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Wintertime buoyancy forcing, changing seawater properties, and two different circulation systems produced in the Adriatic

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[1] Measurements performed in winter 2002/2003 and spring 2003 off the east Adriatic coast showed that the East Adriatic Current (EAC) peaked in January/February (as expected from previous findings) and again in May (not expected). The first maximum corresponded with the considerable cross-shore variability of seawater properties, the colder, fresher water prevailing close to the coast, the warmer, saltier water dominating the open sea. The second maximum coincided with the massive intrusion of warm, saline water from the south Adriatic. Meteorological and hydrologic forcing was anomalous over the measurement interval: during winter 2002/2003 the cooling and river outflows were strong, during spring 2003 the pronounced warming coincided with exceptional dryness. In order to interpret the two EAC maxima a simple numerical model reproducing response of the Adriatic-Mediterranean system to the wintertime forcing was developed. It was found that the first maximum could be related to the coastal freshwater input and offshore evaporation in the Adriatic area, and that the second maximum was probably due to the wintertime surface cooling of the Adriatic while warmer conditions prevailed above the Mediterranean. The resulting horizontal density gradients supported two different circulation systems, one within the Adriatic, the other between the Adriatic and east Mediterranean, and they differed not only in spatial but also in temporal scales, therefore supporting the occurrence of two distinctive EAC maxima.

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1. Introduction

[2] In the years 2002 and 2003 intensive multidisciplinary studies were organized in the north Adriatic [*Lee et al.*, 2005]. They comprised meteorological sampling from a variety of platforms as well as half-year measurements of currents at numerous locations, extensive drifter deployments, continuous operation of high-frequency radars, regular hydrographic surveys, high-resolution towed profiler campaigns, microstructure measurements and remote sensing. The present paper is based on data collected in the framework of one of the projects contributing to this effort, named 'East Adriatic Coastal Experiment (EACE)'. The project concentrated on the current that flows into the north Adriatic off the east, Croatian coast and thus influences to a considerable degree processes there.

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[3] Previously, the surface current along the east coast was seldom investigated *per se*, but was often considered as a branch of the general circulation system in the Adriatic. It was known already to *Voss* [1677] that 'in the Adriatick Sea the Waters move along the Shores of Dalmatia and Croatia, even to the bottom of the Gulph of Venice' and that 'from thence by a contrary motion they wash the coast of Italy until they return to the place from whence they came'. On the basis of temperature and salinity data collected during several summer seasons *Wolf and Luksch* [1887] concluded that inflow along the east coast and outflow along the west coast are connected not just by recirculation in the northernmost part of the Adriatic but also by cross-basin currents flowing south of Istria and close to Palagruža. The next important step was made by *Zore* [1956]: by computing geostrophic currents for a series of cruises over a few-year interval she concluded that the inflow is more pronounced in winter, the outflow in summer. *Hendershott and Rizzoli* [1976] considered dense water formation on the Adriatic shelf during winter and noticed that the related cyclonic flow may be isolated from flow in the south Adriatic. *Artegiani et al.* [1997], by analyzing geostrophic currents computed from climatological temperature and salinity data, arrived at the conclusion that the inflow is better developed

in the colder part of the year, the outflow in the warmer part. *Poulain* [2001] utilized data provided by satellite-tracked drifters and found that the Adriatic cyclonic circulation is more pronounced during summer and autumn; in winter he detected the outflow similar to the inflow. It would thus appear that there is a consensus on the existence of the East Adriatic Current (EAC) but that there are also differing findings on its season-to-season variability. Still, prevalent is the opinion that at the sea surface the EAC culminates in winter.

[4] Investigation of the Adriatic intermediate and bottom circulations has also a long tradition. Using an early hydrographic data set *Nielsen* [1912] concluded that the Adriatic is a site of dense water formation during winter, implying an inflow in the surface and intermediate layers, an outflow in the bottom layer. *Schott* [1915] considered some additional hydrographic data, and arrived at the conclusion that during summer there is an outflow in the surface and bottom layers, an inflow in the intermediate layer. *Zore-Armanda* [1963] defined the Adriatic water masses and discussed their spreading; for winter she clearly distinguished water masses being generated on the shelf from those originating in the deeper part of the basin, for both winter and summer she considered year-to-year variability of seawater properties and related flows. Still on the basis of hydrographic data *Artegiani and Salusti* [1987] followed dense water formed during winter in the north Adriatic as it flows along the Italian coast in the bottom layer, partially sinks to the Jabuka Pit and partially overflows the Palagruža Sill and sinks to the South Adriatic Pit. *Kovačević et al.* [1999] utilized long-term Eulerian current measurements to demonstrate that in the Otranto Strait inflow in the intermediate layer is found on the east side, outflow in the bottom layer on the west side. Performing least-squares tracer analysis of water masses *Vilibić and Orlić* [2001] showed that the intermediate layer inflow to the Adriatic peaked in the years 1968–1971, 1980 and 1987–1989 and that it was weaker in between. *Manca et al.* [2002] used long-term ADCP measurements to demonstrate that the bottom outflow from the Adriatic attains maximum in March and April, with the transport depending on the Adriatic surface buoyancy forcing and dense water generation during the previous winter. Finally, *Vilibić* [2003] considered long-term hydrographic data collected at the bottom of the Jabuka Pit and correlated them with the surface fluxes and Po River discharge; he showed that a month is needed for dense water to arrive to the Jabuka Pit after being generated in the north Adriatic. The overall picture emerging from these studies is of a cyclonic gyre in both the intermediate and bottom layers, with the inflow prevailing in the intermediate layer, outflow dominating the bottom layer. This would imply that the EAC occupies the whole water column, but no direct observations of the deep flow, or of its temporal variability, were previously available.

[5] The present meteorological, CTD and ADCP measurements, designed so as to document air-sea fluxes, seawater properties and variability of the EAC, will be described in the second section, along with some routinely performed observations. In the next three sections the data collected will be analyzed. As will transpire from the sections, the main finding of the project is that the EAC may peak in winter and again in spring. A simple numerical model of the Adriatic/Mediterranean system will be developed in the sixth section in order to interpret this finding. In the final seventh section importance of the finding for an understanding of the Adriatic general circulation will be briefly discussed.

2. Data

[6] With the aim of documenting meteorological conditions in our measurement area, we have mounted Automatic Meteo-Oceanographic Station (AMOS) on the Veli Rat lighthouse (Figure 1). The station was equipped with sensors, produced by Aanderaa Instruments, measuring solar and net radiation, air and sea temperature, air pressure, wind direction, speed and gustiness, air humidity and precipitation. All sensors except the rain, air pressure and sea temperature gauges were placed on the top of the lighthouse, 49 meters above sea level. They were thus exposed to winds from all directions, the surrounding terrain being almost flat. Air pressure and precipitation were recorded in front of the lighthouse, at a 4 m height, whereas sea temperature was measured off the nearby coast, at a 0.5 m depth. For the wind speed and direction mean values at 10 min intervals were recorded, for the wind gusts maximum speeds over 10 min intervals were taken. Precipitation, solar and net radiation were registered as sums at 10 min intervals. All the other parameters were measured continuously and sampled every 10 min.

[7] AMOS was set in operating mode on 2 November 2002 and it collected data until 27 June 2003. The measured data were transferred in real time from the station to the Institute of Oceanography and Fisheries and have been stored there as a raw data set. Due to some technical problems (primarily with power supply unit), two large gaps occurred in all the time series (from 10:00 to 13:10 EMT on 25 November 2002 and from 16:00 EMT on 15 March 2003 to 11:00 EMT on 23 March 2003). Additionally, in the beginning of the measurement period (i.e. until 14:40 EMT on 12 December 2002) no precipitation data were recorded due to the break of electric cable. Likewise, no sea temperature data were collected between 20:30 EMT on 11 November 2002 and 23:50 EMT on 25 January 2003 and between 11:10 EMT on 28 January 2003 and 12:20 EMT on 9 February 2003, because the sensor was broken twice while being exposed to extreme wave conditions. Finally, there were some smaller gaps in the time series, which could be bridged by interpolation.

[8] All AMOS data were quality controlled following three steps: (1) visual inspection of plotted time series, (2) check of homogeneity of time series, and (3) comparison with data simultaneously recorded at Zadar (meteorological parameters except solar and net radiation), Split (solar and net radiation) and Mali Lošinj (sea surface temperature). The Zadar and Mali Lošinj stations are part of the permanent network supervised by the Hydrologic and Meteorological Service of the Republic of Croatia, whereas the Split station is owned by the Institute of Oceanography and Fisheries; their position is shown in Figure 1. Values missing from the Veli Rat time series were interpolated by regressing available Veli Rat data on those simultaneously collected at Zadar (daily

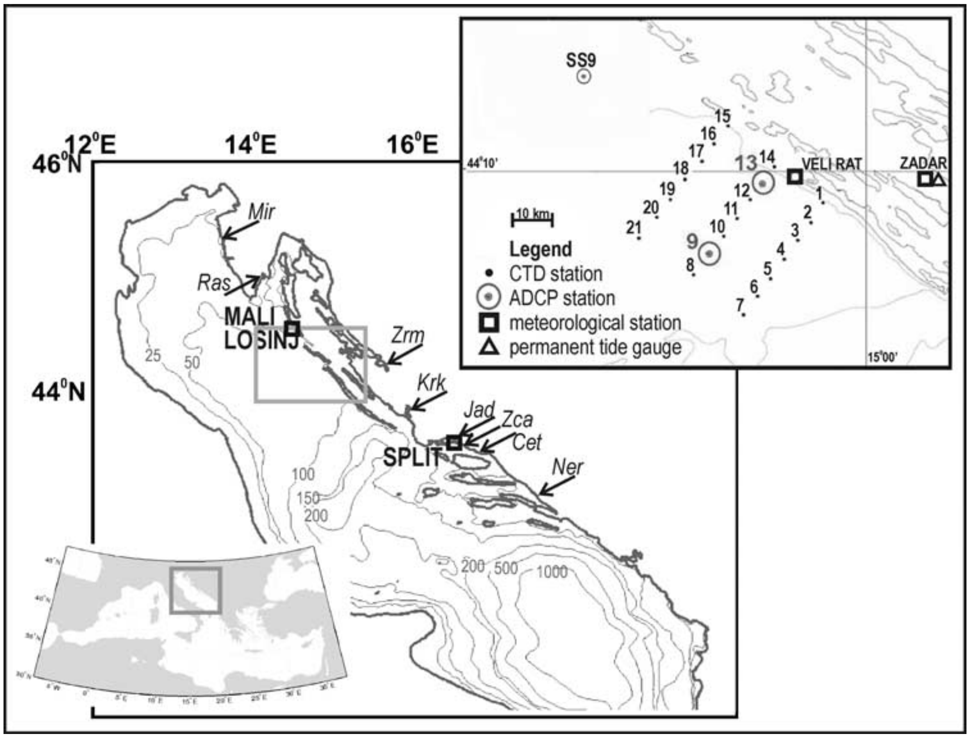

Figure 1. Position and topography of the measurement area. Also indicated is location of meteorological (Veli Rat, Mali Lošinj, Zadar, Split), CTD (1–21) and ADCP (9, 13, SS9) stations, of the Zadar tide gauge, and of the rivers inflowing to the east Adriatic.

values of standard meteorological parameters, r = 0.81–0.99), Split (daily values of solar radiation, r = 0.93) and Mali Lošinj (three readings of sea surface temperature per day, r = 0.78).

[9] CTD measurements were performed on the network of 21 stations off Veli Rat (Figure 1) during seven cruises (30 November–2 December 2002, 14–15 January 2003, 20–21 February 2003, 28 March 2003, 24 April 2003, 19–20 May 2003 and 14 June 2003). Three probes (SBE9, SBE25A and SBE25B), having accuracy of at least 0.002°C in temperature, 0.0003 S/m in conductivity and 0.1% of the full-scale range in pressure, were used in the experiment. The data collected were preprocessed and averaged along the vertical every 1 m. The last two probes were purchased right before the measurements, after being calibrated by the manufacturer in August and September 2002, respectively. They were again calibrated in 2004 and 2005, which demonstrated stability of the sensors. An intercomparison of the probes was carried out during the cruises. It showed perfect agreement of various sensors except for a slight offset of salinity recorded by the first probe; this has been taken into account in the analysis.

[10] Currents were measured at stations 9 (depth 71 meters) and 13 (depth 61 meters, Figure 1) in the interval extending from 30 November 2002 to 14 June 2003, using RDI Workhorse Sentinel ADCPs operating at 300 kHz. Sampling interval was 15 minutes, bin size 2 meters, and width of the contaminated layer about 4 meters. Consequently, ADCPs provided valuable data for 32 layers at station 9 and for 28 layers at station 13. Quality check of the data was performed following the procedure proposed by the Intergovernmental Oceanographic Commission [*UNESCO*, 1993]. The instruments were mounted on the sea bottom using trawl-safe barny frames as described by *Perkins et al.* [2000]. The frames enabled current measurements to be continuously performed over more than six months. Previous time series, collected with the aid of classical current meters deployed on moorings, did not extend beyond 1–2 months due to a heavy fishing activity in the area.

