Geostrophic Circulation Patterns in the Northeastern Adriatic Sea and the Effects of Air-Sea Coupling: May-September 2003

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Abstract

CTD data were collected weekly during 20 cruises from May to September 2003 over a 19 station grid in a coastal region of the northeastern Adriatic Sea as part of Project *ADRICOSM*. Relative geostrophic velocities indicated fine scale circulation patterns in in the area consisting of two pronounced circulation cells, of cyclonic and anti-cyclonic character, and that were present in the area for most of the investigated period.. These motions were induced primarily by spatial variations in the temperature field and may be strengthened during episodes of very strong northeasterly bora wind, when the investigated region is not heated (cooled) uniformly.

Keywords

temperature, salinity, geostrophic currents, air-sea coupling, northern Adriatic.

Introduction

The general circulation of the Adriatic has long been established as being cyclonic, consisting of a counterclockwise movement of water northwestward along the Croatian coast (East Adriatic Current; EAC) and a southeastward flow along the Italian coast (West Adriatic Current; WAC). One of the first more detailed studies in the region [*Mosetti and Lavenia*, 1969], based on dynamic height computations in the 1966-1968 period, showed that the EAC may penetrate into into the northernmost part of Adriatic in spring although in autumn can be deflected offshore near the southern tip of the Istrian peninsula to gradually join the WAC, with a smaller cyclonic gyre north of this line remaining.

Based on subsequent current meter investigations from 1971-1982, *Zore-Armada and Vučak* [1984] proposed a schematic for the mean annual surface circulation showing it to consist of both a cyclonic and anti-cyclonic gyre in the northern Adriatic lying to the north and south, respectively, of a line between the river Po delta and Rovinj, as presented in Figure 1. Mean seasonal drifter data, collected in the 1990-1999 period [*Poulain*, 2001], did not indicate the presence of an anti-cyclonic gyre although did suggest the presence of a cyclonic gyre in the summer period. For the autumn/winter period drifter data were too scarce to draw firm conclusions.

However, long-term currentmeter investigations by *Brana and Krajcar* [1995] found evidence of a southward current in the open waters (at station RV07) of the northeastern Adriatic that was especially strong in September, consistent with Figure 1. *Supić et al.*

[2000] showed that currents along the Istrian coast are highly variable with a very strong outflow (termed the Istrian Coastal Countercurrent, ICCC) occurring in some years of the 1966-1997 interval in August in the coastal zone off Istria. The possibility that the ICCC is part of an anti-cyclonic gyre in the northeastern Adriatic has been discussed by *Supić et al.* [2003]. The climatology of the geostrophic circulation in the northern Adriatic as given by *Krajcar* [2003] would support earlier assumptions that stronger southerly motions observed in the northeastern Adriatic in summer are part of an anti-cyclonic gyre.

As a shallow sea shelf area, atmosphere-ocean coupling by wind forcing, with distinct wind regimes from both the northeast (bora) and southeast (sirocco), has been found important in influencing surface circulation patterns [*Zore-Armanda and Gačić,* 1987*; Orlić et al.,* 1994*; Brana et al.,* 1996] in addition to a significant contribution from the large freshwater runoff from the river Po on the Italian coast [*Franco et al.,* 1982] and derived buoyancy forcing.

Previous studies of northern Adriatic circulation have typically been based on direct current measurements at several points in the area or on analysis of geostrophic currents derived from low resolution hydrographic data that provide a general map of circulation characteristics. However, these studies do not address the fine-scale composition and nature of local circulation patterns. We report herein high resolution CTD data collected under the framework of the Adriatic Sea Integrated Coastal Areas and River Basin Management System Pilot Project (*ADRICOSM*). These hydrographic data were elaborated to provide a description of water mass composition, distribution and geostrophic circulation patterns of the northeastern Adriatic Sea in the May-September 2003 period. In addition, the interaction between circulation and meteorological forcing were investigated and the results discussed in the context of present knowledge of northeastern Adriatic circulation patterns.

Data

Temperature and salinity data were collected over a 19 station grid during 20 one-day weekly cruises over the warm part of the year from May to September 2003 off the Istrian coast of Croatia in the northeastern Adriatic (Figure 1). Data were collected, using a SeaBird Electronics SBE 25 CTD at every 8 cm (sampling frequency 8 Hz) from the surface to 2 m above the bottom and average values were calculated for each 0.5 m depth interval. Daily values of standard meteorological data (air pressure, air temperature, wind speed, fractional cloud cover (measured in one-tenths), water vapor pressure and precipitation) and sea surface temperature (SST) data were measured at Pula Meteorological Station (44° 52' N, 13° 55' E) and in Pula harbor (44° 51.5' N, 13° 49.8' E), respectively, in the interval from 1 May to 30 September 2003. The data were collected three times a day at 6, 13 and 20 h UTC (with the exception of the precipitation data which were estimated daily). These data were provided by the Hydrometeorological Institute in Zagreb (meteorological data) and by the Maritime Meteorological Center in Split (sea surface temperature data). Daily values of Po river discharge rate were derived from data collected at station Pontelagoscuro. The data were supplied by Assessorato Programazione, Piafinicazione e Ambinete of the Emilia Romagna region (Italy). Sea surface temperature (SST) and chlorophyll *a* maps were derived from AVHRR and SeaWiFS satellite data processed and distributed by the Satellite Oceanography Group from the Institute of Atmospheric Sciences and Climate (ISAC, Rome) of the National Research Council (CNR) of Italy.

Methods

CTD data were used to compute geostrophic velocities relative to the 25 m level for each pair of neighboring stations at the three sections perpendicular to the coast (Poreč: RV01→RV05, Rovinj: RV07→RV12, Pula: RV13→RV18) and the Frontal section parallel to the coast with two components – a northern component between the Poreč and Rovinj sections (frontal northern, FN section: RV05→RV07) and a southern component between the Rovinj and the Pula section (frontal southern, FS section: RV07-RV19-RV18) for each cruise (Figure 1). Geostrophic velocities were calculated according to standard methods (*Supić et al.,* 2000, and references therein). As the bottom depths at the two near-shore stations of the Poreč section were less than 25 m, values for salinity and temperature at depths greater than 22-24 m at those stations were taken to be equal to the nearest existing data. Relative geostrophic velocities at every 0.5 m interval between the surface and 25 m depth were used to compute net relative geostrophic transports (see, for example, *Marinone and Ripa*, 1988). At the Poreč, Rovinj and Pula sections, geostrophic velocity and transport values are denoted as positive when they mark an inflow (northwestward) into the northern Adriatic. At the FN and FS sections, values are positive when water movement is directed towards the coast (northeastward).

