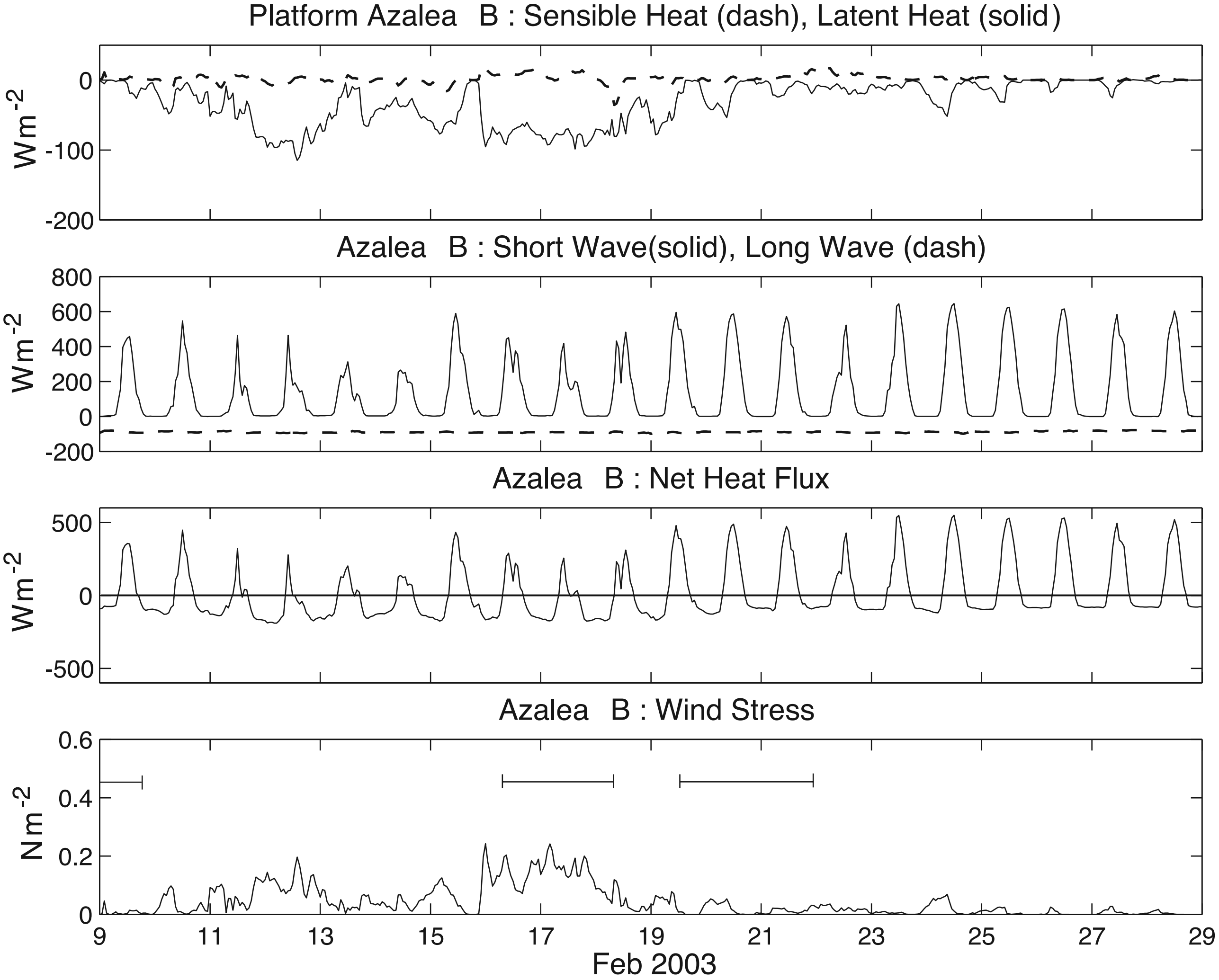

Figure 12. Azalea February 2003 heat fluxes and wind stress. Boras defined by Zadar winds are indicated by the horizontal bars in fourth panel.

when the winds component from 060° had a speed greater than 2.6 m s^{-1} and lasting longer than 24 hours (Table 8). Three so-defined bora events occurred in February 2003, starting on 31 January, 11 February and 15 February. The bora, which lasted from 0700 UTC 11 February to 0400 UTC 14 February, will be studied in greater detail in the next section.

5. Bora Case of 11–14 February 2003 Over the Northern Adriatic

5.1. Large-Scale Synoptic Setting

[29] This section reviews the synoptic patterns influencing the 11–14 February bora based upon the COAMPS reanalysis. One day before the bora began, on 10 February, a large 500 hPa low was centered over the southern Black Sea coast with a trough extending to the west, reaching over central Italy. Near the start of the bora, at 1200 UTC, 11 February, there was a large low over the Black Sea with a trough reaching to 45° N 20° E. On the twelfth, at 0000 UTC, part of this large low pinched off into an isolated low center over the northern Adriatic (Figure 8a). On the thirteenth, this low moved to the south Adriatic, and on the fourteenth, the low broadened over Italy, dominating central Europe. This bora was over by 1200 UTC 14 February, when the 500 hPa low shifted to the west of Italy.