[11] Simultaneously with the currents some other parameters were measured as well: bottom temperature at stations 9 and 13 by Pt100 resistors mounted together with ADCPs inside the barny protecting cases, and bottom pressure at station 9 by a SBE26 wave and tide recorder deployed in the same way. The latter data set could be related to tide-gauge record collected at the Zadar station (Figure 1), which belongs to the permanent network maintained by the Hydrographic Institute.

[12] Freshwater input by rivers, prior to and during the present experiment, was documented by the discharge or water level data originating from eight major rivers that are distributed along the Croatian coast of the Adriatic. Daily time series of river discharge, extending from 1 September 2002 to 31 August 2003, were obtained for Mirna, Raša, Krka, Jadro and Žrnovnica, while for Cetina and Neretva only water levels were available. All the river mouths are indicated in Figure 1. The respective stations belong to the standard network supervised by the Hydrologic and Meteorological Service of the Republic of Croatia. The data for Zrmanja, the major river in vicinity of the measurement site, were not available for the interval mentioned. Consequently, the discharge of Zrmanja was

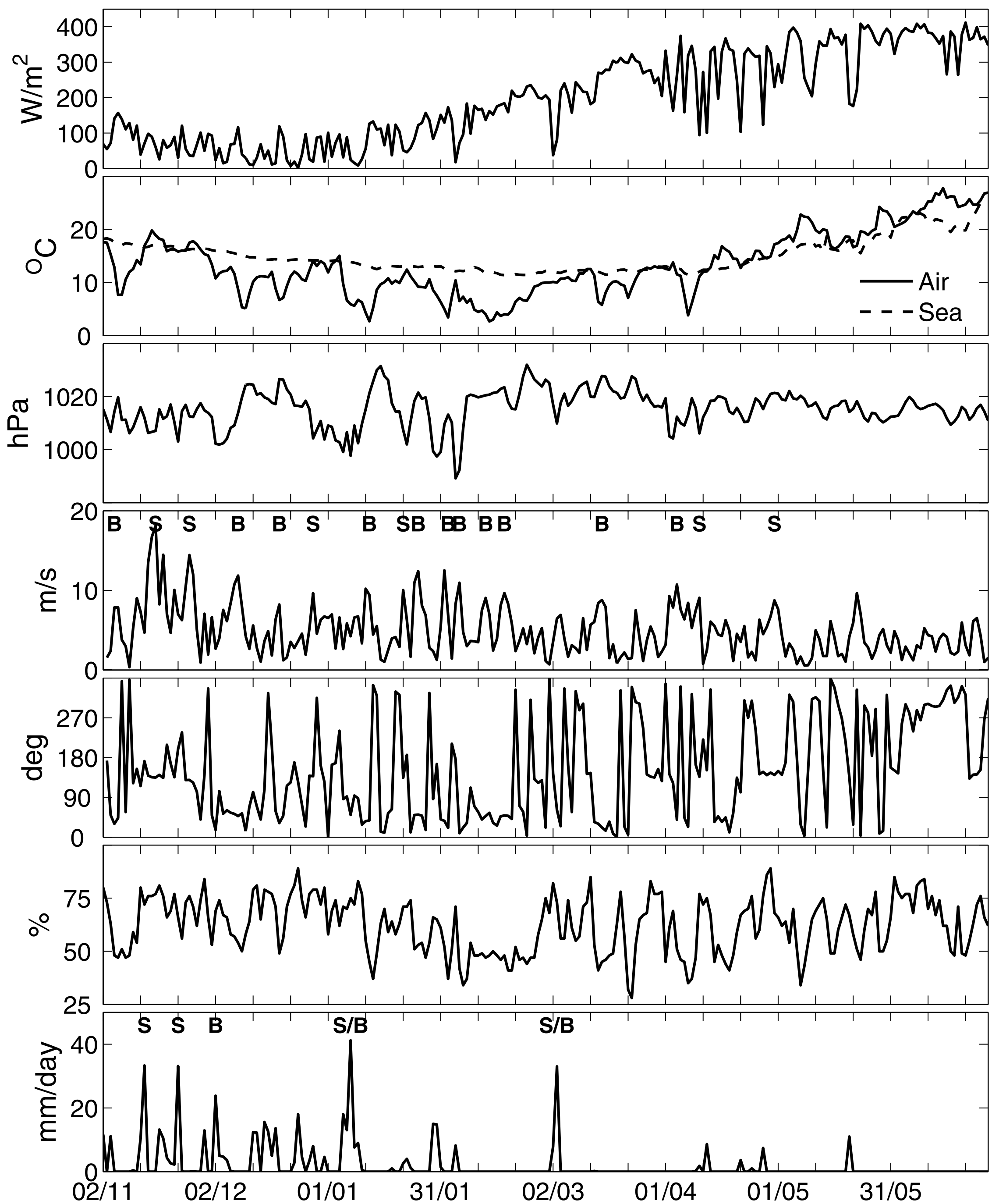

Figure 2. Daily values of solar radiation, air and sea temperature, air pressure, wind speed, wind direction, air humidity and precipitation recorded at Veli Rat between 2 November 2002 and 27 June 2003. B indicates a bora episode, S stands for a sirocco episode. The last wind speed maximum, recorded on 22 May 2003, was due to the wind blowing from the northwest, and therefore it departed from the simple bora-sirocco pattern.

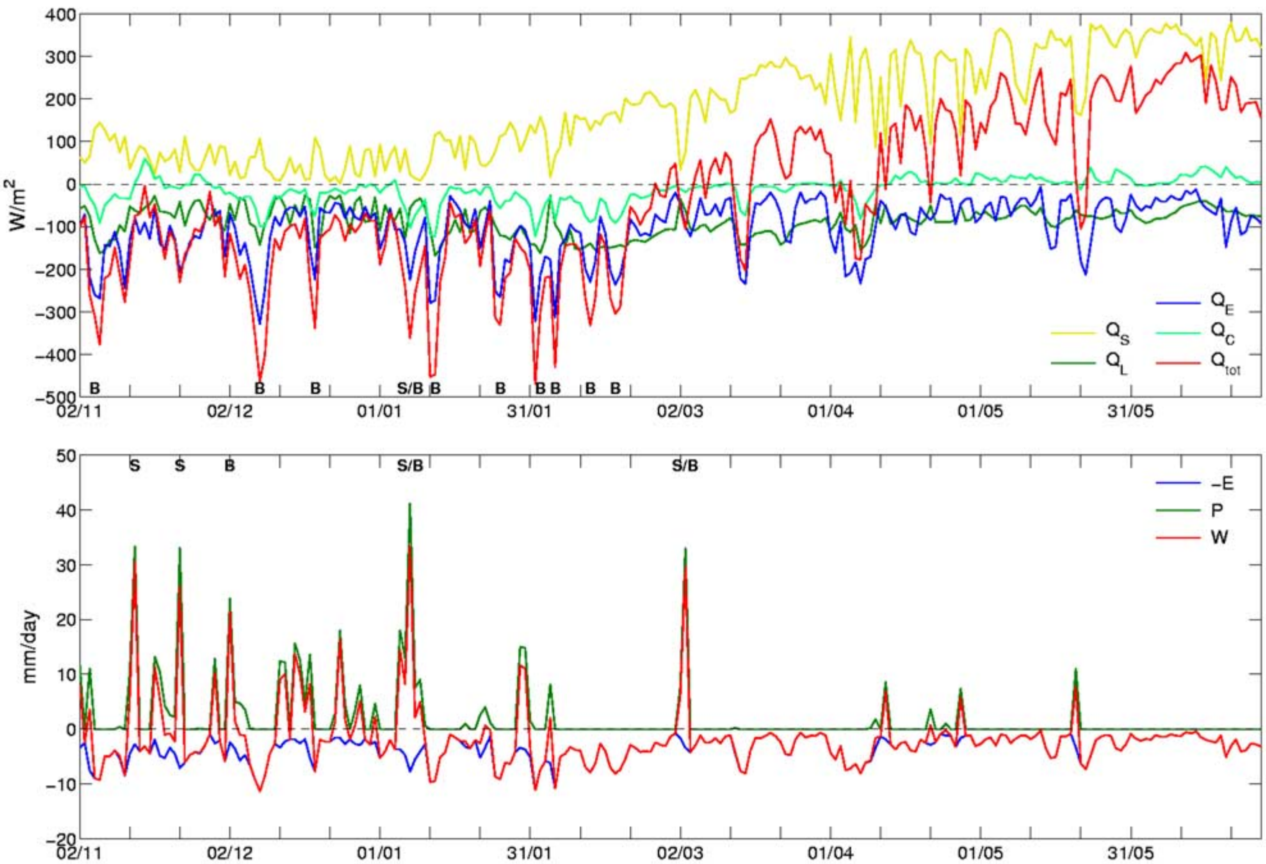

Figure 3. Daily values of the surface heat (top) and water (bottom) fluxes computed from data that were recorded at Veli Rat between 2 November 2002 and 27 June 2003. Positive values imply that the sea gains heat or water. B indicates a bora episode, S stands for a sirocco episode.

estimated from the Krka data, using linear relationship ($r = 0.91$) previously established from simultaneous time series for the two rivers.

3. Meteorological and Hydrologic Conditions

[13] Daily values of various parameters measured at Veli Rat are shown in Figure 2. As is usually the case in the Adriatic, meteorological conditions could most easily be interpreted if related to the winds blowing at the time [*Penzar et al.*, 2001]. According to our data, between November 2002 and June 2003 an interchange of the sirocco (SE wind) and bora (NE wind) episodes prevailed and these were stronger and more frequent in winter than in spring. Most often, sirocco brought warm, humid air to the Adriatic area and was accompanied by precipitation. Bora, on the other hand, usually implied advection of cold, dry air and it coincided with clear-sky conditions. There were, however, some exceptions to this pattern. Thus, on 25 November 2002 and 30 April 2003 sirocco episodes were not visible in precipitation data. They represented so-called 'dry sirocco' events, being related to an anticyclone over the southeast Europe rather than to a cyclone over the north Italy [*Deutscher Wetterdienst*, 2002, 2003]. On 2 December 2002 bora was accompanied by precipitation. This was the so-called 'dark bora' since it was influenced not just by an anticyclone over the northeast Europe but also by a cyclone over the south Adriatic [*Deutscher Wetterdienst*, 2002].

[14] From the daily time series collected at Veli Rat surface fluxes of heat and water were computed. Downward heat flux was determined from measured solar radiation, taking into account the sea albedo computed by *Payne* [1972]. Components of upward heat flux were determined through parameterization schemes for the long-wave radiation [*Bignami et al.*, 1995] and for the sensible and latent heat fluxes, the latter two supplemented by the often-used turbulent exchange coefficients [*Rosati and Miyakoda*, 1988]. Because cloud cover information was not available for Veli Rat, daily cloud fraction was obtained by dividing the measured solar radiation with the estimated clear sky radiation. Finally, surface water flux was determined from the latent heat flux and precipitation data. All the fluxes are shown in Figure 3. Although computed from data that were mostly collected on the top of the lighthouse, they showed better agreement with fluxes determined for the nearby open-sea area [*Dorman et al.*, 2006, Figure 15] than fluxes computed from data scaled to the standard height, presumably due to the onshore-offshore wind strengthening being similar to the vertical wind speed increase. Episodes of the strongest surface heat loss were related to the bora wind, as marked

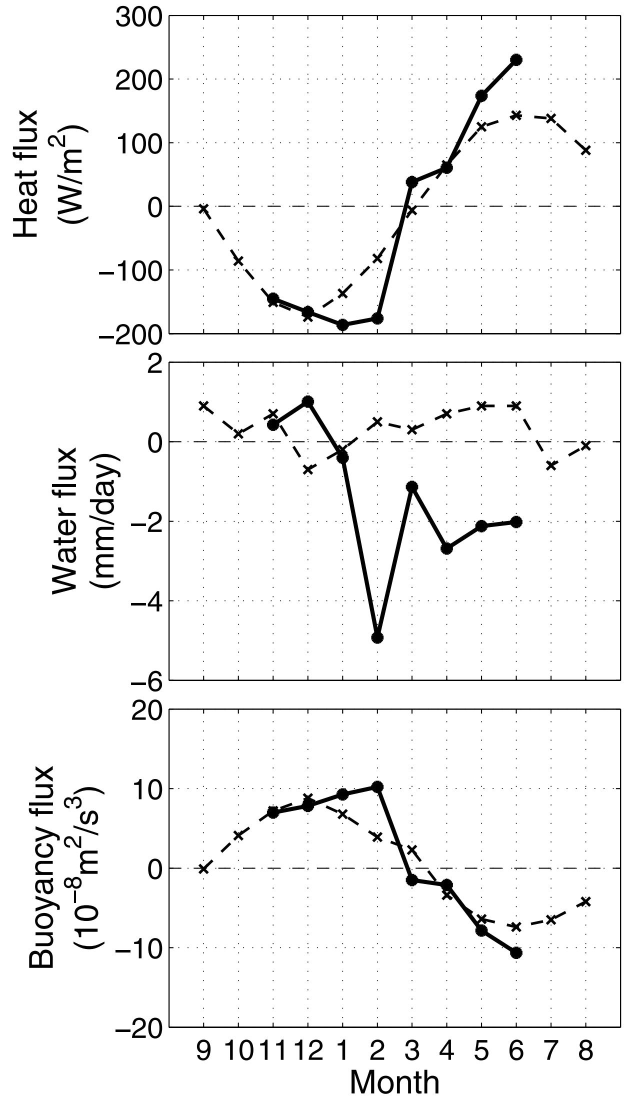

Figure 4. Monthly mean values of the surface heat (top), water (middle), and buoyancy (bottom) fluxes determined for Veli Rat over an eight-month interval extending from November 2002 to June 2003 (solid line). Also shown are climatological values for Mali Lošinj (dashed line).

in the figure. An apparent exception was the event of 7 January 2003, but even in this case sirocco rapidly gave way to bora, the latter being then responsible for the upward heat flux. Episodes of the strongest surface water gain are also marked in the figure. They are somewhat more complex, and include – besides the simple sirocco events – the case of dark bora of 2 December 2002 as well as the cases of sirocco turning to bora on 7 January and 3 March 2003.