Error ($E_{T,S}$) values, representing how well geostrophic transport across a section S of total area A_S represent daily-averaged real current transport across the same section, were calculated as:

$$E_{T,S} = A_S * E_{AC\text{-}G25},$$

where $E_{AC\text{-}G25}$ is the error between daily-averaged current and the corresponding geostrophic current relative to 25 m depth (Appendix). An assumption was made that the error in the geostrophic approximation of real currents is the same at any depth between the reference level and the surface. Although the wind velocity peaked at 6.8 m s^{-1} for the cruise on 15 September we have used the error estimate for wind velocity of 6.4 m s^{-1} as this latter was the maximal wind speed given in *Krajcar et al.* [2003] (see Appendix).

Inflow and outflow of water near the Istrian coast based on geostrophic transport was analyzed based on two hypothetical boxes bounded by the Poreč, Rovinj and FN sections and the coast (Box 1) and the Rovinj, Pula and FS sections and the coast (Box 2). The excess transport was calculated as the difference between the total transport into a box and the total transport out of that box. For example, excess transport in Box 2 is the sum of transport through the Pula and FS sections minus the transport through the Rovinj section. The corresponding error in excess transport, E_{ET} was calculated by:

$$E_{ET}^2 \text{(Box 1)} = E_{T,\text{ Poreč}}^2 + E_{T,\text{ Rovinj}}^2 + E_{T,\text{ FN}}^2 \quad \text{and}$$

$$E_{ET}^2 \text{(Box 2)} = E_{T,\text{ Rovinj}}^2 + E_{T,\text{ Pula}}^2 + E_{T,\text{ FS}}^2.$$

The data collected at Pula Meteorological Station were used to compute daily values of air-sea heat flux (Q; taken as the sum of insolation Q_s, longwave radiation Q_l, latent Q_e and sensible heat Q_c fluxes) and water flux (W; difference between precipitation P and evaporation E) following the methods described in detail in *Supić and Orlić* [1999]. Q_s was computed after the formula proposed by *Reed* [1977] and adapted for use in the Mediterranean area by *Gilman and Garrett* [1994]:

$$Q_s = Q_o\, Tr\,(1 - 0.637\, n + 0.0019\, h)(1 - \alpha),$$

where Q_0Tr is the clear sky radiation dependent on time of the year and latitude, n is the cloud cover fraction in tenths, h is the noon solar altitude in degrees, and α is albedo of the sea surface taken to be α = 0.08. Q_s was corrected for error resulting from inappropriate use of this relationship at very low cloud levels and Tr (transmission factor for a clear atmosphere) was assumed to be 0.665 between May and October and 0.700 for the rest of the year as attenuation due to aerosols is seasonally variable [*Gilman and Garrett*, 1994]. Q_l, Q_e and Q_c were computed by a set of formulae proposed by *Gill* [1982]:

$$Q_l = -0.985\, \sigma\, T_s^4\, (0.39 - 0.05\, e^{1/2})(1 - 0.6\, n^2),$$

$$Q_e = L\, C_E\, \rho_a\, u\, (q_a - q_s),$$

and

$$Q_c = C_H\, c_p\, \rho_a\, u\, (T_a - T_s),$$

were σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}), T_s is the sea surface temperature (K), e is the water vapor pressure (mbar), u is scalar wind speed, q_a-q_s is the difference between the observed specific humidity and the saturation humidity at the sea surface, $T_a - T_s$ is the difference between the air and sea surface temperature, L is latent heat of evaporation with a constant value of 2.5×10^6 J kg^{-1}, ρ_a is the air density taken to be

1.25 kg m^{-3}, c_p is the specific heat of air with a values of 1010 J kg^{-1} K^{-1}, and C_E and C are dimensionless coefficients, assumed to equal to constant values $1.5x10^{-3}$ and $1x10^{-3}$, respectively. Downward water flux (*W*; mm d^{-1}) was computed as the difference between precipitation (*P*) and evaporation [$E = - Q_e/(L\rho_0)$], assuming that seawater density ρ_0 and latent heat of evaporation L have constant values of 1000 kg m^{-3} and $2.5x10^6$ J kg^{-1}, respectively. Positive values of fluxes denote heat or water gain by the sea.

Spatial and temporal variations of water mass transports were analyzed by the Empirical Orthogonal Functions (EOF) method using standard statistical software.

Results

Meteorological Conditions

Daily values of meteorological parameters and SST at Pula, as well as Po river discharge rates, during the May-September 2003 interval are shown in Figure 2. Monthly averaged values of these data, with the exception of fractional cloud cover, showed a significant (greater than one standard deviation, σ) departure from monthly averages computed for the northeastern Adriatic from data gathered between 1966-1992 [*Supić and Orlić*, 1999]. While air-pressure values were significantly lower than average, the values of air temperature, wind speed and SST were, for the most part of the period analyzed, significantly greater than the long-term averages. Precipitation was significantly lower than usual in both June and July. Throughout the observed period departures from monthly values of Po river discharge rates were especially great, with discharge values far lower (by up to 3σ) than the long-term average [*Supić and Orlić*, 1999].

Surface fluxes

In general, surface heat flux, Q, was positive from May to August and became negative in September (Figure 3). During the entire interval from May to September daily values of surface water flux were, apart from several precipitation episodes, negative. Both air-sea heat and water fluxes were highly dependant on evaporation. The periods of intense air-sea heat/water exchange were related to episodes of intense evaporation occurring under conditions of strong wind with a pronounced NE (bora) component as, for example, on 29 July and from 31 July – 02 August. Strong evaporation was also noted on two occasions when a strong wind was blowing from the south (sirocco) as, for example, on 02-04 July and 30-31 August. The correlation coefficient between evaporation and the NE component of wind (0.64 for 153 pairs of data; relevant at the 99% level) was however much higher than that between evaporation and the NW wind component (0.22).