[30] At the surface on 10 February before the start of the bora, there was a large anticyclone over central Russia at sea level. From the anticyclone, a ridge extended to Romania while a weak Mediterranean cyclone shifted eastward to 20° E. As a result, the sea level isobars were parallel to the NE Adriatic coast. Near the start of this bora, the center of a ridge extending from the central Russian anticyclone shifted to near the Black Sea. By 0000 UTC on 12 February, the Mediterranean cyclone edged eastward to 22° E, with a weak trough extension reaching to southern Italy (Figure 8b). Sea level isobars then crossed the northern Adriatic coast at an oblique angle, forcing offshore bora flow. The central Russian anticyclone center shifted west to Belarus, remaining there for the next couple of days. By 1200 UTC 12 February, the Mediterranean low had moved east to 30°E, while a trough extended to the southern tip of Italy. Sea level isobars continued to cross the northern Adriatic coast at an oblique angle, maintaining bora winds. This situation continued through the thirteenth. On the fourteenth at 0000 UTC, the eastern European anticyclone

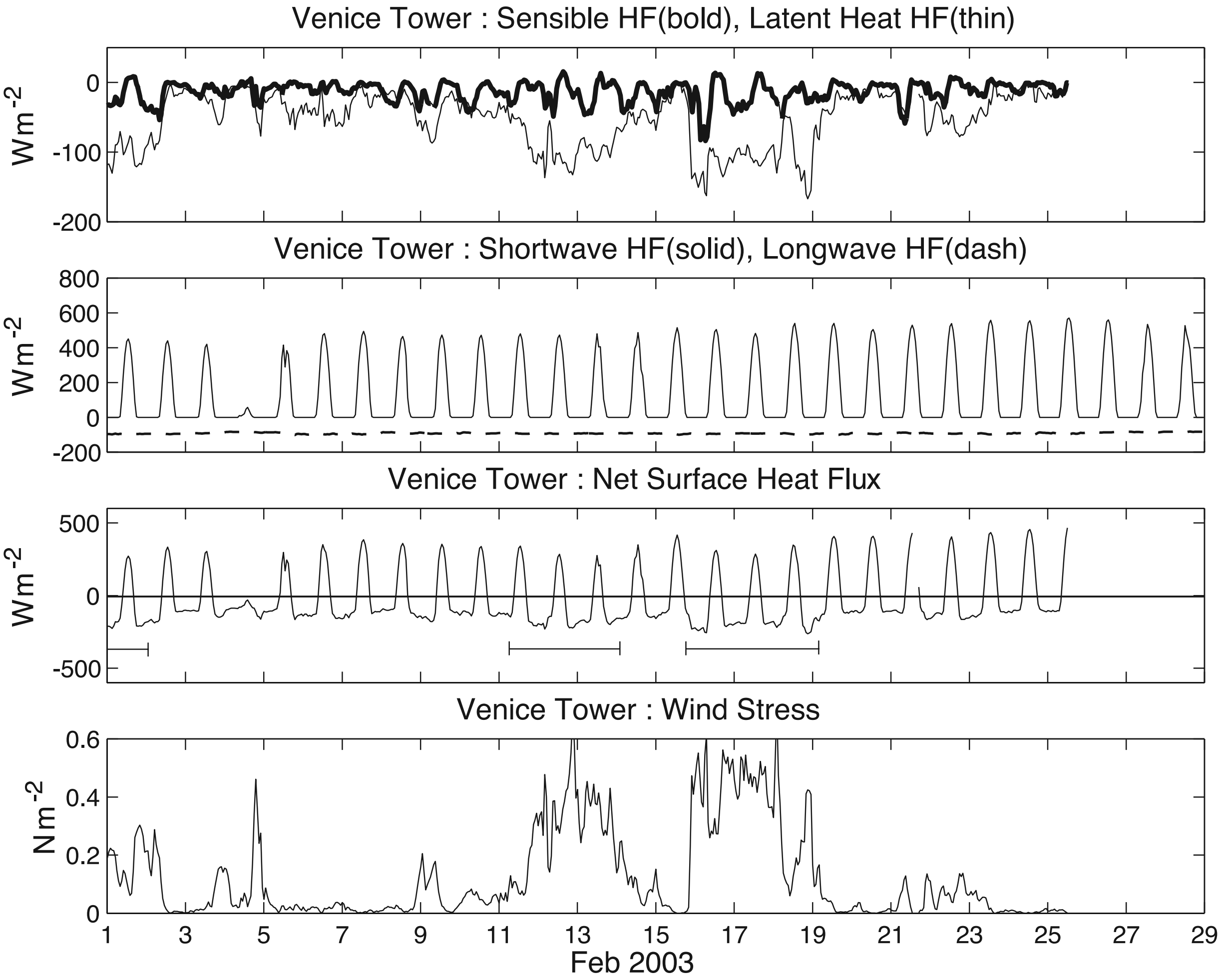

Figure 13. Venice Tower February 2003 heat fluxes and wind stress. Boras defined by Zadar winds are indicated by the horizontal bars in the third panel.

shifted over Denmark with a ridge extending to Romania. At the same hour, a new, weak cyclone appeared over Tunisia. Just after the end of the bora, at 1200 UTC on 14 February, the new Mediterranean weak cyclone axis shifted to the west coast of Italy.

[31] There can be weak, nonbora flow from an easterly direction over the NE Adriatic as there was before 11 February. However, for faster bora wind speeds, upper level support is necessary to reinforce the surface flow such as when the 500 hPa low was over the northern Adriatic during the 11–14 February bora.

5.2. RADARSAT Sea Surface Winds

[32] RADARSAT detected sea surface features are related to the sea surface wind speed [*Horstmann et al.*, 2002; *Vachon et al.*, 1998]. Detailed structures of the bora winds over the northern Adriatic for this case study were captured by the 0500 UTC 12 February 2003 RADARSAT image, shown by *Lee et al.* [2005]. Of note is that all of the major details of the jets and wake zones originating in the eastern Adriatic are matched in the RADARSAT. However, a small-scale difference between COAMPS 10-m winds and RADARSAT is that the latter reveals that the Trieste Jet is actually two close, parallel jets that remain separate across the entire northern Adriatic. The Trieste double jet was repeated in a 0500 UTC 26 January 2003 RADARSAT image taken during another bora (not shown). It is possible that the Trieste double jet was caused by a narrow topographic rise separating the gap just east of Trieste into two, close gaps. Another small-scale difference is that the RADARSAT images better define a narrow, weak wind zone 10–25 km wide along the central Italian coast that probably reflects blocking by the Italian coast and mountains.