[15] From the surface heat and water fluxes determined on a daily time scale monthly mean values were computed and were supplemented by the surface buoyancy flux (obtained following *Phillips* [1966]). These are in Figure 4 compared with the corresponding averages determined for station Mali Lošinj over a 27 year interval (1966–1992 [*Supić and Orlić*, 1999]). The procedure is supported by findings of *Dorman et al.* [2006], which imply that Veli Rat and Mali Lošinj belong to a similar surface-forcing regime. Obviously, January and February 2003 were characterized by strong cooling, subsequent spring by strong heating. Mean heat loss in January and February 2003 was about 170 W/m^2, double than the average for the area. In contrast, heat gains in May and June 2003 surpassed the average values by 60%. Surface water flux was close to the average from November 2002 to January 2003, and it was anomalously directed upwards during the following months. Mean water flux between February and June 2003 was −2.5 mm/day, totally opposite to the average (+1.0 mm/day). In winter 2002/2003 (i.e. until the end of February 2003) surface buoyancy loss was considerably stronger than is typical for this part of the year, thus reflecting the intensive heat loss. In spring 2003 (i.e. from the beginning of March 2003) surface buoyancy gain was much more pronounced than the averages would suggest, obviously due to the heat gain controlling it more strongly than the water loss.

[16] Time series of monthly mean river discharge and water level are shown in Figure 5 and are compared there with the long-term climatology supplied by the Hydrologic and Meteorological Service of the Republic of Croatia. All the rivers that still have a predominantly natural flow regime (Mirna, Raša, Zrmanja, Krka, Jadro and Žrnovnica) had a significantly increased discharge prior to or at the beginning of our measurement program, i.e. in November 2002 and January 2003. In February 2003 discharge did not depart significantly from climatological values; Jadro and Žrnovnica still had a somewhat increased discharge, while discharge of Istrian rivers (Mirna and Raša) was slightly below the long-term average. However, in March 2003 a long-lasting dry period started: until the end of the experiment river discharges remained one standard deviation below climatological values. The autumn/winter positive and the spring negative anomaly was not that pronounced on the southernmost rivers, Cetina and Neretva, since the flow of Cetina is entirely controlled by power plants and Neretva is also heavily influenced by human activity.

4. Seawater Properties

[17] Our CTD sampling was performed with along-transect resolution of ca. 5 km and an even coarser cross-transect resolution, once per month. This opens the question of errors due to aliasing in space and time. To analyze aliasing in space we have used underway temperature and conductivity data taken by R/V *Knorr* at a 5 m depth while passing over our measurement area on 4 June 2003 (C. M. Lee, personal communication). The data were averaged and recorded at a 1 min time interval along the ship path, which – with the typical cruising speed of 8 knots – gave the sampling interval of ca. 250 m. The analysis of aliasing followed the procedure developed by *Pasarić et al.* [2006]. Temperature, salinity and density-anomaly sequences were first linearly interpolated every 100 m, thus obtaining regularly sampled series. Direct comparison revealed that no spurious data were introduced by this operation. The series were then sub-sampled with space steps of Δs = 1, 2, 5, 10 km, the sub-sampled series were linearly interpolated back to 100 m intervals, and the squared differences were calculated. The starting point for sub-sampling was system-

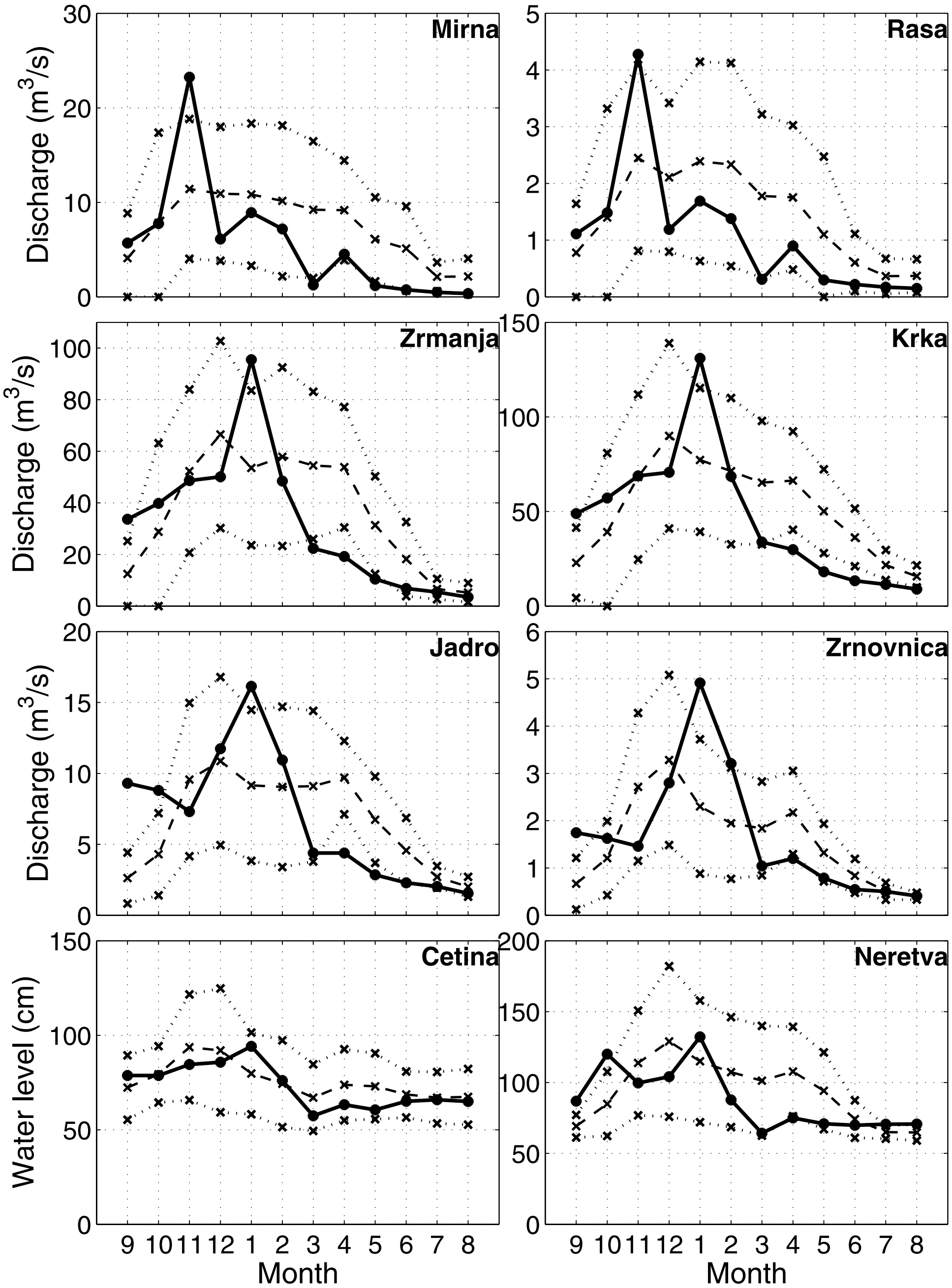

Figure 5. Monthly mean values of discharge and water level documenting east Adriatic river outflows between September 2002 and August 2003 (solid line), compared with the long-term monthly means (dashed line) and corresponding standard deviations (dotted lines).

atically varied within the first Δs kilometers of the sequence (with a step of 100 m), and squared differences thus obtained were averaged. Finally, 5 km averages were calculated and square root was taken. The obtained root mean square (RMS) error was found to reach at most 0.2°C, 0.06 and 0.07 kg/m^3 for temperature, salinity and density anomaly, respectively.

[18] The aliasing in time was analyzed using time series of bottom temperature measured at stations 9 and 13 over six months with a 15 min sampling interval. The procedure is analogous to the case of aliasing in space: Sub-sampling was performed with various time steps (Δt = 1, 5, 15, 30 days), the sub-sampled series were linearly interpolated back to 15 min intervals, and the squared differences were calculated between this and the original series. The starting point for sub-sampling was systematically varied within the first Δt days of the sequence (with a 1 h step) and squared differences thus obtained were averaged. Finally, 5 day averages were calculated for all the four series of mean squared differences, whereupon the square root was taken, giving overall RMS error. The results show that the error due to the monthly sampling may reach 0.3°C.

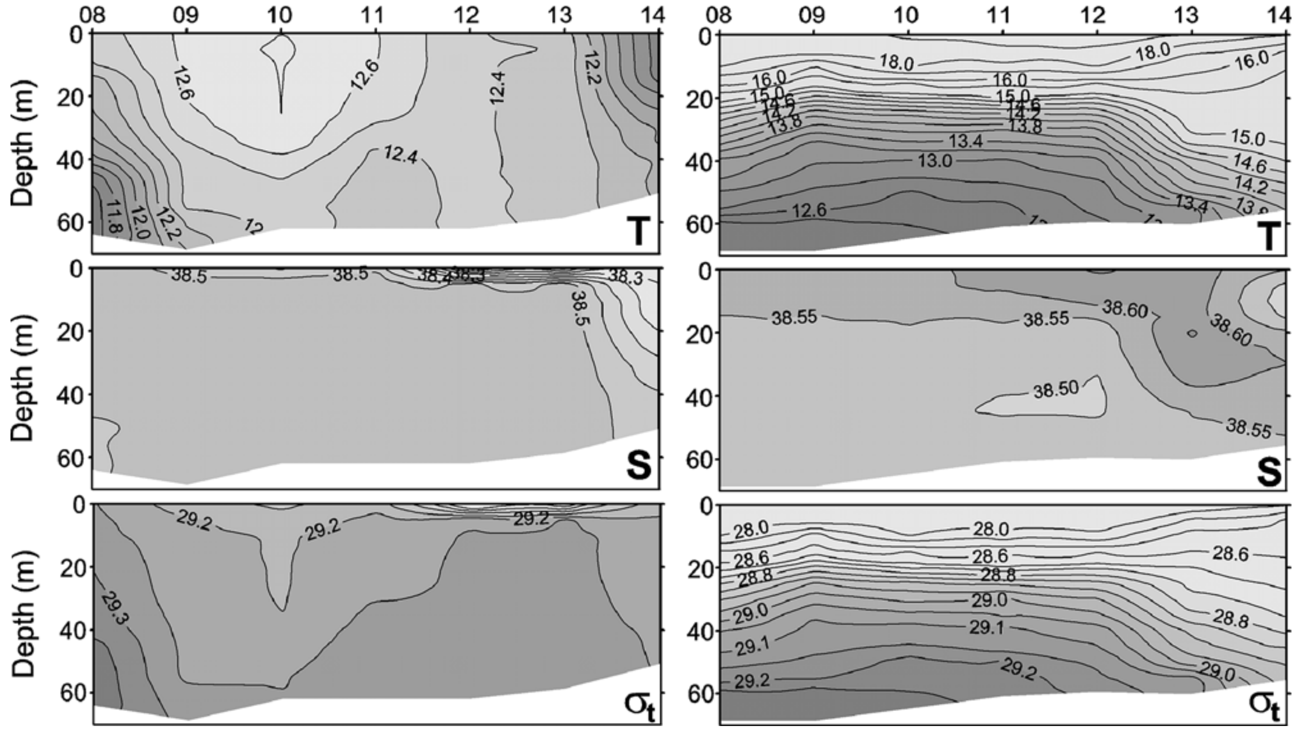

Figure 6. Vertical profiles of temperature, salinity and sigma-t value measured at the transect extending from station 8 to station 14 in February 2003 (left) and May 2003 (right).