Oceanographic Conditions

Temperature, salinity and density (σ_t) varied over the entire area investigated, and ranged from 16.8-28.6 ^{o}C, 36.5-38.6 and 23.7-27.9 at the surface, respectively, and 10.2-24.4 ^{o}C, 38.1-38.8 and 26.2-29.4 at the bottom, respectively. While temperatures gradually increased, and density decreased, from May to the end of August and September, salinity remained highly variable throughout the period as shown, for example, for station RV07 (Figure 4).

Identifying individual water masses based on temperature and salinity characteristics is difficult for shallow shelf seas such as the northern Adriatic Sea due to the wide variation in temperature for water of a given salinity. While inexact, two water masses based on salinity values alone were generally defined: low salinity water (LSW) with values lower than 37.8 and high salinity water (HSW) with values greater than 38.5. LSW was always found at the surface while HSW was found throughout the water column. Presumably LSW derives mainly from Po river fresh waters although the contribution of other rivers in the northern Adriatic cannot be discounted. HSW has a similar salinity to modified Levantine intermediate water (MLIW; S>38.5) although is present at shallower depths (<50 m). This may be the result of MLIW intruding into the northern Adriatic at shallower depths due to the bathymetry.

While significant variations in surface temperature from May to September can be related to changes in surface heat flux, surface salinity changes seem to be independent of the air-sea water flux. However, a positive correlation (0.36; significant at more than 80 % confidence level) was found between average (for the entire area) surface salinity changes and northeasterly wind indicating that, on the day when bora blows, surface salinity generally rises (Figure 5). At a 2-day time lag surface salinity was highly negatively correlated (0.40; at the 95 % confidence level) to the NE wind component, indicating a reduction in salinity possibly due to Po freshened waters arriving in the area after the bora event.

Comparison with long-term averages at station RV07 [*Lyons et al.*, 2006] showed that both temperature and salinity at the surface were significantly higher than predicted based on long-term statistically modeled values for the May-September period and may be related to the high temperatures and low rainfall over Europe during 2003 [*Luterbacher et al.*, 2003]. Riverine input, in particular from the river Po, was dramatically lower than usual over the investigated period [*Lyons et al.*, 2006]. Other rivers local to the Istrian coast, whose discharges are on average much smaller than that of the Po river (Mirna, 10 m^3 s^{-1}; Dragonja (data unavailable); *Pasarić, 2004*), are not considered to impact significantly on the hydrographic conditions. From March to August 2003 the discharge rates of Istrian rivers were one standard deviation lower than usual (M. Pasarić, personal communication). In addition, the usual large Po spring freshwater input was absent. While an impact from freshwater input from rivers on the north Italian coast (Gulf of Trieste) or from Kvarner Bay cannot be discounted, they would not be expected to have a strong impact on the area adjacent to the Istrian coast based on the circulation schematic in figure 1. During the summer waters of river Po origin, which are usually confined to an area near the Italian coast during winter, normally spread over the northern Adriatic as a distinct surface layer with lower salinity due to changes in seasonal circulation patterns and that, on average, reaches the Istrian coast in late April or May [*Krajcar,* 2004]. From salinity data and chlorophyll satellite imagery, it was observed that Po waters did not intrude to the usual extent although less-saline water of Po origin was present near Poreč in mid-June and near Rovinj in mid-July. From November to January, water of density greater than usual was not formed (data not shown), in spite of strong cooling, presumably due to higher than usual input from the river Po [*Lyons et al.*, 2006]. From March, inspite of low input of fresher waters of riverine origin, strong heating of the surface resulted in stratification that reduced vertical mixing processes causing water of greater density than usual (σ_t>29 kg m^{-3}) to remain for most of the warm period near the bottom

There was little evidence of eddies based on CTD and satellite imagery although on 16 and 30 July pools of low salinity and less dense water were found on the Rovinj section. These were 15-20 km in diameter and characterized by closed horizontal salinity and density isolines to depths of 1.7 m and 0.8 m respectively. While dynamic height analysis suggested that these would have anti-cyclonic motion, their spatial movement with time could not be tracked based on our cruise frequency or resolved from satellite imagery. As these were essentially only limited surface features they were not found to impact significantly on the geostrophic circulation. The low eddy activity during this study should be qualified by stating that eddies with time scales of only several days and those that may straddle the boundary of our investigated area may not have been identified.

The mean hydrographic conditions, taken as average density, temperature and salinity values (for the upper 25 m of the water column) at four sections shows a highly stratified water column at all sections (Figure 6). The density at offshore stations of the Poreč and Rovinj sections was greater than the near-shore stations, while at the Pula section density offshore was lower than near-shore. This was induced by the temperature distribution rather than the salinity distribution (Figure 6). The temperature at the surface was relatively uniform at all stations. At 25 m depth, near-shore stations also showed similar temperature values. However, at the Poreč and Rovinj sections, lower temperature values offshore were noted at 25 m, while higher temperatures were found offshore at the Pula section. Average salinity values were lower at offshore than near-shore stations of the Poreč and Rovinj sections, presumably due to the presence of fresher water of river Po origin at the surface. Average salinity values were high for the entire Pula section. The highest salinity values at each section were noted at 20 m depth although the highest overall values were noted for the Pula and Rovinj sections where HSW appeared to intrude from the southwest.

Time series of the average temperature, salinity and density, computed from the 25 m water column over the entire area in the investigated period, showed that density changes were most induced by changes in temperature (correlation coefficient 0.99) than by salinity (correlation coefficient 0.11).

There was no evidence of strong vertical frontal features near the Istrian coast although the arrival of less-saline waters in the area at the end of May and the first part of July did create some horizontal variations in salinity. Therefore we assume that most changes in average density are related to depression/uplift of isopycnals induced by heating/cooling of the water column. These isopycnal uplifts coincided with strong wind events (e. g. Figure 4).

Geostrophic Currents

The Poreč section was characterized by a northward flow (up to 14 cm s^{-1}, typically 2-4 cm s^{-1}) of water from mid-May to mid-July. Periodic southward flows (up to 16 cm s^{-1})

appeared and were generally located in a 10 km coastal strip in the upper 10-15 m of the water column. From mid-July to the end of August, this southward flow became more strongly established and peaked at 19 cm s^{-1} at the end of August while on the western, offshore part of the section and near the bottom, a northward flow (typically 1-3 cm s^{-1}) persisted. From the start of September northward currents (2-4 cm s^{-1}) gradually became dominant over the entire section.