5.3. Surface Measurements

[33] Increased wind speeds associated with the 11–14 February bora are readily apparent at the fixed surface stations near the coast (Figures 4 and 7). The fastest winds are at the Piran buoy and Venice tower (above 18 m s^{-1}) that are in the Trieste Jet. This is followed by not as strong winds (around 15 m s^{-1}) at the Ada platform which is touched by the edge of the Trieste Jet. The inland station of Pula, in a transition between the Istria peninsula wind wake and the Senj Jet, has bora event wind speeds around 10 m s^{-1}. In the mid-Adriatic, Veli Rat (in a nominal wind wake) and Ancona winds peak at the more moderate speed of 10 m s^{-1}. In contrast, platforms such as Amelia and Garibaldi in the midwestern northern Adriatic have the weakest northern Adriatic bora winds that tend to average 6–8 m s^{-1} for bora events. It should be pointed out that bora event wind speeds

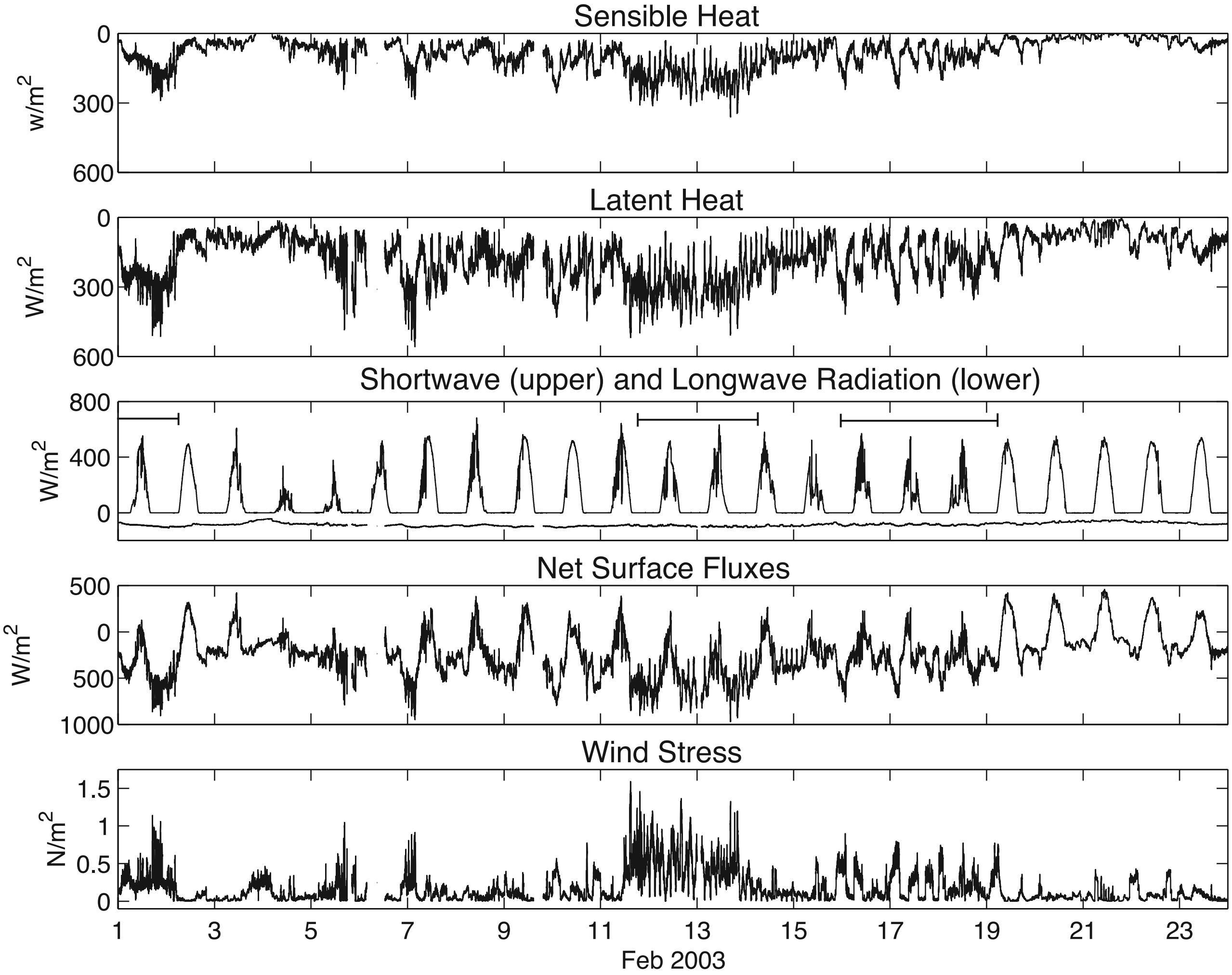

Figure 14. RV *Knorr* February 2003 heat fluxes and stress, based on 10-min averages. Boras defined by Zadar winds are indicated by the horizontal bars in the third panel.

in the NE wind wakes are reduced compared to the jets but are not necessarily "light" (traditionally <2.5 m s^{-1}).

[34] A specific bora signal is hard to see in the air temperature and sea minus air temperature that contain both strong diurnal trends and longer-scale, synoptic trends extending over several days (Figure 5). Throughout the month, there are large, positive sea minus air temperature differences along all of the NE coast, and near zero sea minus air temperature differences measured at platforms in the midwestern northern Adriatic.

[35] At the beginning of this bora, the *Knorr* steamed northbound along the Croatian coast between 43.2° N and 44.7° N from 0130 UTC to 1847 UTC on 11 February 2003. The near sea surface flow (Figure 9) was offshore for the entire leg. Winds at the southern end (off Šibenik) were strong, then weaker off Zadar, followed by the strongest winds off Senj. The smaller Novalja Jet is not identifiable in this transect, possibly due to the result of a moving measurement platform during temporal change – this bora began at 0700 UTC while the track began at 0000 UTC. On the following two days of this bora, 12 and 13 February, the *Knorr* cruised back and forth along tracks perpendicular to the Senj Jet over an area bounded by 44.40–44.75 ° N and 13.60–14.15 ° E, which is in the Senj Jet core, south of Pula (not shown). On these two days, the surface winds were persistently strong northeasterly and without any obvious diurnal trends or shifting of the wind jet structure.