[19] Having in mind these errors, we could consider changes of water properties in our measurement area. Data collected at the transect extending from station 8 to station 14 illustrate salient points of this variability. In February 2003 (Figure 6, left) colder, fresher water was advected from the coast, warmer, saltier water was dominating the open sea. In the outer part of the transect an intrusion of colder water could be noticed close to the bottom, probably representing the North Adriatic Dense Water (NAdDW [*Zore-Armanda*, 1963; *Artegiani and Salusti*, 1987]) that was generated in early winter in the north Adriatic and then spread towards the middle Adriatic. In May 2003 (Figure 6, right) stratification was well developed, with warmer, saltier water occupying the surface layer, colder, fresher water the bottom layer. An intrusion of warm, saline water was detected in the intermediate layer at stations 12–14, probably related to the Levantine Intermediate Water (LIW [*Zore-Armanda*, 1963; *Vilibić and Orlić*, 2001]) inflowing from the southeast.

[20] Temporal variability could be considered in some detail using the time-depth plots constructed for the outer station 7 and the inner station 14 (Figure 7). At the inner station temperature was lowest close to the sea surface in February 2003, whereas at the outer station it achieved minimum in the bottom layer in March/April 2003. Warming in spring reached to a greater depth at the inner station than at the outer station. Considerable cross-shore salinity gradients were observed throughout winter, whereas similar values were recorded at the two stations in spring. This again shows that in winter colder, fresher coastal water interacted with warmer, saltier open-sea water, the latter being somewhat modified by dense water descending from the north Adriatic. In spring vertical stratification was well developed, as was an inflow of warmer, saltier water from the south Adriatic.

[21] CTD data collected at stations 15–18 in the surface (0–10 m), intermediate (20–30 m) and bottom (>50 m) layers were compared to corresponding climatological values. The latter were determined from data collected between 1904 and 1982 and stored in Marine Environmental Database of the Adriatic Sea (MEDAS) that had been organized by the Institute of Oceanography and Fisheries. Figure 8, when related to Figure 4 illustrating the surface forcing, reveals that due to strong cooling in January and February 2003 temperature decreased from about 17°C observed during our first cruise (1°C above long-term average near the bottom) to approximately 12°C during the third cruise (close to the average). After that, the intermediate and bottom temperatures stayed below average with the maximum anomaly occurring in May 2003 (1°C below the average). On the contrary, the surface temperature in June 2003 surpassed average values by more than 2°C, because the surface heating was pronounced in May and June 2003. Throughout the experiment salinity was more uniform along the vertical than climatological averages would suggest: the difference between the surface and bottom salinity did not surpass 0.06 (Figure 8). Due to extremely dry conditions prevailing between February and June 2003 (Figures 4 and 5) the surface salinity minimum, which usually occurs in May after river runoffs are at the maximum, could not be seen at all. In fact, salinity increased during the experiment, by about 0.2 in the surface layer and 0.1 in the bottom layer.

5. Currents

[22] Our ADCP measurements documented processes extending over a broad frequency range. Small temporal scales (diurnal or smaller) are to a considerable degree influenced by tides. Hence, tidal currents have been

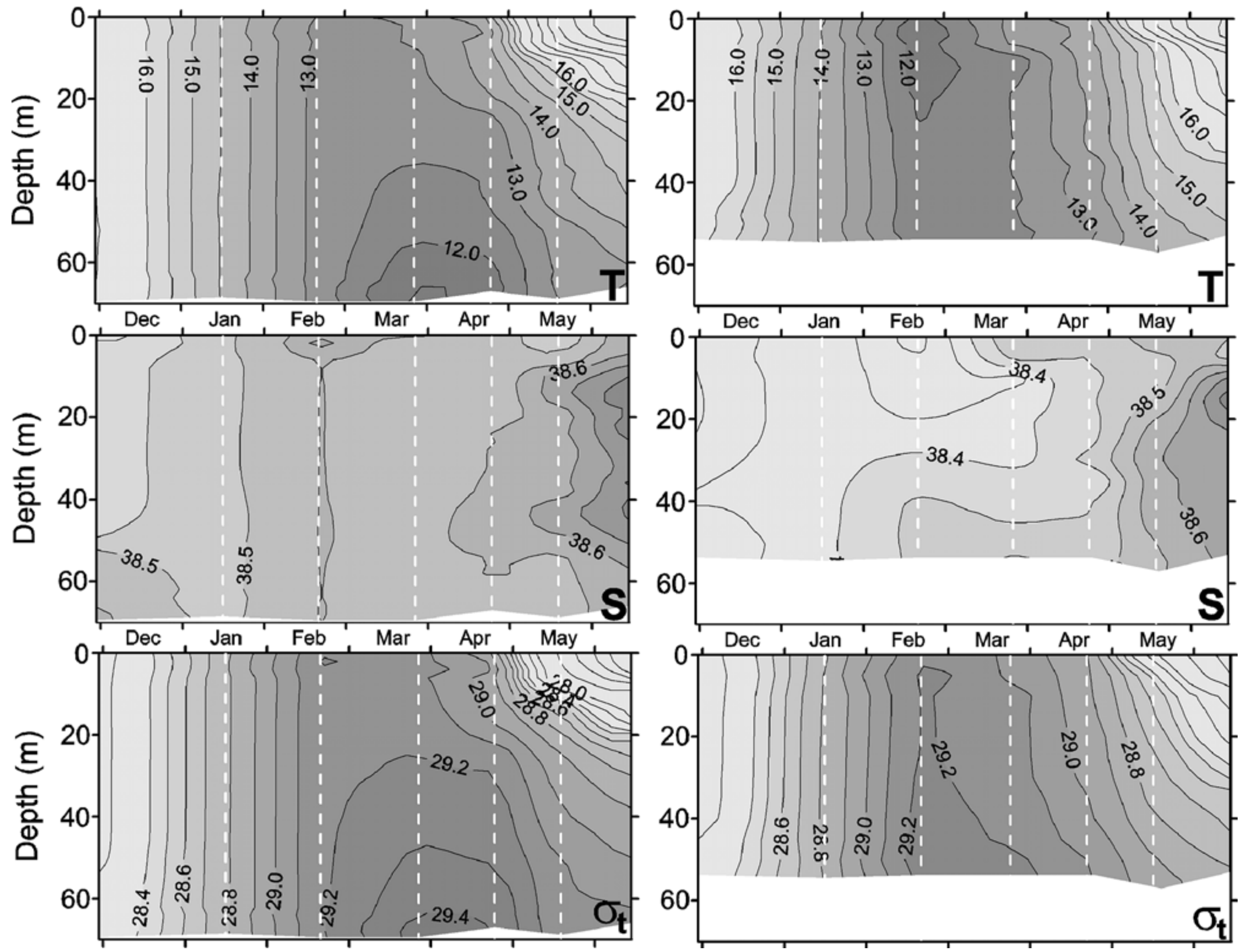

Figure 7. Time-depth distribution of temperature, salinity and sigma-t value at the outer station 7 (left) and the inner station 14 (right). Dashed lines denote the times of CTD casts.

extracted from the data using MATLAB tidal package, which follows the *Foreman* [1978] method and had been evaluated by *Pawlowicz et al.* [2002]. Harmonic analysis was performed on the original current time series, allowing for seven major tidal constituents (M2, S2, N2, K2, K1, O1, P1) to obtain parameters that describe current ellipses: length of the major and minor axes and inclination of the axes. The ellipses for each tidal constituent are drawn in Figure 9 as a function of depth, with the clockwise and anticlockwise rotations being clearly distinguished. Obviously, tidal currents are almost linearly polarized in our measurement area and are aligned with the coast, as already found by numerical modelers [*Cushman-Roisin and Naimie*, 2002]. Bottom friction manifests itself in the well-known veering at semidiurnal periods [e.g., *Sverdrup*, 1927] and a different behavior at diurnal periods, in the layer extending to about 10 m above the bottom.

[23] The harmonic constants obtained were used to eliminate tidal signal from the original time series. The six-month series of detided currents were submitted to spectral analysis in order to investigate the existence of possible periodic motions. The power density spectra were determined by the Welch method using Hanning non-overlapping windows of 21.3-day length, thus implying 76 degrees of freedom [*Press et al.*, 2001] and ensuring optimum balance between frequency resolution and statistical stability. The spectra for the along-basin (L) and cross-basin (T) current components at different depths are presented in Figure 10 as contours of power density. On the upper axes two characteristic periods are shown, the local inertial period (17.2 h) and the period of the fundamental Adriatic seiche (21.2 h). The former was much more pronounced at station 9, the latter was similar at both stations. Inertial signal appeared in both current components, and it is interesting that the signal occurred at the period somewhat exceeding the local inertial period – probably due to the internal Poincaré wave being Doppler-shifted by the EAC [see also *Orlić*, 1987]. Currents related to the Adriatic seiche were aligned with the coast, and they were clearly visible since the length of our time series made efficient detiding possible; the only previous study of such currents concentrated on an exceptionally strong episode [*Leder and Orlić*, 2004].

[24] The current variability at time scales longer than a day is illustrated by Figures 11a and 11b, for February and May 2003. The vectors represent currents submitted to a low-pass digital filter having the cut-off frequency of 1/48 h^{-1} and the filter half-length equal to 168 h or 7 days

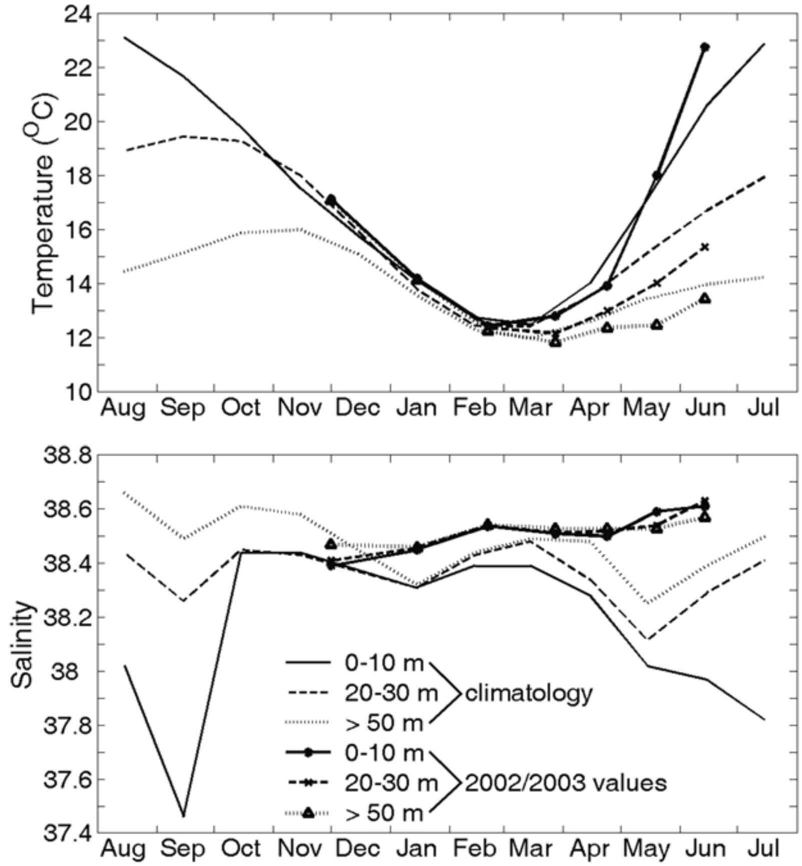

Figure 8. Temperature (top) and salinity (bottom) climatological averages computed for the northeastern part of the measurement area over the 1904–1982 interval (lines), compared with the values taken at stations 15–18 between November 2002 and June 2003 (symbols and lines). The data were collected in the surface (0–10 m, solid lines), intermediate (20–30 m, dashed lines) and bottom (>50 m, dotted lines) layers.

[e.g., *Emery and Thomson*, 1997] and then sampled with a one-day interval. At these time scales the Adriatic is to a great extent influenced by the wind episodes associated with synoptic atmospheric disturbances that last a few days [e.g., *Orlić et al.*, 1994; *Beg Paklar et al.*, 2001; *Pullen et al.*, 2003, and references therein]. Consequently, on the top of the figure time series of the wind, measured at the Veli Rat station, is shown as well; the wind was processed in the same way as the currents. The current variability generally corresponded to the wind changes, although in spring there were some events in the sea that were not related to the local wind. Both in winter and spring response of the currents to the wind forcing appeared to be stronger at station 13 than at station 9. The response was barotropic in winter, baroclinic in spring, due to different stratification and, hence, stability conditions.