Geostrophic currents at the Rovinj section displayed similar behavior to those calculated for the Poreč section. However, from mid-July a more pronounced and constant southward flow (up to 23 cm s^{-1}) than observed for the Poreč section became established while in September rapidly diminished. Northward velocities were typically about 2-4 cm s^{-1} throughout the investigated period.

The strongest geostrophic currents were found for the Pula section. Throughout the entire period a southeastward current was established (up to 28 cm s^{-1}) that oftentimes extended to the bottom of the water column. Northwestward flow remained relatively constant at 2-4 cm s^{-1} (peaking at 13 cm s^{-1}), typically throughout the water column, on the western part of the section.

The Frontal section parallel to the coast was generally characterized by a current flow towards the Istrian coast on the southern (FS) part and away from the coast on the northern (FN) part (typically 3.5 cm s^{-1} and 4.5 cm s^{-1} respectively, peaking at 8 cm s^{-1}).

Overall, geostrophic circulation of the upper water column suggests that cyclonic motion is typically present north of the Rovinj-Po delta line while anti-cyclonic motion is present south of that line (Figure 1). As the geostrophic velocities were generally greater than the associated error (Table A2) it suggests that geostrophic circulation described above may be considered representative of real daily currents in the area during the investigated period.

Water Mass Transport

Four different mass transport situations were noted (Figure 7). On thirteen occasions there was cyclonic motion north of Rovinj and anti-cyclonic motion south of Rovinj while on three occasions this pattern was reversed. Only cyclonic motion was noted in the area on three occasions while only anti-cyclonic motion was found once. Average transport values and the first EOF mode (Table 2) gave a similar circulation pattern to the most common pattern described above.

The accuracy by which geostrophic transports represent real daily average current fields was tested by computing excess transport for each cruise in two hypothetical boxes, bounded by the Poreč, Rovinj and FN sections and the coast (Box 1) and the Rovinj, Pula and FS sections and the coast (Box 2, Table 1). Any change in computed sea level in a box should not exceed real sea level change (differences in daily sea levels were up to 25 cm at Rovinj in the March-September 2003 period; *Čupić*, 2005). The excess transport in the two boxes implied much larger sea level changes, typically of about 1 m at Box 1 and of about 2 m at Box 2 (values of gain or loss of 7000 m^3 s^{-1} would suggest a sea level rise or fall of approximately 1 m day^{-1}). However, the excess transport into/out of each box is lower than, except for three cases at the Pula section in Box 2, the estimated error in excess transport for that box. Therefore we conclude that the transports, including the estimated error, are a realistic representation of average daily transports in the area in almost all cases.

For 100 calculated individual mass transports, the transport values in 40 cases were greater than the calculated associated error (Table A2) indicating that in 40% of cases the direction of transport may be viewed as a realistic representation of real transport direction.

Hydrographic Conditions Supporting Geostrophic Flow

Higher mean density offshore at Poreč and Rovinj induce dominant northward flow through those sections while lower density offshore at Pula induces southward flow (Figure 6). Higher offshore mean density at the Poreč section than the Pula section results in mean flow towards the coast. As the mean density distribution is primarily induced by temperature, we conclude that temperature is the key factor in driving the mean circulation pattern.

Temporal changes in geostrophic transports were, at all sections, primarily induced by temporal changes in temperature. For example, temporal changes in transports at Poreč, Rovinj, Pula, FN and FS sections in the investigated period were highly (0.83, 0.86, 0.90, 0.77 and 0.63, respectively) correlated to temporal changes in RHO_{X1} - RHO_{X2} where

RHO_{X1} and RHO_{X2} are average densities of the 25 m deep water column at extreme stations X1 and X2 of a certain profile (RV01 and RV05 at Poreč, RV07 and RV12 at Rovinj, RV18 and RV13 at Pula, RV05 and RV07 at FN and RV07 and RV18 at FS). Temporal variations in RHO_{X1} - RHO_{X2} at Poreč, Rovinj, Pula, FN and FS sections were driven by thermal changes, as time series of RHO_{X1} - RHO_{X2} at all sections were more related to T_{X1} - T_{X2} (correlation coefficients 0.93, 0.94, 0.97, 87 and 0.94 respectively) than to S_{X1} - S_{X2} (correlation coefficients 0.18, 0.31, 0.44, 0.37 and 0.44 respectively), where T_{X1} and T_{X2} are average temperatures and S_{X1} and S_{X2} average salinities of the 25 m deep water column at extreme stations at each profile. In addition, the largest transports at Poreč (northward; 02 June, 09 September), Pula (southward; 30 June, 19 August) and Frontal (eastward; 01 September) section occurred when T_{X1} - T_{X2} was large while the corresponding S_{X1} - S_{X2} was very small (0.03-0.05). At the Poreč section**,** on both dates, there was a deep and warm water pool near the coast and cold water in deeper layers offshore while at the Pula section, on two dates, there is a warm water pool offshore and colder water near the coast (Figure 8). Similarly, the Frontal section showed colder deep water near Poreč and a warm water pool near Pula. However, at the Rovinj section one of the two largest transports (28 July) occurred when T_{X1} - T_{X2} was close to zero while S_{X1} - S_{X2} amounted to 0.35. On this occasion a deep and lower salinity water pool was observed offshore while very saline water was present near the coast.

Water Transport Correlation Coefficients

Mass transport at the Frontal section showed significant correlations to scalar wind speed, wind velocity, evaporation and surface heat flux (Table 3). Correlation values between transport at Rovinj and Pula sections and meteorological conditions were not found to be significant at zero time lag although transport at the Poreč section was found to be significantly related to changes in water flux. When excluding data from two cruises which were conducted in wind conditions of greater than 6 m s^{-1} (1 and 15 September), the correlations with scalar wind speed, wind velocity, evaporation and surface heat flux became small suggesting that data from these cruises are responsible for the high correlations. Enhancement of water transport towards the Istrian coast seems to be directly related to the strength of wind from the northeast (bora) that, in turn, explains the strong positive and negative transport correlations with evaporation and air-sea heat flux respectively. During both cruises large eastward geostrophic transports were primarily induced by thermal differences where the average temperature at RV18 was much higher than at RV05 due to the presence of a deep warmer water pool.