6. Sea Surface Fluxes

6.1. Heat Flux

[36] The net surface heat flux (positive into the ocean) (Q_{NET}) is the sum of four components: the net shortwave radiation flux (Q_{sw}), the net longwave radiation flux (Q_{LW}), the sensible heat flux (Q_{SEN}) due to sea minus air temperature differences, and the latent heat flux (Q_{LAT}) due to evaporation. Ten-minute averaged surface measurements made on the *Knorr* were used to estimate these heat flux components. The two radiation fluxes were computed using standard methods described by *Beardsley et al.* [1998] and *Pawlowicz et al.* [2001]. The sensible and latent fluxes (and wind stress) were computed using the COARE 2.6a bulk algorithm described by *Fairall et al.* [2003]. This code was developed and tested for a broad set of nonequatorial conditions that include those observed in the Adriatic during the winter. On the basis of uncertainties of 5% in Q_{sw}, 10 W m^{-2}

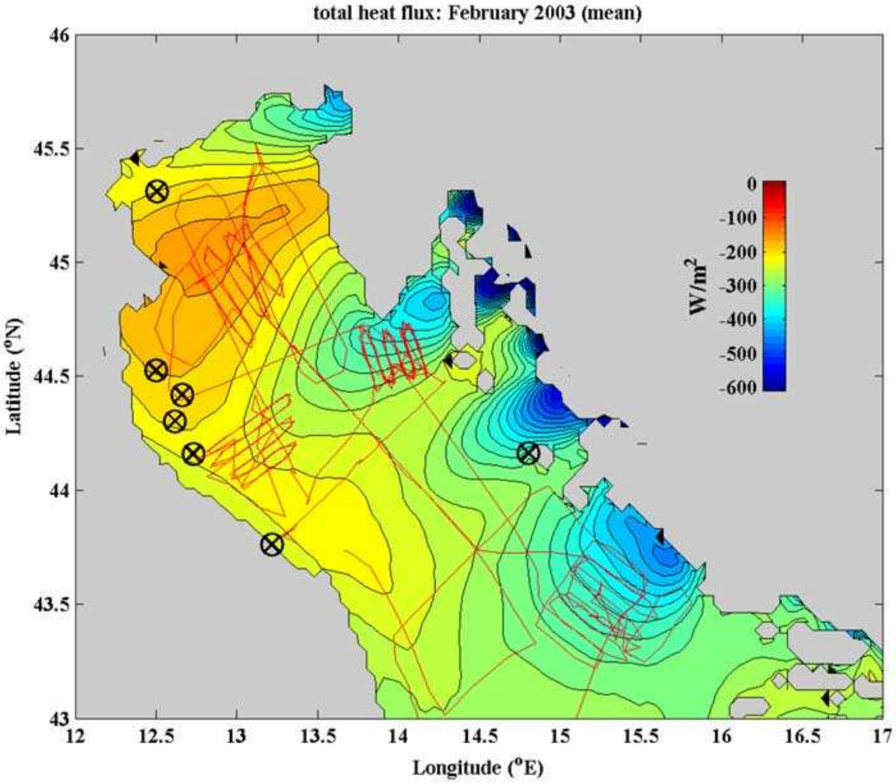

Figure 15. February 2003 COAMPS mean net heat flux. Negative values are a heat loss by the sea. R/V *Knorr* cruise track is in red. Crosses designate a fixed meteorological station (locations in Figure 1, left).

in Q_{LW}, and 7% in Q_{SEN} and Q_{LAT}, the uncertainties in Q_{NET} are 33 W m^{-2} for the entire *Knorr* cruise.

[37] Unlike the *Knorr*, most of the fixed stations did not have a downward longwave radiation measurement. In order to make them comparable, the downward longwave radiation was computed in the same way for all of the fixed stations. The calculation uses the COARE formulation with fixed cloud amount (0.15) to modify the downward, longwave radiation. The station anemometer height was adjusted to 10 m.

[38] The greatest fixed station net ocean surface loss was on the NE coast at Veli Rat (Figure 10). This was expected with the large magnitude sea minus air temperature difference and moderate winds. Still, the lack of clouds allowed enough solar radiation so as to make the net heat flux positive for a few hours around local noon time. The mean net heat loss of -215 W m^{-2} (Table 2) is largest of all of the fixed stations. Of course, the COARE formulations are intended for over water conditions. Nevertheless, the results are consistent with *Knorr* which had similar heat flux deficits offshore of this area.

[39] Smaller net heat losses occurred at the coastal Ancona meteorological mast, with greater cloud cover and somewhat larger sensible heat variations (Figure 11). The net heat flux was dominantly negative, with the ocean surface gaining heat only during the central portion of the solar day when the sky was clear. As a consequence, the average net heat flux was significantly negative (-76 W m^{-2}, Table 3).

[40] The situation shifted in the midwestern northern Adriatic as represented by the Azalea platform (Figure 12). The latent heat experienced smaller variations, the sensible heat was small, and the sky was only partly cloudy or clear. The heat flux was strongly positive during daylight and weakly negative during darkness, so that the daily average was a modest +19 W m^{-2} (Table 5). A similar situation and average (+2 W m^{-2}, Table 6) occurred for the Garibaldi platform (not shown). The difference between the net heat flux at these two platforms is less than the estimated error.

Table 9. Comparison Between COAMPS Simulations and R/V *Knorr* Measurements[a]

	Source	Mean	Standard Deviation	Mean Bias	RMSE	Correlation Coefficient
Q_{SEN}, W m^{-2}	COAMPS	−94	67	10	53	0.67
Q_{SEN}, W m^{-2}	*Knorr*	−84	59	10	53	0.67
Q_{LAT}, W m^{-2}	COAMPS	−181	99	8	85	0.61
Q_{LAT}, W m^{-2}	*Knorr*	−173	91	8	85	0.61
Q_{NET}, W m^{-2}	COAMPS	−303	240	61	166	0.78
Q_{NET}, W m^{-2}	*Knorr*	−242	229	61	166	0.78
Stress, Pa	COAMPS	0.1611	0.1366	0.0074	0.1575	0.51
Stress, Pa	*Knorr*	0.1685	0.1754	0.0074	0.1575	0.51

[a] *Knorr* statistics, 31 January to 24 February: heat flux (positive downward, W/m^2) and wind stress (N/m^2).