[25] In order to get an insight into the seasonal variability of the current field, monthly mean currents have been calculated. The original 15 min data were averaged over complete months only. The time series of monthly mean currents at different depths, registered at the two stations, are shown in Figure 12. An inflow prevailed at station 13 throughout the six-month interval, whereas currents were weaker at station 9 and did not indicate an inflow during December 2002 and January and February 2003. Obviously, station 13 was positioned closer to the EAC core than station 9. The currents were of almost uniform direction along the vertical. Temporal variability of the currents did not follow expected pattern, since at station 13 the inflow was strongest in January/February 2003 and again in May 2003, whereas at station 9 it was actually better developed in spring than in winter. It may be concluded that in January/February 2003 the EAC was concentrated close to the Croatian coast, in May 2003 it was distributed more widely. On both occasions there was some variability of the inflow along the vertical, but reversal never occurred. Transport across the transect extending from station 8 to station 14, roughly estimated from data collected at stations 9 and 13, peaked in January 2003 (0.123 Sv) and in May 2003 (0.120 Sv).

[26] To what extent were these monthly mean currents influenced by the wind? In order to answer this question we had removed all hourly data, corresponding to winds exceeding 7 m/s at Veli Rat, from the recorded current time series, and have then computed monthly mean values from the reduced data set. The procedure is supported by the well-known fact that the Adriatic currents lag only slightly behind the wind [e.g., *Orlić et al.*, 1994]. The new monthly mean values are shown in Figure 13. Although the winter current maximum at station 13 is somewhat reduced with

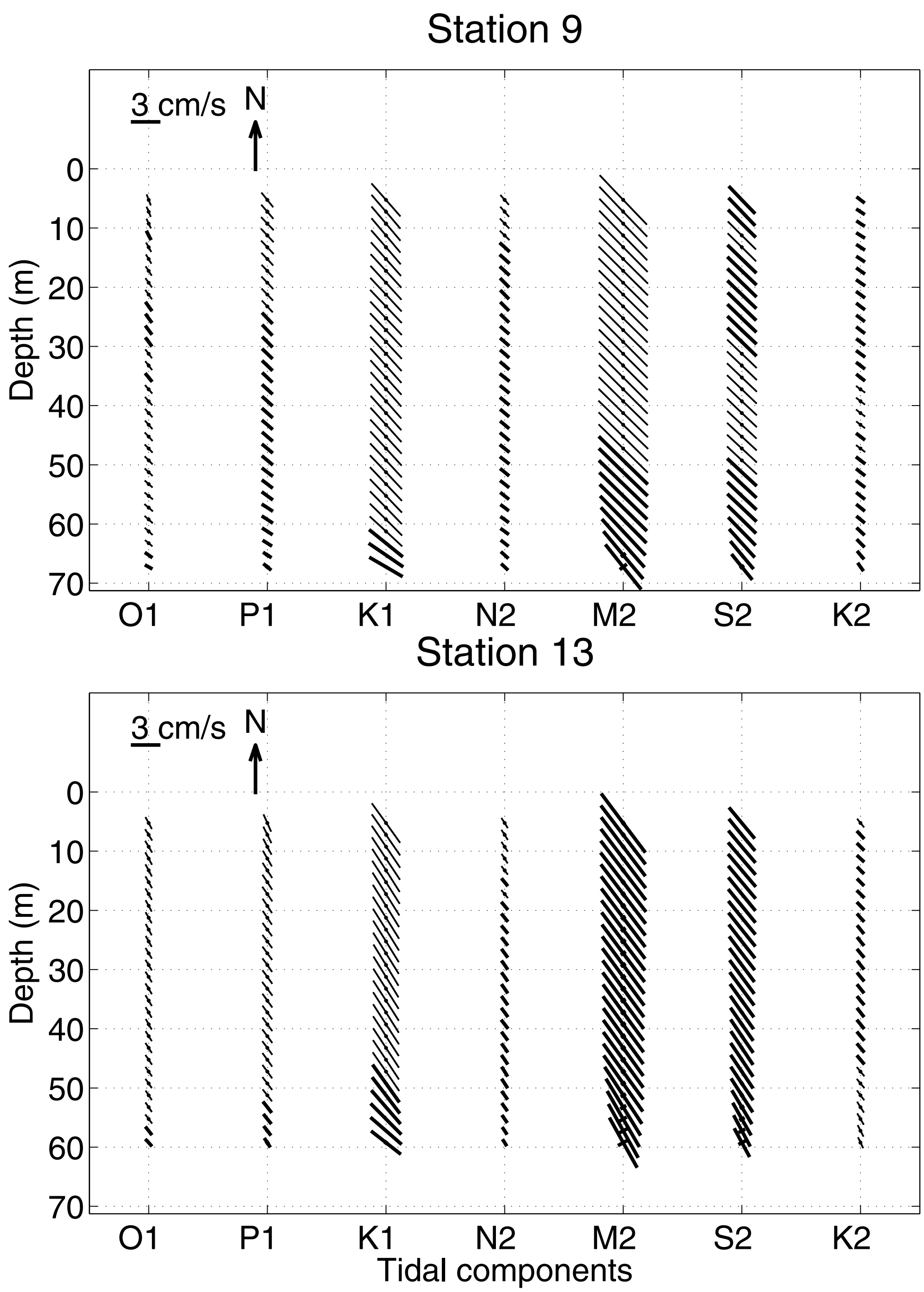

Figure 9. Tidal ellipses for seven major constituents recorded at various depths of stations 9 and 13. Thin (thick) symbols denote the clockwise (anticlockwise) rotation of tidal current vectors.

respect to that shown in Figure 12, it is still clearly separated from the spring one. It would thus appear that the winds are not of particular importance for the EAC variability at monthly time scales, and that the EAC may be interpreted primarily as a branch of some thermohaline circulation system.

[27] Let us also briefly consider along-shore variability of the EAC. The currents recorded along Senigallia-Susak transect in the scope of the Adriatic Circulation Experiment (ACE, J. W. Book, personal communication) could be used for the purpose. The EAC was well developed at station SS9, positioned to the northwest of our station 13 (Figure 1). The time series at the two stations were not collected over a same interval, but they did overlap between December 2002 and April 2003. Thus, differences of monthly mean currents could be computed between stations SS9 and 13. They show that in January/February 2003 the EAC was much stronger at station 13 than at station SS9. The data for April 2003 suggest the same relationship, but it could not be properly verified for the second EAC maximum since ACE current meters were recovered in the beginning of May 2003 and, therefore, did not document inflow along the Croatian coast in that month.

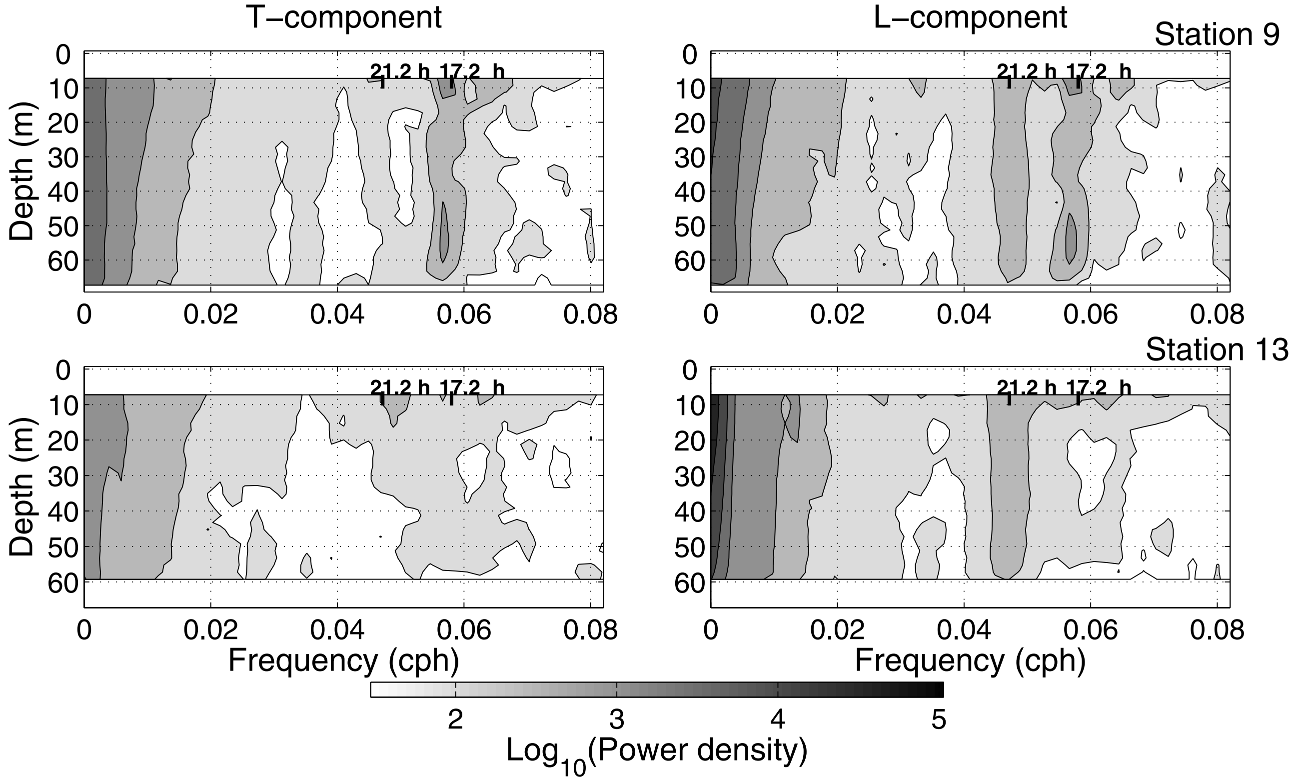

Figure 10. Power density spectra of detided current components (L – along-basin, directed northwestward, T – cross-basin, directed northeastward) determined as a function of depth for stations 9 and 13. Also indicated is the local inertial period (17.2 h) and the period of the fundamental Adriatic seiche (21.2 h).

[28] The most surprising result of our ADCP measurements is the second maximum of EAC. In order to check this finding, we have determined surface geostrophic currents from the cross-basin sea level slope. For such a computation we had at disposal sea levels routinely recorded at Zadar as well as bottom pressures measured at station 9 (Figure 1). The latter data set could be used to compute sea levels by assuming hydrostatic balance along the vertical, by utilizing vertical density profiles from our cruises and linearly interpolating them between the cruises, and by taking air pressures recorded at Veli Rat into account. The computed geostrophic currents represent average surface flow in the whole area extending from station 9 to Zadar and thus encompass channels and inlets which may have dynamics differing from that in our measurement area. In spite of this, the computed currents were successfully compared to the measured ones – to the northwest currents recorded at a 4 m depth and averaged for stations 9 and 13. Assuming that the six-month averages of the measured and computed surface currents are equal, one can easily calculate absolute sea levels at station 9. Both sea level series, together with the computed and measured surface currents, smoothed by a 30 day running average, are displayed in Figure 14. The agreement of the computed and measured surface currents is good. Slow change, with a period of about three months, can be observed in the series, with the currents peaking in January/February 2003 and again in May 2003. Thus, the occurrence of the second EAC maximum has been confirmed by an independent data set, and therefore had to be interpreted with care.

6. Discussion

[29] The present analysis has shown that meteorological and hydrologic forcing was anomalous in winter 2002/2003 and spring 2003: during winter the cooling and river outflows were strong, during spring the pronounced warming was combined with exceptional dryness. In winter considerable cross-shore variability of hydrographic properties was observed, with the colder, fresher water prevailing close to the coast, the warmer, saltier water dominating the open sea. In spring massive intrusion of the warmer, saltier water was detected along the east Adriatic coast. Different hydrographic conditions corresponded to distinctive maxima of the EAC: in January/February 2003 and in May 2003. The EAC was concentrated close to the coast in winter whereas it was more widespread in spring, and it stretched over the whole water column throughout the two seasons considered.