No correlation was found between EOF mode 1 and meteorological conditions (Table 3). Time lag correlation coefficients showed a relationship, at the 80% level of significance (0.28-0.39), between bora wind and water mass transport (Table 4). The results indicate that mass transports through the Frontal section and the Poreč, Rovinj and Pula sections, were related to bora wind after a 2 and 3-4 day delay, respectively. As data were not collected every day we cannot use the magnitude of these time lags with certainty. However, such time lags show qualitatively that transports may be reinforced after bora episodes.

Time lag correlations for the three sections perpendicular to the coast mainly arose due to data collected on 2 June and 25 June when large transports were observed several days after bora events. Both periods between 26 May-2 June and 16 June-26 June were characterized by moderate bora wind episodes which slowed down the heating process which normally occurs at that time of year. However, notable differences were observed between the stations. At the Poreč and Rovinj sections the 25 m deep water column gained heat more rapidly in the coastal zone while at Pula section heat gain was greater offshore. This was shown by more pronouned deepening of the isotherm near-shore at Poreč and Rovinj than offshore while more pronouned deepening of the isotherm was noted offshore at Pula (Figure 9). As salinity changes during the intervals concerned were relatively small (except in the 26 May-2 June interval at the Rovinj section) they had less effect on changes on the overall density of the water column.

The second (negative) correlation, between water transport at the frontal section and wind from the NE with a 2-day time lag, was found to depend only on data collected on 1 September when very strong positive transports occurred several days after a strong sirocco episode. However, as the sirocco episode was immediately followed by a bora episode it is not clear if this time lag correlation can be accepted with a high degree of confidence. Examples given below illustrate of the effect of bora wind episodes on geostrophic circulation patterns.

Case 1: 13-23 May

Data collected on 13 and 23 May were prior to and after the strong bora episode of 14-16 May. The temperature at the sea surface decreased over the entire area after the bora event, although thermal stratification was greater at the Poreč and Rovinj sections than at Pula and Frontal sections (Figure 10). After bora, an intrusion of fresher water at the surface of the western part of the Poreč and Rovinj sections was noted (Figure 10). Geostrophic velocity plots before bora suggest that water is transported towards the coast from the southwest, between the Pula and Rovinj sections, and proceeds northwestwards away from the coast between Rovinj and Poreč (Figure 11). However, after sustained bora for several days, transport toward the coast was found for the entire Frontal section, a strong southerly flow through the Pula section became established and an intensification of the northward flow through the Rovinj and Poreč sections was noted. These data would imply that bora wind induces an eastward transport of water towards Istria that is subsequently deflected north and southwards, thus becoming part of cyclonic and anti-cyclonic circulation cells respectively (Figure 1). Northward flow through the Poreč and Rovinj sections, as well as eastward flow through the FN section, was enhanced after bora due to average density increasing offshore (and in the northern part of the FN section) in spite of the arrival of freshened water at the surface. This suggests that cooling offshore, and hence temperature, was the major influencing factor. No freshened water was found at the Pula section and the increase in southward transport between RV14-RV16 after bora was mainly due to higher temperatures in the middle of the profile (at stations RV14-RV16).

Satellite data showing chlorophyll *a* distribution in this time period also indicate that, as bora wind becomes established, high pigment-containing water that was originally localized in the western part of the northern Adriatic subsequently becomes distended in a loop that stretches from south of the Po river delta northwards and eastwards (Figure 12). This is consistent with the arrival of freshened waters in the area after bora episodes, as found by high negative correlations between surface salinity and intensity of NE wind component at a 2 day time lag (Figure 5). As chlorophyll *a* distribution may be considered in certain cases as a proxy for sea surface currents in the area [*Mauri and Poulain,* 2001] water mass movement deduced from satellite data is consistent with our circulation pattern based on geostrophic currents.

Case 2: 19-26 August

On 20 August chlorophyll *a* (Figure 12) was generally constrained to the western part of the northern Adriatic while over the course of a week high pigment-containing water gradually formed a clockwise loop across the Adriatic towards the coast of Istria with the expected arrival of low salinity water noted on the 26 August.

Geostrophic velocity plots on 19 August (Figure 13) show an easterly water mass transport, particularly between Poreč and Rovinj, with a northward and southward deflection of this water mass as it approaches the coast. The northward deflection trough the Poreč section was weak while the southward deflection was relatively strong through the Rovinj and Pula sections. The bora event of 25 August significantly altered this situation (Figure 13). After bora the anti-cyclonic motion shifted north of the usual Po-Rovinj demarcation line, with strong southward transports through the Rovinj and Pula sections. This atypical circulation pattern, based on density differences along the Poreč and Rovinj sections, appears to be related to a warm, 10-15 m deep, low salinity water pool at offshore stations that was not usually present. (It should be noted that the box model based on geostrophic transport on 26 August was not found to be appropriate although reasons for this are not clear at this point.)

Discussion

Due to unusual meteorological and hydrological conditions temperature and salinity in the coastal zone off Istria were, during the investigated interval, highly above the average, as detailed in *Lyons et al.* [2006]. As expected from previous work (e. g. *Supić and Ivančić*, 2002) temporal changes in temperature were generally related to air-sea fluxes while the relationship between salinity and air-sea fluxes was not evident as salinity in the region is typically more affected by the river Po during the warm part of the year. It was found here that salinity decreases during bora wind episodes after two days, presumably as a consequence of the eastward transport of Po freshened waters. Spreading of Po waters after bora events has been previously documented [*Sturm et al.*, 1992]. Direct current measurements by *Zore-Armanda and Vučak* [1984] suggested that greater freshwater input from the river Po resulted in stronger eastward water mass movement that subsequently turns both north and south upon reaching the Istrian coast, this latter deflection constituting part of an anti-cyclonic circulation cell. Similarly, *Supić et al.* [2000] also found that the intensity of the southward flow was correlated with high summer Po discharge rates. As freshwater input in 2003 was very low, riverine input should not have had such a significant effect on water transport. In this work, density was found to be more dependant on temperature rather than salinity, consistent with the results of *Supić and Ivančić* [2002].