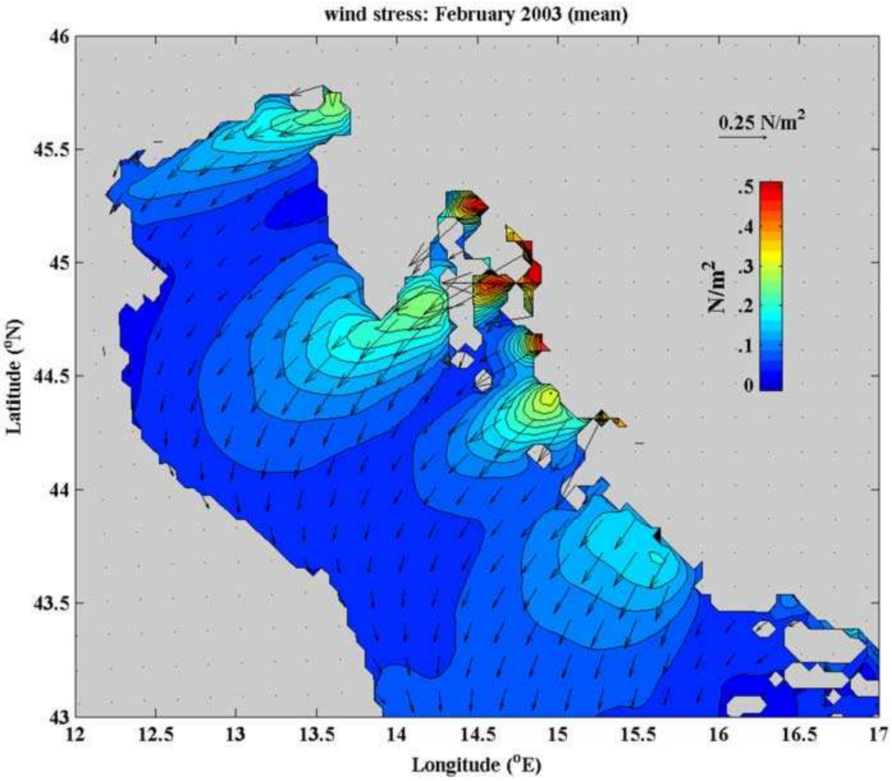

Figure 16. February 2003 COAMPS mean 10-m wind stress. Arrows point with the stress.

[41] At the Venice tower, the latent heat flux was strong while the sensible heat was weak due to the small sea minus air temperature differences (Figure 13). This was offset by the presence of few clouds, allowing for strong solar radiation. Similar to the situation at Azalea, the surface heat balance was negative at night while briefly peaking to high positive midday values. The resulting average net heat flux was −50 W m^{-2} (Table 4).

[42] The *Knorr* cruised over most of the northern Adriatic from 31 January to 24 February 2003 (Figure 1, right). Large ranges in latent heat and sensible heat fluxes were experienced (Figure 14). These two fluxes at times overwhelmed the shortwave flux, so that net heat flux diurnally oscillated between large negative values reaching −1000 W m^{-2} before sunrise and swinging to positive heat gains of +200 to +400 W m^{-2} around noon. The net heat flux for the entire cruise was −238 W m^{-2} (Table 7a). The greatest, most persistent heat loss was on 11–14 February when a bora was in progress. During this event, the *Knorr* first ran to the north along the central Croatian coast (Figure 9), and then spent two days cruising back and forth in the strongest bora jet west of Senj and south of Pula. Faster winds and greater sea minus air temperature differences caused the net heat loss for 11–14 February to be a factor of two greater than for the rest of the cruise (Table 7b).

[43] COAMPS was used to compute the mean February net heat flux over the entire northern Adriatic (Figure 15). The greatest net heat loss was at the heads of the four wind jets on the east side of the Adriatic with maximum values reaching 600 W m^{-2}. This loss decreased across the Adriatic, reaching the smallest loss in the midwestern Adriatic over the sea surface temperature cold pool (Figure 3). The measured *Knorr* net heat loss on 11–14 February was consistent with the COAMPS analysis along the Croatian central coast. Values at Veli Rat were somewhat lower but were consistent with the lower-speed, coastal zone which might not be completely resolved by COAMPS. On the western northern Adriatic coast, the Ancona mast measured a net heat flux (−76 W m^{-2}, Table 3) that was less than that estimated by COAMPS (−250 W m^{-2}). At Venice on the NW coast, the net heat flux was a little lower (−50 W m^{-2}, Table 4). This seems to be reasonable in spite of it being necessary to use the air temperature taken in the city of Venice rather than the Venice tower. However, the gas platforms in the western Adriatic actually had net heat flux balances insignificantly different from zero (+2 and +19 W m^{-2}, Tables 5 and 6) whereas the COAMPS net heat loss was moderately negative (−150 to 200 W m^{-2}). Overall, the agreement of modeled heat fluxes with those observed by the *Knorr* is good, with a net heat flux correlation coefficient of 0.78 (Table 9). Modeled heat fluxes are slightly stronger than the observed RMSE of heat flux. The COAMPS heat flux patterns appear consistent with expectations but he differences among the fixed station, the ship and COAMPS are unresolvable at this time.