[30] Whereas the first EAC maximum reflects the previous findings on the Adriatic circulation, the second represents the novel result of the present study. We hypothesize that the first EAC maximum was related to coastal freshwater input and offshore evaporation in the Adriatic area, and that the second EAC maximum was due to wintertime surface cooling of the Adriatic while warmer conditions prevailed above the east Mediterranean. Thus, two circula-

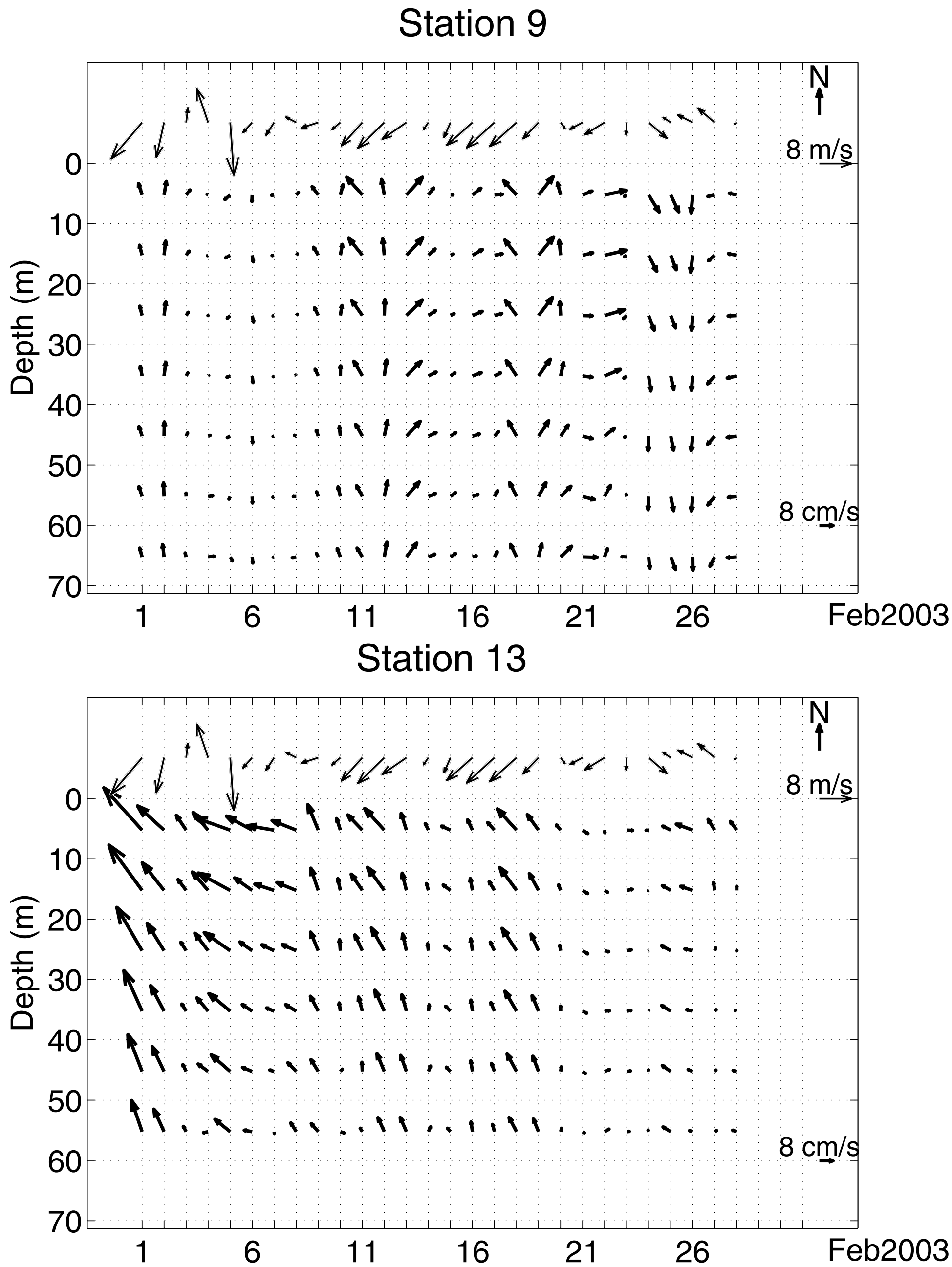

Figure 11a. Wind measured at Veli Rat and currents recorded along the vertical at stations 9 (top) and 13 (bottom) during February 2003. Variability at subdiurnal time scales was eliminated by a low-pass digital filter. Depiction of wind and currents follows the same convention.

tion systems could develop in response to the wintertime forcing, one haline, the other thermal, and since they probably differed in spatial scales (100 km vs. 1000 km) it is reasonable to expect that they also differed in temporal scales. In order to test this hypothesis, we have developed a simple numerical model of the Adriatic-Mediterranean system.

[31] Numerical experiments have been performed using Princeton Ocean Model (POM) – a three-dimensional primitive equation model with complete hydro- and thermodynamics [*Blumberg and Mellor*, 1987]. Model equations are traditional equations for the conservation of mass, momentum, heat and salt coupled with the equation of state [*Mellor*, 1991]. In the present application three simplifications were used: the hydrostatic, Boussinesq and 'f-plane' approximations. The model has a second order turbulence closure submodel described by *Mellor and Yamada* [1982], which provides two prognostic equations for the turbulent kinetic energy and turbulent macroscale. The horizontal viscosity and diffusivity coefficients are obtained using Smagorinsky diffusion formulation adapted to sigma coordinate system [*Mellor and Blumberg*, 1985].

[32] Experiments were made for an idealized basin, which mimics the Adriatic and east Mediterranean Seas

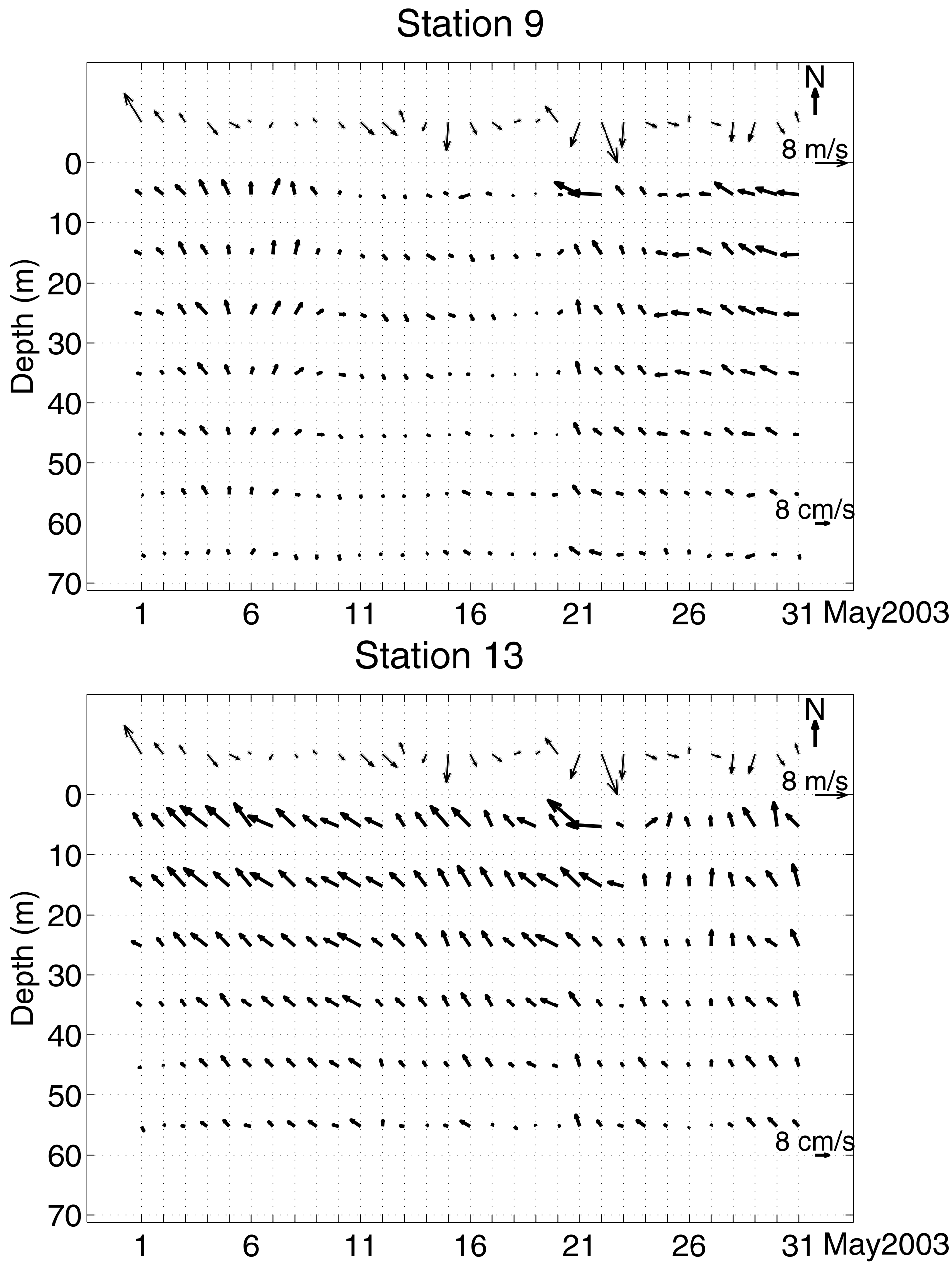

Figure 11b. As in Figure 11a, except for May 2003.

(Figure 15a). The Adriatic is approximated by a rectangular basin 800 km long and 200 km wide, having depth equal to 200 m. It is connected to another rectangular basin representing the east Mediterranean, which is 800 km long, 2100 km wide and 1500 m deep. Horizontal resolution in the experiments was 10 km. Along the vertical 16 unequally distributed sigma layers were used, with a better resolution in the surface and bottom layers. Courant-Friedrichs-Lewy criterion was satisfied with external time step of 24 s and internal time step of 480 s. Duration of numerical experiments was 150 days. In all experiments it was assumed that the background vertical viscosity/diffusivity (umol) equals 10^{-6} m^2/s, and that the coefficient controlling the horizontal mixing (horcon) amounts to 1 m^2/s [*Mellor*, 2003].

[33] Initial conditions for all the experiments were uniform temperature and salinity fields with values of 15°C and 38, respectively, and the state of rest. Numerical experiments have been organized so as to illustrate the effects of separate thermal and haline forcing and of combined thermohaline forcing. In the experiment with haline forcing river discharges were assumed to be equally distributed along the Adriatic coasts while horizontally uniform evaporative flux was distributed over the whole Adriatic. At each sea point along the Adriatic coasts a river having a 90 m^3/s discharge was imposed in the top model layer. The river was introduced as a source term in the continuity equation [*Kourafalou et al.*, 1996], and was therefore modeled as a volume of zero salinity water in the form of a coastal 'mound'. Coastal salinity in the immediate vicinity of the

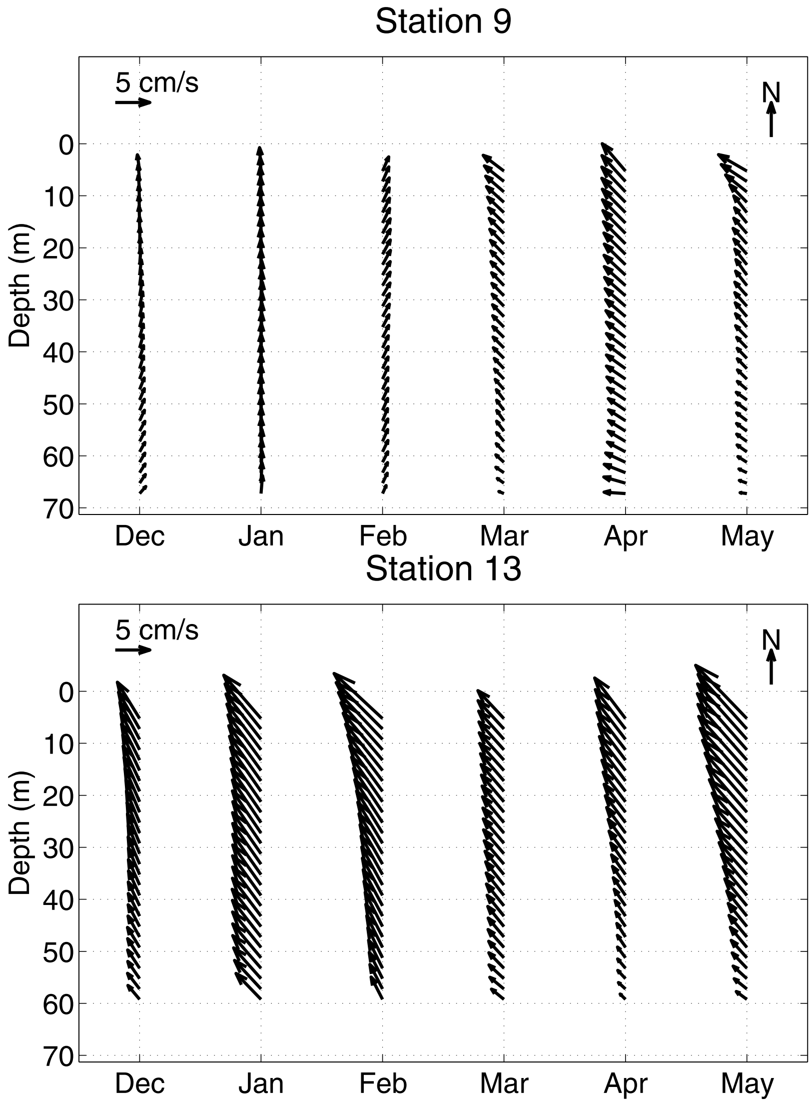

Figure 12. Monthly mean currents recorded throughout the water column of stations 9 and 13 between December 2002 and May 2003.

source was then determined by model mixing. To equilibrate the fresh water inflow, evaporative loss of 10^{-7} m/s was assumed at each grid point in the small rectangular basin approximating the Adriatic. The water loss was introduced in the equation of salt conservation as its surface condition. In the experiment with thermal forcing surface heat loss of 1000 W/m^2 was assumed over the entire Adriatic. The thermal forcing was imposed via surface condition in the equation of heat conservation. In the experiment with thermohaline forcing the surface heat and water fluxes and river inflows were applied simultaneously.