Geostrophic calculations typically show that in upper parts of the water column there is a water movement directed towards Istria from the southwest or west and is subsequently deflected both northwestward and southeastward as it approaches that coast. As surface geostrophic currents are typically larger than the estimated error, they may be considered as a good representative of the daily-averaged current field. Geostrophic transports may be considered representative of daily-averaged transport in about 40% of cases, where the direction of geostrophic transport in the 0-25 m layer corresponded to the direction of real daily-averaged transports. Changes in geostrophic currents were generally induced by thermal changes and only occasionally by salinity changes.

In spite of hydrographic conditions being significantly different from typical values, the derived geostrophic circulation pattern is in good agreement with the mean circulation scheme proposed by *Zore-Armanda and Vučak* [1984] and long-term direct current measurements by *Brana and Krajcar* [1995], the geostrophic climatology given by *Krajcar* [2003] and long-term means of geostrophic currents in the eastern coastal area [*Supić et al.*, 2000].

As the large range of salinity values typically seen during the warm part of the year were not apparent in 2003, the high spatial uniformity of temperature would be expected to result in geostrophic currents that are not as strong as those in years with large density variations due to greater freshwater input and stronger thermo- and haloclines. While long-term average geostrophic currents in the coastal zone have been found to be up to 7 cm s^{-1} during the warm period of the year [*Supić et al.*, 2000], speeds found during 2003 have oftentimes exceeded this. Long-term direct current measurements at station RV07 [*Brana and Krajcar*, 1995] found velocities ranging from 5-15 cm s^{-1}.

In this work, analysis of correlation coefficients indicates that an increase in scalar wind speed (from the NE) is significantly related to the strengthening of water mass transport eastwards across the northern Adriatic towards the Istrian coast. While transport across the Frontal section showed an immediate response to bora forcing, correlations between bora wind and northward and southward transport parallel to the coast only became significant after a 3-4 day time lag. However, data were not collected every day after bora episodes and this may impact on the time-lag correlations. While results here show qualitatively that strong wind events induce large mass transport with a time delay, although more detailed conclusions on time lag correlations should only be supported by data collected continuously after strong wind events rather than the snapshots presented here. Data suggest that cyclonic and anti-cyclonic motions were reinforced during bora wind. The strengthening of these motions appears to be based mainly on enhanced, temperature-induced density differences between stations. Enhanced cooling at the surface during wind events and the presence of cold water at the bottom of the water column maintains higher density offshore near Rovinj and Poreč while density offshore near Pula remains lower. At this point, it is difficult to give a definitive explanation for why bora acts to produce spatial differences in thermal characteristics of the water column. Such differences may be related to possible inhomogeneity in the bora wind field which induces inhomogenous cooling/warming of water in different areas. Differences in heating/cooling may also be induced by bathymetry as heating of deeper and shallower water columns would not result in the same temperature distribution. The role of advection can also not be neglected. For example, bora wind might induce inflow of warmer water from the central into the northern Adriatic with lower density near Pula arising during such intrusions.

The modeling work of *Kuzmić and Orlić* [1987] predicted a cyclonic gyre in the northernmost part of the Adriatic and an expected anti-cyclonic cell further south near the end of the Istrian peninsula after bora wind. Although there was an associated uncertainty with this latter circulation cell due to its proximity to the open boundary set for the modeling exercise, this predictive model result closely resembles the data described in this report. Recent detailed ocean-atmosphere modeling work by *Pullen et al.* [2003] has also hinted that an anti-cyclonic gyre near the south Istrian coast may become established after bora when using a high resolution model. Analysis of current meter data from 1984-1993 by *Krajcar* [2003] showed that an average bora episode induces a northeastward motion at RV07 and southeastward motion at RV18 from 0-1 days after the bora maximum. Therefore the reinforcement of the cyclonic and anti-cyclonic geostrophic circulation pattern after bora wind, as determined herein on the basis of geostrophic currents, is consistent with results from both the modeling work and direct current analysis of others. That implies that geostrophic currents play an important role in the northern Adriatic response to bora wind forcing.

Conclusions

Collection of data with weekly frequency has allowed the most accurate description to date of the evolution of the thermohaline structure and geostrophic circulation patterns near the Istrian coast in the warm period of the year. During the investigated period it was observed that:

1. Changes in temperature were generally well related to air-sea heat flux, but salinity was not found to be related to air-sea water flux. However, decreases in surface salinity were highly correlated with bora wind suggesting a wind-induced eastward movement of freshened waters of river Po origin that arrived in the area two days after the bora episode. Density changes were primarily induced by changes in temperature rather than salinity changes.

2. Geostrophic currents indicate that for much of the inevstigated period there were cyclonic and anti-cyclonic motions in the surface layer north and south, respectively, of the line between Rovinj and the river Po. A similar pattern is given by geostrophic transports for the upper 25 m layer.

3. By assessing the error in the geostrophic current aproximation it has been shown that surface geostrophic currents typically represent a realistic daily average current field and, in about 40% of cases, the direction of the geostrophic transport in the 0-25 m layer corresponded to the direction of real daily-averaged transports.

4. Geostrophic motions were primarily induced by thermal differences although the presence of low salinity water in the surface layer can, on occasion, significantly alter the density field.

5. An intensification of geostrophic transports for both the cyclonic and anti-cyclonic circulation appeared to be directly related to northeasterly (bora) wind speed.

In spite of the summer of 2003 was characterized by anomalously high temperatures and low Po river flow rates, geostrophic circulation patterns were found to be similar to the climatological mean. However, the results obtained for 2003 should be qualified by further studies directed to when the northern Adriatic is under the influence of different meteorological and riverine conditions.

Acknowledgement

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Appendix

Geostrophic currents as representatives of real currents in the northeastern Adriatic

The following comparison between measured and computed currents at station RV07 in 1992, based on the data described in *Krajcar et. al.* [2003; Figure A1], shows that geostrophic currents computed with respect to the 20-30 m reference level can be taken as a reasonable approximation of daily averaged real currents in the northeastern Adriatic. Geostrophic currents show closer resemblance to low pass filtered currentmeter data than to daily averaged data.