6.2. Wind Stress

[44] The measured wind stress patterns over water are related to the surface wind speeds and the sea minus air temperature difference. As expected, these patterns were largest close to the NE coast in high-speed jet cores (Tables 2–7b). The most extreme mean stress value was 0.397 N m^{-2}, with individual peaks a factor of 3 greater than the mean (Figure 14, fifth panel) that was experienced

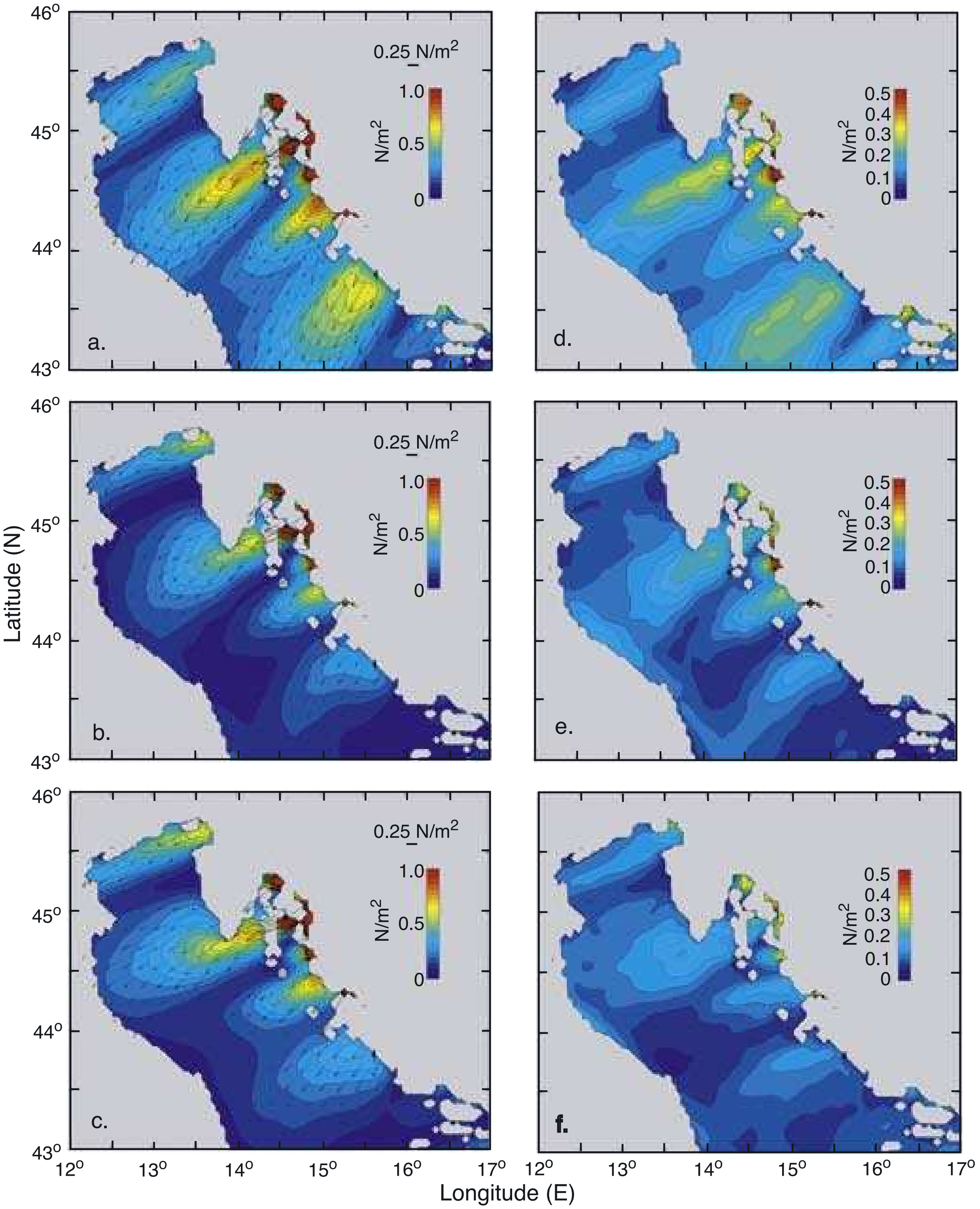

Figure 17. (a, b, c) COAMPS mean and (d, e, f) standard deviation of the 10-m wind stress for the three boras of February 2003 as defined by the Zadar winds. The first is from 1400 UTC 31 January to 0600 UTC 2 February (Figures 17a and 17d), the second is from 0700 UTC 11 February to 1400 UTC 14 February (Figures 17b and 17e), and the third is from 2100 UTC 15 February to 0500 UTC 19 February (Figures 17c and 17f).

by the *Knorr* along the Croatian coast during a bora. The wind stress during the bora was strong at the Venice tower (Figure 13, fourth panel) as a result of being located on the western extension of the Trieste Jet, and was supported by the RADARSAT observations and the COAMPS analysis mentioned earlier. The stress was more moderate in the lower-speed areas such as Veli Rat (Figure 10, fourth panel) and on the opposite side of the Adriatic at Ancona, 0.071 N m^{-2} (Figure 11, fourth panel). The stress was even less at the gas platforms in the western Adriatic, 0.042 N m^{-2} at Azalia platform (Figure 12, fourth panel).

[45] COAMPS simulated the mean wind stress over the northern Adriatic for February 2003 (Figure 16). As would be expected from the wind field (Figure 2), the four bora NE