[34] In all the experiments forcing was imposed on the Adriatic basin only, and it was multiplied by a bell-shaped function tracing its variability over a 30 day winter interval (Figure 15b). As illustrated by Figures 4 and 5, surface water loss and coastal water gain peaked in the beginning of 2003, and were thus reasonably well approximated by the function. At a first glance, the approximation was not so good for the surface heat loss, because the cooling lasted from October 2002 to February 2003 (Figure 4), i.e. much longer than assumed in the numerical experiments. It should be taken into account, however, that in the beginning of the cooling season about 10^9 J has to be removed from the sea per square meter of the sea surface in order to reduce the temperature of the surface layer and to destroy the thermocline. It therefore takes about three months to homogenize the water column, whereupon convection may extend to the bottom. Rather than simulating the former process, we have initialized numerical experiments with the uniform temperature field and have allowed for intense cooling and consequent occurrence of horizontal temperature gradients in the beginning of 2003. The simulations were designed with the aim of interpreting events in the year 2003, and – in particular – the lack of forcing after the initial 30 day interval is atypical. But, as will be discussed in the concluding section, the anomalies of the year 2003 were in fact advantageous, since they enabled the two circulation systems that occur in response to the wintertime forcing to be analyzed, without having to consider the third system that develops when the springtime forcing is pronounced. Thus,

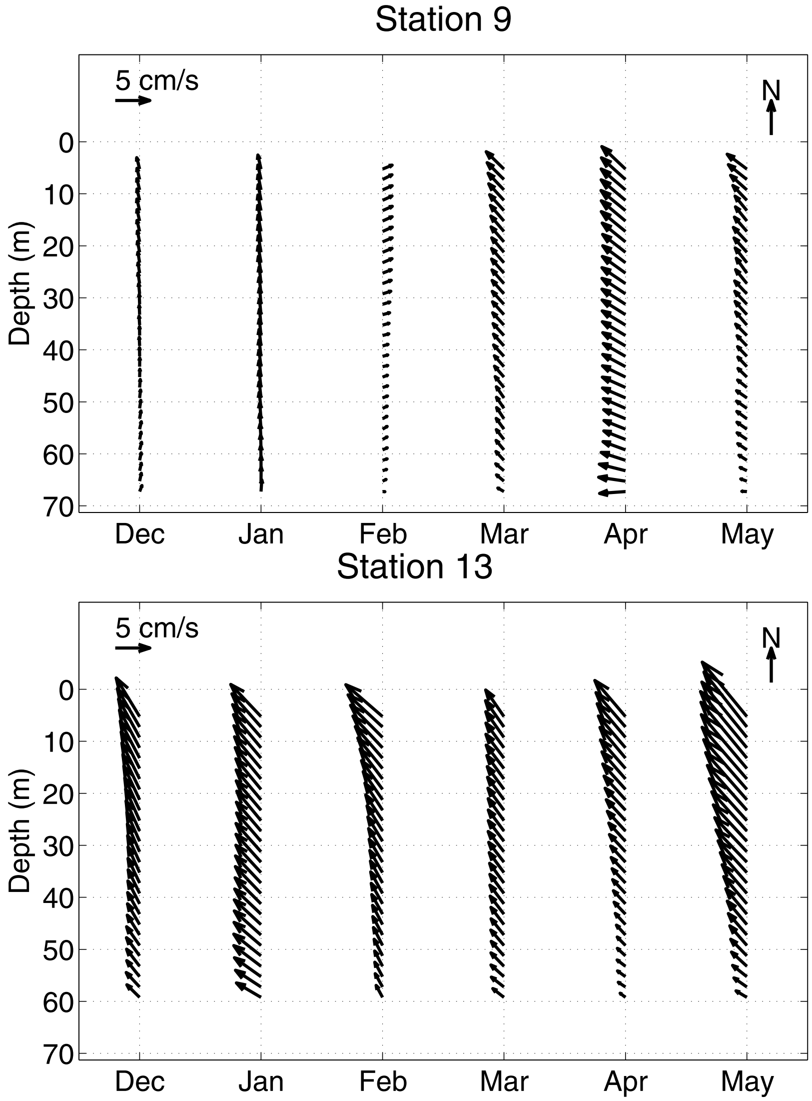

Figure 13. As in Figure 12, except that the currents related to hourly wind speeds exceeding 7 m/s at Veli Rat were excluded from the analysis.

the model reproduces – in a grossly simplified way – processes in a particular, anomalous year, but secures an insight that may be used to interpret conditions in a typical year.

[35] Surface along-shore currents, simulated at section N stretching across the 'north Adriatic' basin (Figures 15a and 15b), are shown in Figure 16 as a function of cross-basin distance (counted from 'Italian' side) and time. Currents obtained in the experiment with haline forcing indicate formation of a cyclonic circulation in the surface layer soon after the forcing attains maximum (Figure 16a). They reach 10 cm/s and are concentrated in a narrow area off both coasts, especially between 10th and 40th day. After 40 days, with the forcing being switched off, dissipation in the current field could be observed, and after 120 days the initial structure disappears. In contrast to this, currents following from the experiment with thermal forcing are weak during the first 60 days, i.e. throughout the forcing episode and some 30 days after its cessation (Figure 16b). After that incoming current appears off 'Croatian' coast and after 100 days outgoing current emerges off 'Italian' coast, indicating gradual development of cyclonic gyre in the surface layer of the 'north Adriatic' basin. The currents reach 20 cm/s, with significant speeds being confined to the coasts, although the coastal flows are broader than in the experiment with haline forcing. By adding the currents obtained under the separate haline and thermal forcing (Figure 16c) it is shown that the two may be easily distinguished since they are widely separated in time. Currents resulting from thermohaline forcing (Figure 16d) somewhat differ from currents produced by thermal-cum-haline forcing, as illustrated by the difference between them (Figure 16e). Despite these nonlinear effects, the two circulation systems are still clearly visible, one characterized by a rapid response to the forcing, the other by a delayed one. In all experiments currents in the bottom layer (not shown) are opposed to those in the surface layer and are much weaker.

[36] Numerical modeling has strongly supported interpretation according to which the EAC maximum in January/

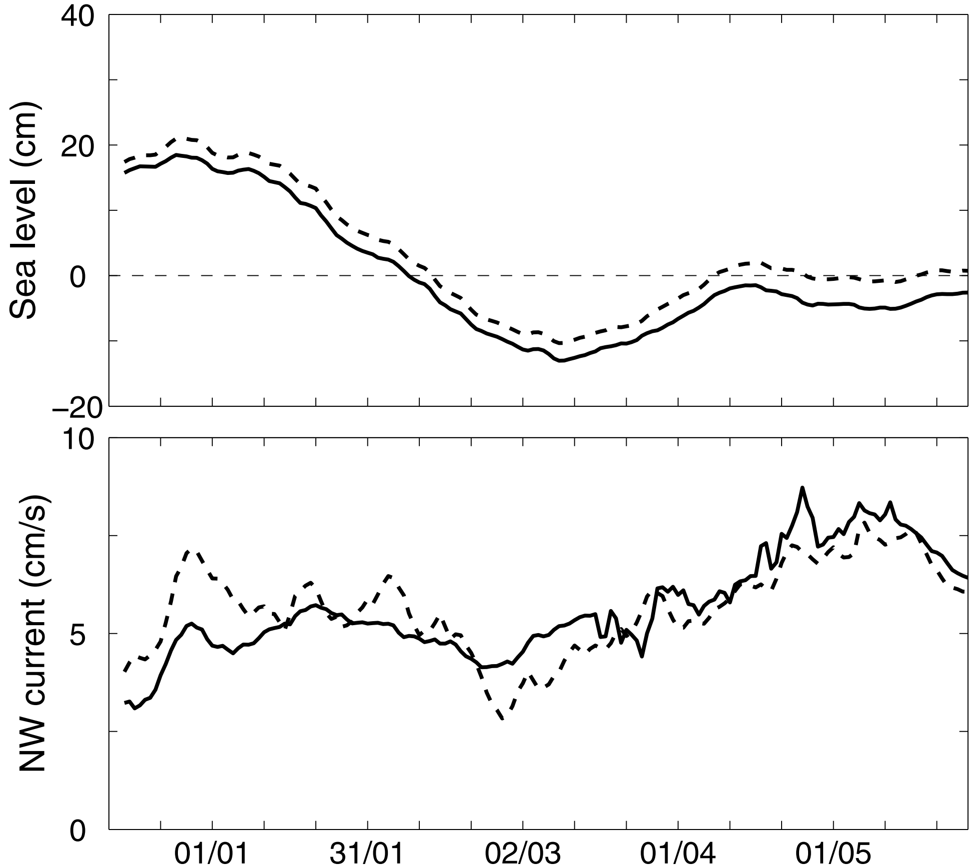

Figure 14. (top) Sea levels at stations 9 (solid line) and Zadar (dashed line). (bottom) Computed (solid line) and measured (dashed line) northwestward surface currents averaged over the measurement area. All time series were smoothed by a 30 day running average.

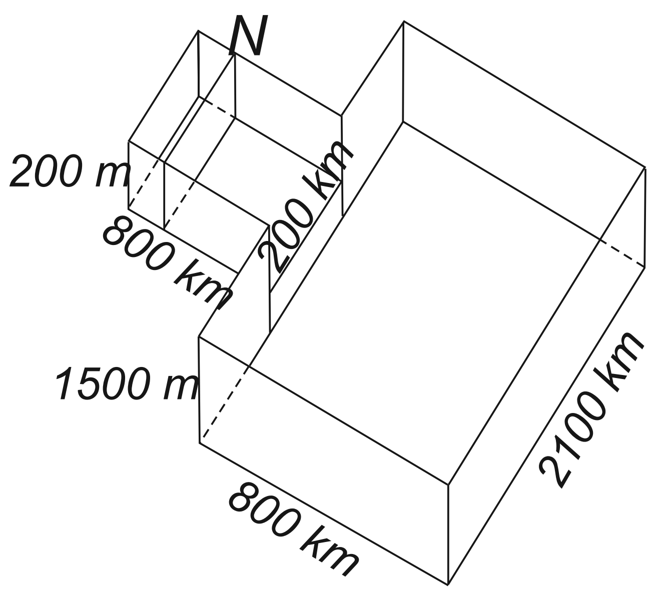

Figure 15a. Numerical model domain. Also shown is position of section N for which modeling results are discussed in some detail.

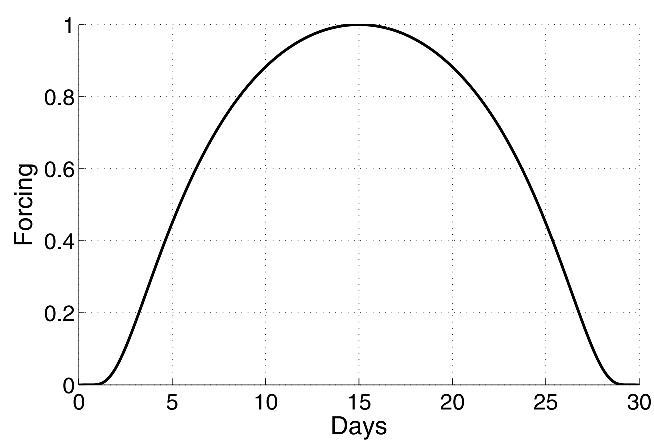

Figure 15b. Bell-shaped function, determining temporal variability of the forcing during 30 days that initiated numerical simulations.