Surface (8 m) and bottom (30 m) currents were sampled at 10 minute intervals and daily averaged (AC) and ten-day filtered currents (FC) were computed for each day of 1992 [*Krajcar et al.*, 2003]. Temperature and salinity data were collected on 12 days during monthly cruises in 1992 at standard depths (0 m, 5 m, 10 m, 20 m and 30 m) at stations SJ105, RV07 and RV12 and geostrophic currents, relative to both 20 m and 30 m, between stations SJ105 and RV07 and between stations RV07 and RV12 were computed. The values obtained were linearly interpolated to obtain geostrophic currents relative to 20 m (G_{20}) and 30 m (G_{30}) at 8 m depth at RV07.

The differences between daily averaged (AC), or filtered (FC), currents and geostrophic currents (AC-G_{20}, AC-G_{30}, FC-G_{20}, FC-G_{30}) are similar to, or even smaller than, the differences between daily-averaged and filtered currents (AC-FC) (Figure A1, Table A1).

Geostrophic currents were found to be more similar to filtered (FC) than to daily averaged (AC) directly-measured currents.

Correlation coefficients between directly measured and geostrophic currents became higher, and root mean square (RMS) values lower, for cruises with greater wind speeds excluded. Oceanographic cruises are typically not conducted during very strong wind episodes and the maximal daily average of wind speed during an oceanographic cruise in 1992 did not exceed 6.4 m s^{-1}. During periods of low wind, real current velocities measured at 30 m were low, suggesting that 30 m may be an appropriate reference level for calculating geostrophic velocities. Small differences between G_{20} and G_{30} imply that any depth between 20 m and 30 m may be used as the reference level.

Estimation of the accuracy of using geostrophic currents, relative to 20 or 30 m depth, as a representative of daily averaged (E_{AC-G20} or E_{AC-G30}) or ten day filtered (E_{FC-G20} or E_{FC-G30}) currents in various wind conditions was taken to be equal to the corresponding RMS error. These error values were averaged to obtain error estimates for the 25 m reference level (E_{AC-G25} and E_{FC-G25} , Table 2).

Alternatively, error between measured and computed currents (E') can be estimated as the sum of errors arising from the error in geostrophic approximation of the difference between surface and bottom real currents (ED) and the error in the assumption that at the reference level there is no motion (ER; $E'^2=ED^2+ER^2$). For example, ED_{AC-G30} (2.9 cm s^{-1} at wind speeds less than 6.5 m s^{-1}, 1.7 cm s^{-1} at wind speeds less than 4.6 m s^{-1}, 1.4 cm s^{-}

^{1} at wind speeds less than 3.1 m s^{-1} and 1.2 cm s^{-1} at wind speeds below 2.1 m s^{-1}) was computed as the RMS of AC at 8 m minus AC at 30 m minus G_{30} at 8 m and ER_{AC-G30} (1.7 cm s^{-1} at wind speeds less than 6.5 m s^{-1}, 1.9 cm s^{-1} at wind speeds less than 4.6 m s^{-1}, 2.0 cm s^{-1} at wind speeds less than 3.1 m s^{-1} and 1.4 cm s^{-1} at wind speeds below 2.1 m s^{-1}) as RMS of AC at 30 m respectively. However, as 12 values of AC at 8 m minus AC at 30 m minus G_{30} at 8 m were highly correlated to AC at 30 m (correlation coefficient was 0.47), indicating that ED_{AC-G30} and ER_{AC-G30} are not independant, we believe that E'_{AC-G20} (3.4 cm s^{-1} at wind speeds less than 6.5 m s^{-1}, 2.5 cm s^{-1} at wind speeds less than 4.6 m s^{-1} and 1.8 cm s^{-1} at wind speeds below 2.1 m s^{-1}) is generally an oveestimated error.

Tables

Table 1. Average transports (C) and loadings for the first (F1; 50.35% of total variance) and second (F2; 24.38% of variance) mode of EOF analysis for the Poreč, Rovinj, Pula, FN and FS sections. Positive values indicate transport towards the coast (through FN, FS sections) or northwards (though Poreč, Rovinj and Pula sections).

	C	F1	F2
Poreč	6196	6215	7154
Rovinj	706	12933	6580
Pula	-9429	-10146	4684
FN	2659	-8241	2812
FS	12040	7951	-7689

Table 2. Net relative excess transport ($m^3 s^{-1}$) into Box 1 (T_{B1}) and Box 2 (T_{B2}) with the corresponding estimated errors ($E_{T,B1}$) and ($E_{T,B2}$) during oceanographic cruises performed on a given date. Bold values indicate occasions when excess transport exceeded the estimated error.

Date	T_{B1}	$E_{T,B1}$	T_{B2}	$E_{T,B2}$
13 May	-4642	15091	-3577	19397
25 May	-4476	16506	11996	21215
26 May	5022	16506	867	21215
02 Jun	-4942	16506	-13994	21215
09 Jun	-2529	15091	-4676	19397
16 Jun	-58	16506	-2504	21215
25 Jun	-15657	16506	-14600	21215
30 Jun	7733	16506	-19323	21215
07 Jul	297	15091	12798	19397
16 Jul	9273	15091	-18853	19397
21 Jul	-2807	16506	11841	21215
28 Jul	-9241	15091	**55436**	**19397**
11 Aug	-9440	15091	-14558	19397
19 Aug	-8340	16506	-19267	21215
26 Aug	7797	16506	**45196**	**21215**
01 Sep	-14238	24995	**37373**	32125
09 Sep	-5282	16506	-18821	21215
15 Sep	4509	24995	7138	32125
22 Sep	-5243	16506	-8352	21215
30 Sep	-4338	16506	-6015	21215

Table 3. Correlation coefficients between 19 or 20 values of net relative geostrophic transports at the Poreč, Rovinj, Pula and Frontal sections, the first (F1) and second (F2) EOF modes and the corresponding daily values of meteorological parameters at Pula – air pressure p, air temperature T_a, scalar wind speed u, fractional cloud cover N, water vapor pressure e, precipitation P, evaporation E, surface heat flux Q, surface water flux W and wind speed from the NE (u) and NW (v) directions. Correlation coefficients significant at the 95 % level are shaded.