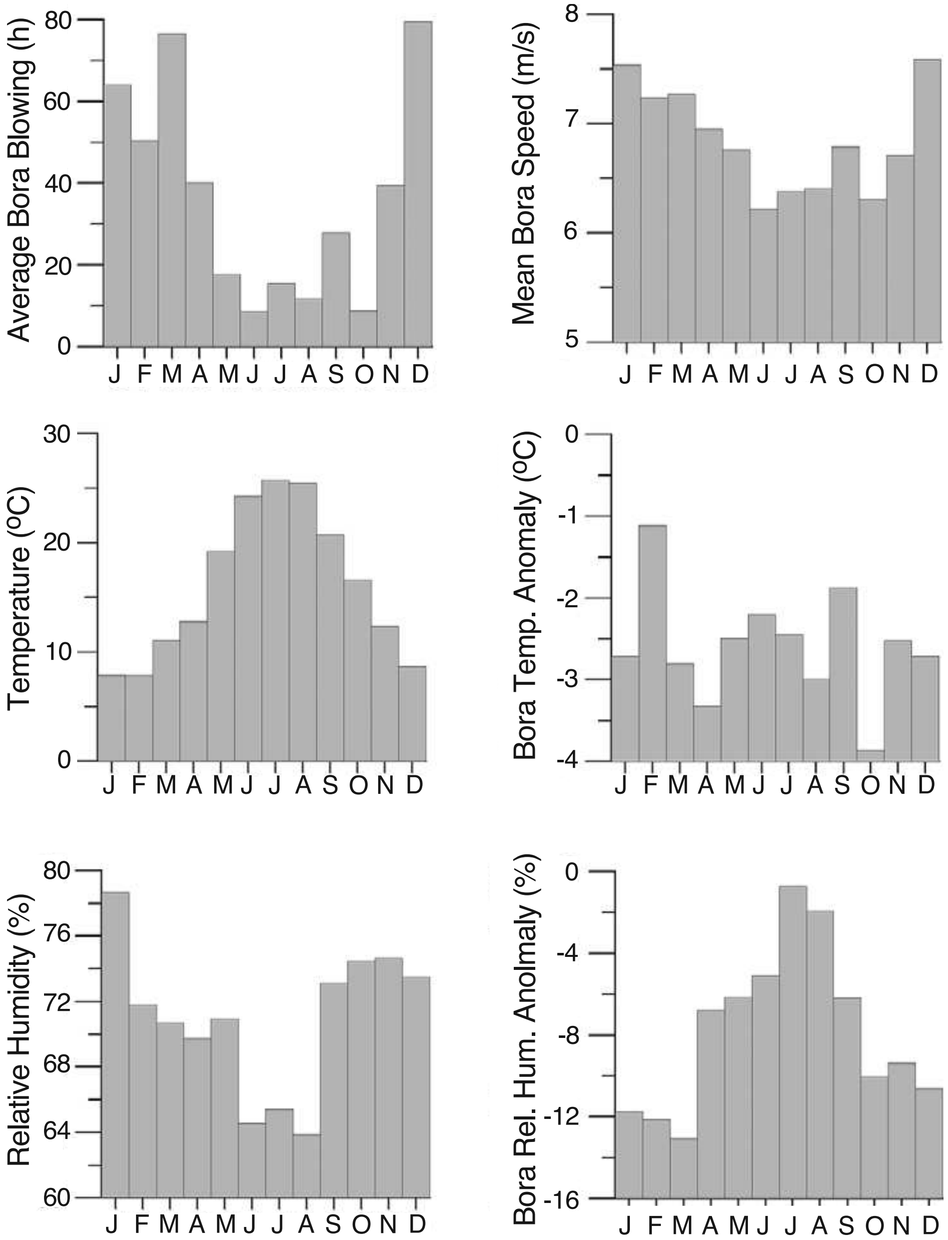

Figure 18a. Annual trend of monthly bora winds, air temperature relative humidity, and anomalies at Mali Lošinj for 1997–2003.

coastal jets dominated the wind stress in the NE half of the Adriatic. Compared to the winds, the stress magnitudes in the core of the jets are enhanced by stress being a function of the square of the wind speed and the instability associated with the large sea minus air temperature difference. The greatest mean stress over water reaches 0.5 N m^{-2} over the channels between the Croatian mainland and the islands near Senj. If considering the more open coastline, the Trieste, Senj and Novalja jets are more comparable in their maximum values or area covered. The southern most jet at Šibenik is similar in area but much weaker in the maximum. In contrast, the NW half of the northern Adriatic has a very weak mean stress. The wind stress standard deviation in the different jets is large and is of similar magnitude to the mean stress value in the jet cores (not shown). The large jet core variation indicates that there is considerable variation in the stress in each jet. This will be examined in the following paragraph.

[46] The COAMPS mean wind stress for February compares closely with that over the *Knorr* track, but the correlation is 0.5 and the RMSE is less than the mean value (Table 9). The 11–14 February *Knorr* stress average in the Senj Jet (the zigzag track just south of Pula in Figure 1, left) is nearly a factor of 2 larger, but this may be accounted for by the bora only occurring over a minority of the month whereas the *Knorr* was there only during a bora. The Veli Rat mean monthly stress is nearly a factor of 2 less than COAMPS, although one would not expect this model to resolve the conditions within one grid point of land.

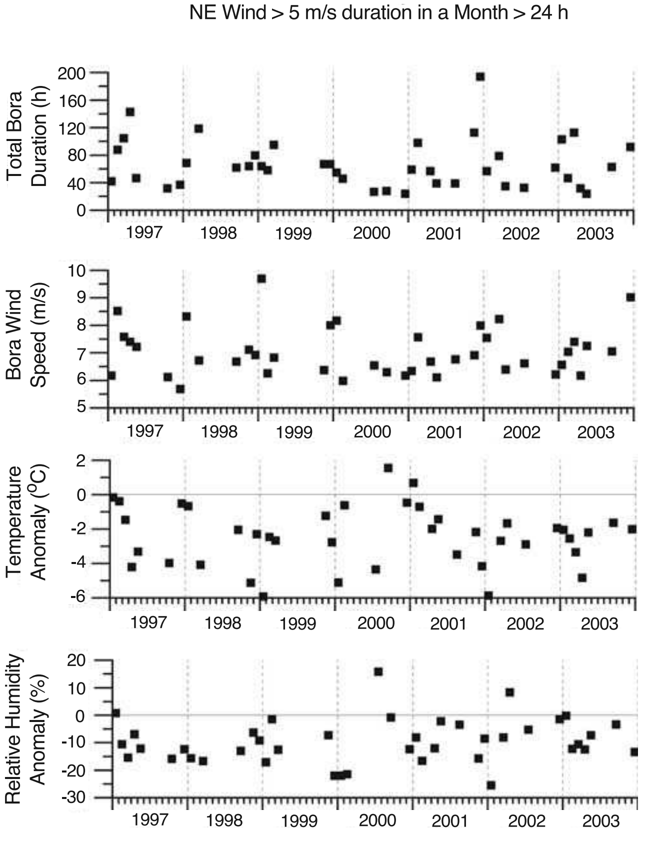

Figure 18b. Time series of mean monthly bora winds, air temperature anomaly, and humidity anomaly at Mali Lošinj for 1997–2003.