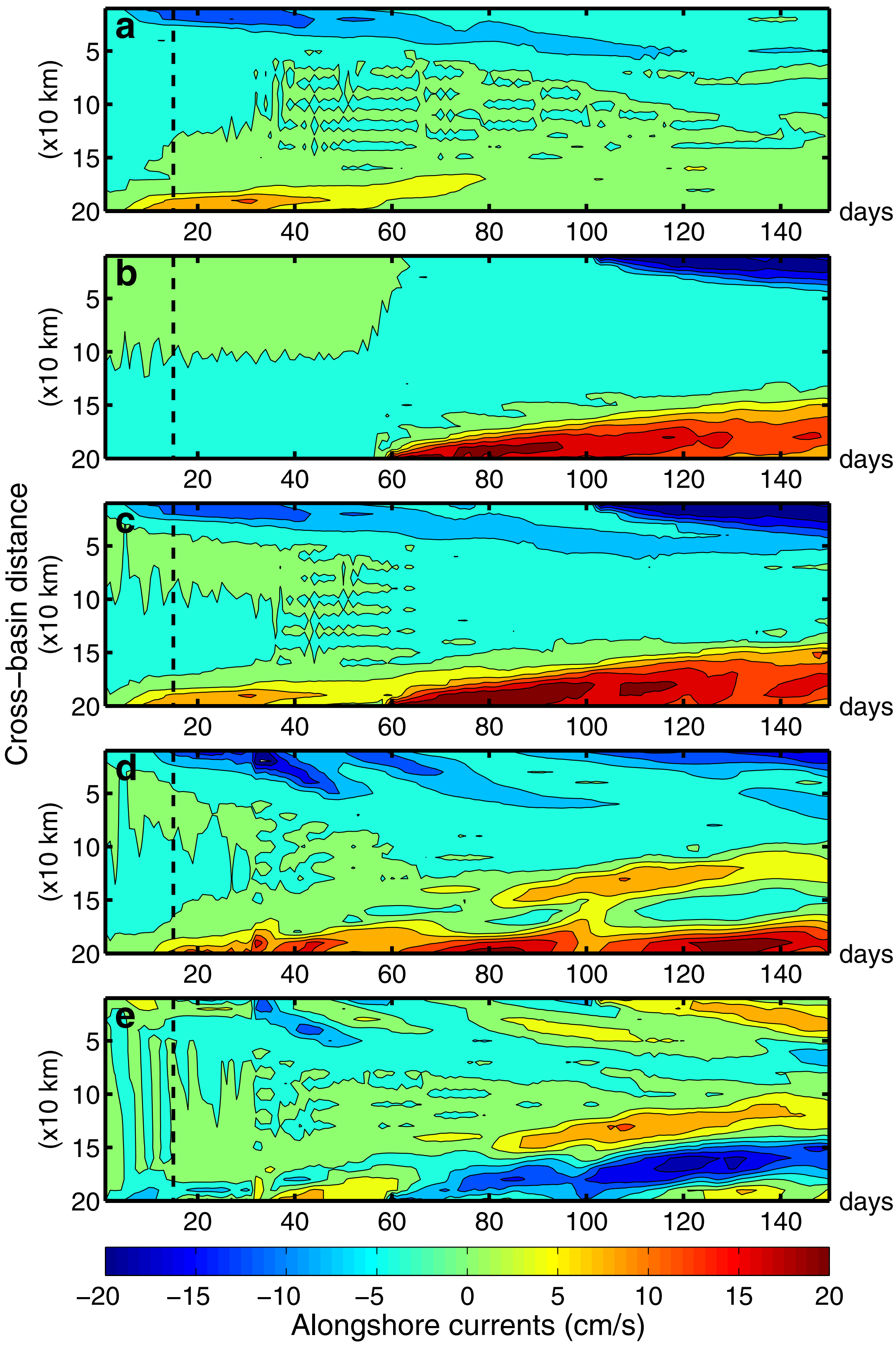

Figure 16. Temporal evolution of the along-basin surface current at section N extending from 'Italian' (0 km) to 'Croatian' (200 km) coast. Positive speeds imply an inflow to the 'Adriatic', with the contouring interval being 4 cm/s. Dashed line denotes culmination of the forcing (15th day). The figures show (a) simulation obtained under haline forcing, (b) simulation resulting from thermal forcing, (c) sum of Figures 16a and 16b, (d) simulation controlled by thermohaline forcing, and (e) difference between Figures 16d and 16c.

February 2003 was related to haline circulation that occurred within the Adriatic, whereas the EAC maximum in May 2003 represented a branch of thermal circulation that developed in the Adriatic-Mediterranean system. According to the model, the difference in temporal scales of the two circulation systems is considerable, which may explain the occurrence of two distinctive maxima. Moreover, the observed difference in width of the inflow – with a narrow current recorded in January/February 2003 and a broader current detected in May 2003 – also corresponds with the modeling results. Of course, there are also some discrepancies between the experimental and modeling findings, most notable being uniformity/reversal of flow along the vertical. It seems that the vertical distribution of currents could be sensitively dependent on mixing conditions and variable bottom topography, but numerical simulation of such effects falls beyond the scope of the present work.

7. Summary and Concluding Remarks

[37] Our meteorological measurements have shown that in winter 2002/2003 an interchange of the sirocco and bora episodes prevailed, spring 2003 was much more quiet. Most often, sirocco resulted in pronounced water gain by the sea, bora in strong heat loss, although there were some exceptions to this pattern related to 'dry sirocco' and 'dark bora' events. Overall, winter was characterized by unusually strong cooling, spring by exceptional heating. Surface water flux was close to the average in winter, but was anomalously directed upwards in spring. River outflows to the Adriatic were also atypical, thus reflecting prevailing meteorological conditions. Most rivers had a considerably increased discharge in late 2002 and early 2003. In February 2003 the discharges did not depart significantly from climatological values. However, in March 2003 a long-lasting dry period started: river discharges remained one standard deviation below climatological values until the end of the experiment.

[38] The sea responded promptly to the forcing. The winter cooling resulted in lower-than-average temperatures, which persisted in the intermediate and bottom layers throughout the spring season. Surface temperatures gradually became greater than long-term averages, due to intensive spring heating. Salinities were close to the averages during winter, but surpassed them during spring thus reflecting anomalously dry conditions. In winter colder, fresher water was advected from the coast, warmer, saltier water was dominating the open sea and was somewhat modified by dense water descending from the north Adriatic. In spring vertical stratification was well developed, as was an inflow of warmer, saltier water from the south Adriatic.

[39] The current measurements revealed a variety of high-frequency phenomena – tides, seiches, inertial oscillations, wind-driven flows. The most interesting finding, however, resulted from an analysis of month-to-month variability: the EAC attained maximum in January/February 2003 and again in May 2003. In the former case the EAC was concentrated close to the coast, reflecting cross-basin variability of salinity at the time. In the latter case it was distributed more widely, in concurrence with the observed massive intrusion of warm water from the southeast. On both occasions there was some variability of the inflow along the vertical, but reversal never occurred. Comparison with some other data showed that the current diminished in a northwestward direction. Its temporal variability was confirmed by computing geostrophic flow from the cross-basin sea level slope.

[40] Using a simple numerical model reproducing response of the Adriatic-Mediterranean system to wintertime forcing we have successfully tested a possible interpretation of the observed current variability. We thus propose that the first EAC maximum was related to coastal freshwater input and offshore evaporation in the Adriatic area, and that the second EAC maximum was due to wintertime surface cooling of the Adriatic while warmer conditions prevailed above the east Mediterranean. Since in the two situations buoyancy sources and sinks operated over different distances, two circulation systems developed: one of them was haline, with the corresponding thermal contribution opposing it because the river inflows were colder than the open Adriatic, the other was thermal, with the related haline contribution acting in the opposite sense due to the positive Mediterranean-to-Adriatic salinity difference. They differed in both spatial and temporal scales, therefore supporting the occurrence of two distinctive EAC maxima.

[41] The two circulation systems were previously modeled on several occasions. Haline circulation developing within the Adriatic was considered theoretically by *Hendershott and Rizzoli* [1976] and *Orlić* [1996], thermally driven interchange between the basins resembling the Adriatic and east Mediterranean by *Spall* [2003, 2004]. The models, however, were based on the steady-state assumption or were integrated until a statistical equilibrium was achieved. Consequently, temporal variability of the currents was not of primary concern. Both haline and thermal circulations may be expected to be reproduced by numerical models of the Adriatic, which (1) allow for the air-sea heat and water fluxes, (2) take the river inflows into account, and (3) are nested into a wider Mediterranean model. By a rare modeling effort that satisfied these criteria *Zavatarelli and Pinardi* [2003] produced realistic wintertime currents. Yet, the simulated currents were averaged over a four month interval (January–April) and therefore haline and thermal contributions could not be considered separately.

[42] Previous theoretical studies indicate that haline circulation occurs within the Adriatic (marginal-sea circulation) whereas thermal circulation develops between the Adriatic and east Mediterranean (negative inter-basin circulation, implying an outflow from the Adriatic in the bottom layer compensated by an inflow from the Mediterranean in the layers above). Our data and model suggest that marginal-sea circulation is a proper winter phenomenon, and that negative inter-basin circulation starts in winter but may persist in spring and thus could interfere with other processes that are characteristic for the warmer part of the year. Most important of these is positive inter-basin (or estuarine-type) circulation, which usually occurs in spring when the Adriatic rivers discharge into the stratified sea and are transported outwards in the surface layer thus supporting an inflow from the Mediterranean in the deeper layers. In spring 2003, however, the latter circulation system was weakly developed, due to anomalous meteorological and

hydrologic conditions, and thus we have observed negative inter-basin circulation in an almost pure form. It may be expected that in a more typical year surface outflow related to positive inter-basin circulation would oppose surface inflow due to negative inter-basin circulation and that the EAC would peak only in winter – in agreement with the prevalent views on the Adriatic dynamics.

[43] It is of some interest to reconsider here the main ideas on the Adriatic circulation. As already mentioned, *Nielsen* [1912] was probably the first to describe negative inter-basin circulation, *Schott* [1915] pioneered the study of positive inter-basin circulation. Their findings were combined by *Zore-Armanda* [1963] in a paradigm stating, basically, that negative inter-basin circulation occurs in winter, positive inter-basin circulation in summer, transitions in spring and autumn. Subsequently, *Hendershott and Rizzoli* [1976] provided evidence on marginal-sea circulation in the Adriatic. This resulted in a modification of the old paradigm, implying that marginal-sea and negative inter-basin circulations develop on similar time scales and that both occur in winter and at the same time retaining the earlier interpretation of dynamics that controls the rest of the year [*Franco et al.*, 1982; *Orlić et al.*, 1992; *Cushman-Roisin et al.*, 2001]. The time now seems ripe for a new paradigm, which would allow for marginal-sea and negative inter-basin circulations being separated in time.

[44] There would be several consequences of the new paradigm. Thus, for example, the widespread practice of computing seasonally averaged currents in the Adriatic should be abandoned in favor of averaging over one month intervals. Whereas the new filter may sometimes be too demanding for experimentalists, it should be readily acceptable to modelers. The new paradigm may also help to explain the apparent discrepancy between the findings of *Zore* [1956] and *Artegiani et al.* [1997] (who showed that the EAC is better developed than the West Adriatic Current, WAC, in winter) and the results published by *Poulain* [2001] (who found the EAC similar to the WAC in winter). Wintertime surface currents considered by *Zore* were related to February/March, those by *Artegiani et al.* to January–April, currents by *Poulain* to January–March. Probably, the results obtained by *Poulain* were mostly controlled by marginal-sea circulation forming within the Adriatic whereas the findings published by *Zore* and *Artegiani et al.* were additionally influenced by negative inter-basin circulation developing between the Adriatic and east Mediterranean.

[45] **Acknowledgments.** We thank the masters and crews of R/Vs *Bios*, *Hidra*, and *Palagruža* for taking part in the East Adriatic Coastal Experiment (EACE) and for their professional and efficient contributions to its field-work phase. We are also indebted to Damir Ivanković and Zlatko Radman for participating in deployment and recovery of instruments in a highly competent and motivated manner. We sincerely thank Craig M. Lee (University of Washington, Seattle, Washington, United States) for providing underway temperature and salinity data taken while R/V *Knorr* traversed our measurement area on 4 June 2003, and Jeff W. Book (Naval Research Laboratory, Stennis Space Center, Mississippi, United States) for supplying processed current data collected in the framework of the Adriatic Circulation Experiment. Hydrologic and Meteorological Service of the Republic of Croatia kindly provided meteorological data collected at Zadar, sea surface temperatures recorded at Mali Lošinj, as well as discharges and water levels originating from the east Adriatic rivers. Comments offered by two anonymous reviewers helped to improve the original manuscript. EACE was supported by the U.S. Office of Naval Research (through the grant 493264 administrated by the University of Washington, Seattle, Washington, United States) and the Croatian Ministry of Science, Education and Sports.

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