However, the COAMPS values near the SW stations are consistent with the weak measured values.

[47] To investigate the structural differences between the bora events, the COAMPS mean and standard deviation were computed for each of the three February 2003 boras. They occurred from 1400 UTC 31 January to 0600 UTC 2 February, from 0700 UTC 11 February to 0400 UTC 14 February, and from 2100 UTC 15 February to 0500 UTC 19 February, and are designated bora 1, bora 2, and bora 3 (Figure 17). It is apparent that the mean and standard deviation vary significantly for each bora and each jet. For bora 1, all jets are strong, especially at Šibenik which is at its greatest value and occupies its largest area of the three events. Also during bora 1, the Trieste Jet center is displaced farthest to the south for the three events. In bora 2, the Senj and the Novalja jets are at their weakest over the open water. In bora 2 and 3, the Trieste Jet is at its strongest and most northerly positions. In bora 3, the Šibenik Jet is a little larger in area than bora 2 but is similar in magnitude. For the event wind stress standard deviations, the largest values are for bora 1, especially for the Senj and the Šibenik jets. Bora 2 has much more moderate values for every jet, and the Senj and Novalja jets have similar values over open water. All of the jets have the smallest standard deviations for bora 3, with the exception of the Trieste Jet which is marginally stronger than for the other two events. The Senj Jet is unique as the means and standard deviations are uniformly high for all three boras at its head, which is over the narrow channels around the Croatian Islands. However, the Senj Jet has greater variability and substantially lower values over the open water so that the stress at the Senj Jet head does not indicate well the stress in the open coast.

7. Climatology at Mali Lošinj 1997–2003

[48] After examining the Adriatic conditions and bora for February 2003, it is of interest to know how representative this period is of the longer term. However, finding a database or measurement that is sufficiently sensitive to the NE Adriatic coastal winds, is of long duration, has small data gaps, and is digitalized is a challenge. Zadar's digital record is too short. The surface station at Mali Lošinj (Figure 1, right) was selected as the record for 1997–2003: it is available, it is reasonably sensitive to bora winds, and bora wind events lasting longer than 24 hours always occur concurrently with those at Zadar. The bora at Mali Lošinj is defined as a northeast wind with speeds greater than 5 m s^{-1} lasting at least 3 hours as suggested by *Poje* [1995]. A bora is considered as a continuing single bora event if the wind velocity falls below 5 m s^{-1} for just 1 hour and then increases above 5 m s^{-1} afterward.

[49] Using the preceding criteria, the bora annual trends are investigated at Mali Lošinj for the years 1997–2003 (Figure 18a). The monthly average number of hours of bora is between 50 and 80 hours for December–March. The fastest mean monthly bora speeds occur during the same months, reaching 7.2–7.6 m s^{-1}. The coldest mean monthly air temperatures are in December–February. However, the average bora temperature anomaly deviation from the monthly mean is irregular, with February having the smallest value.

[50] The monthly mean relative humidity is mostly around 70% in the winter. During boras, the humidity anomaly is about 12% lower for the October–March period. The association with bora wind speeds was examined (not shown). Lower humidity anomalies are linked to faster wind speed in February but there is no significant relationship during this month between the air temperature and the wind speed. A time series of the mean monthly bora event duration, wind speed, air temperature anomaly, and humidity at Mali Lošinj for the period 1997–2003 is shown in Figure 18b. Bora events in this case are defined as previously, but lasting 24 hours or longer. Conditions during February 2003 and the season of December 2002 to March 2003 are not outstandingly different from the average conditions for the preceding seven years.

8. Discussion and Conclusions

[51] Bora wind events dominate the mean northern Adriatic Sea surface environment during the winter so that bora climatology is a key to understanding the over water conditions. The fastest, longest duration bora wind events over the NE Adriatic occur most frequently during December–March. They are associated with higher wind speeds (even in weaker wind wakes) and lower temperature and humidity along coastal Croatia and Slovenia. Bora wind events are correlated with increased wind speeds over the entire northern Adriatic with the fastest speeds on the NE coast, and the weakest speeds in the midwestern northern

Adriatic. Air temperatures over the northern Adriatic have a large diurnal trend and are correlated over the entire Adriatic for synoptic trends of several days.

[52] There are two major over water wind structures that are a result of the complicated topographic interactions with the NE bora winds [*Grubišić*, 2004]. Strong wind jets form by accelerating through coastal mountain gaps. Relatively weak wind wakes form in the lee of the broad, topographic highs. These jets and wakes alternate, covering the NE coast, extending well out over the Adriatic. The Senj Jet is the strongest while the Trieste Jet extends across the Adriatic. A very curious thing about the Trieste Jet is that bora wind speeds do not slow between the Piran buoy and the Venice tower. Another is that the Trieste Jet is two jets that remain separated across the entire Adriatic by a narrow weak velocity zone of constant width (a few kilometers).

[53] The jet bands with high sea minus air temperature differences and low humidity are associated with high heat flux and wind stress on the NE Adriatic. Typical net heat losses reach 500 W m^{-2} and are about half this value in weaker wind areas. Heat fluxes moderate away from the NE coast as the wind speed and sea minus air temperature difference decrease. The net heat loss is near zero over the midwestern northern Adriatic away from the Italian coast.

[54] Stress is highest in the jets in the NE Adriatic, with the most extreme value close to Senj. The overall effect of the jets is to have strong, divergent offshore stress in the NE half of the northern Adriatic with weak stress in the NW half. The NE Adriatic is further broken into four large stress concentrations with each pair separated by a weak stress zone creating alternating divergent and convergent sea surface areas. There is significant variation in the strength and standard deviation structure of the wind stress for each jet with each bora event. The sum of this is that the winds stress values almost everywhere significantly increase with a bora event with the exception of the midwestern northern Adriatic. This zone is where the northern Adriatic winds are weakest, the sea minus air difference is small, and is located far from the NE coast; the resulting weak stress is poorly related to the bora events in the remainder of the Adriatic Sea.

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