	Poreč	Rovinj	Pula	Frontal	F1	F2
p	-0.10	0.00	0.00	0.00	0.10	-0.13
T_a	-0.39	-0.26	-0.17	-0.22	-0.09	-0.34
u	0.00	0.00	-0.10	0.40	0.18	-0.33
N	0.37	0.20	-0.08	0.13	0.17	-0.20
e	-0.06	0.00	-0.35	0.00	0.10	0.17
P	0.37	0.00	0.00	0.00	0.00	-0.35
E	-0.28	-0.22	0.00	0.47	0.04	-0.46
Q	0.10	0.20	0.00	-0.45	0.07	0.27
W	0.45	0.14	0.00	-0.24	0.00	0.53
u (NE)	0.00	-0.17	0.00	0.41	-0.10	-0.1
v (NW)	-0.10	0.00	0.00	-0.14	-0.07	-0.09

Table 4. Correlation coefficients between net relative geostrophic transports at the four sections and the daily values of wind speed from the NE (u) at Pula station taken with different time lags. Correlation coefficients significant at the 80 % level are shaded.

time lag (days)	Poreč	Rovinj	Pula	Frontal
1	0.00	0.00	0.20	0.17
2	0.22	0.24	0.00	-0.30
3	0.28	0.00	0.00	0.13
4	0.39	-0.28	-0.31	0.00
5	0.24	0.00	0.00	-0.14

Table A1 (Appendix). Correlation coefficients (C) and root mean square values (RMS; cm s^{-1}) between time series of measured (AC and FC) and computed (G_{30} and G_{20}) surface (8 m) currents in 1992 for cruises performed in various wind speeds, v (12 pairs of data for v<6.5 m s^{-1}; 11 pairs of data for v<4.6 m s^{-1}; 8 pairs of data for v<3.1 m s^{-1} and 5 pairs of data for v<2.1 m s^{-1}).

Wind Speed	AC-FC	AC-G_{30}	AC-G_{20}	FC-G_{30}	FC-G_{20}	G_{20}-G_{30}
C (v<6.5 m s^{-1})	0.69	0.76	0.80	0.79	0.74	0.97
C (v<4.6 m s^{-1})	0.75	0.95	0.96	0.85	0.79	0.97
C (v<3.1 m s^{-1})	0.91	0.91	0.94	0.98	0.96	0.98
C (v<2.1 m s^{-1})	0.93	0.99	0.98	0.99	0.98	0.98
RMS (v<6.5 m s^{-1})	2.8	2.6	2.7	2.0	2.4	1.0
RMS (v<4.6 m s^{-1})	2.7	1.6	1.9	1.7	2.3	1.1
RMS (v<3.1 m s^{-1})	1.5	1.5	2.0	0.8	1.6	0.9
RMS (v<2.1 m s^{-1})	1.3	1.3	1.9	0.8	1.7	1.0

Table A2 (Appendix). Estimates of error ($cm\ s^{-1}$) between daily averaged (AC) or low pass filtered (FC) currents and relative geostrophic velocities computed for 20, 25 and 30 m reference levels as a function of wind speed (v) in the northern Adriatic. We assume that the error in the geostrophic approximation of real currents is the same at any depth between the reference level and the surface.

Wind Speed	E_{AC-G30}	E_{AC-G20}	E_{AC-G25}	E_{FC-G30}	E_{FC-G20}	E_{FC-G25}
$v<6.5\ m\ s^{-1}$	2.6	2.7	2.7	2.0	2.4	2.2
$v<4.6\ m\ s^{-1}$	1.6	1.9	1.8	1.7	2.3	2.0
$v<3.1\ m\ s^{-1}$	1.5	2.0	1.7	0.8	1.6	1.2
$v<2.1\ m\ s^{-1}$	1.3	1.9	1.6	0.8	1.7	1.3

Figures

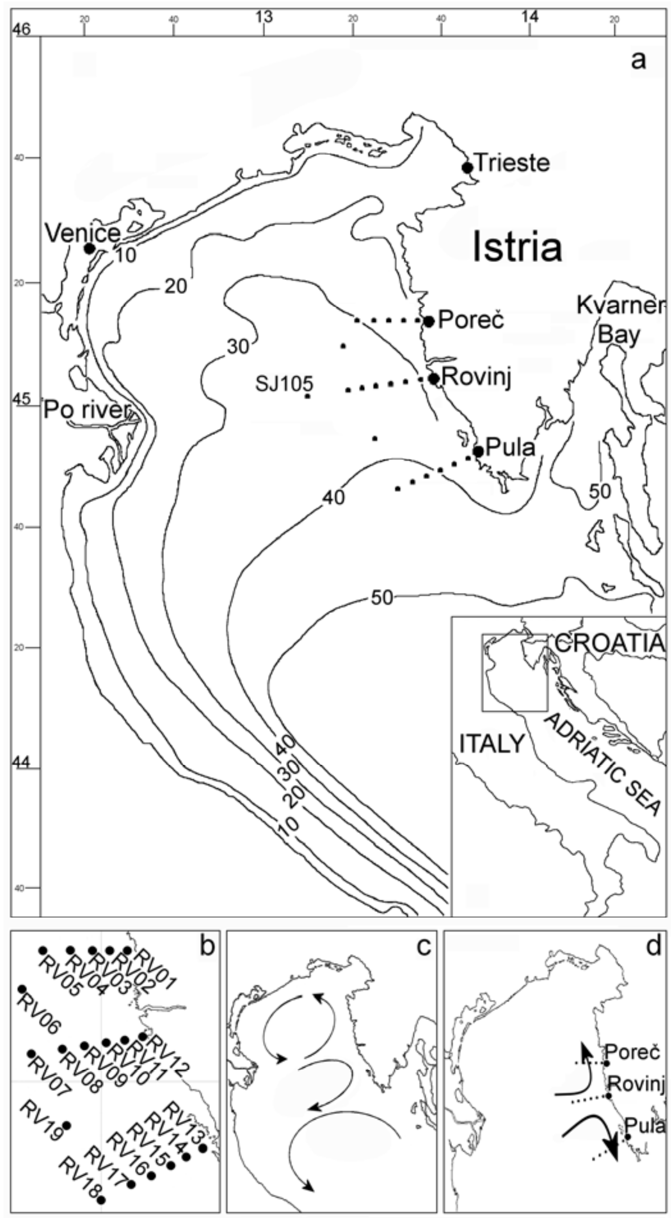

Figure 1 (a) Map of the northern Adriatic Sea with positions of CTD stations, (b) names of stations, (c) general schematic of surface circulation in the northern Adriatic Sea as proposed by *Zore-Armanda and Vučak* [1984] and (d) average mass transport based on results presented in this paper.

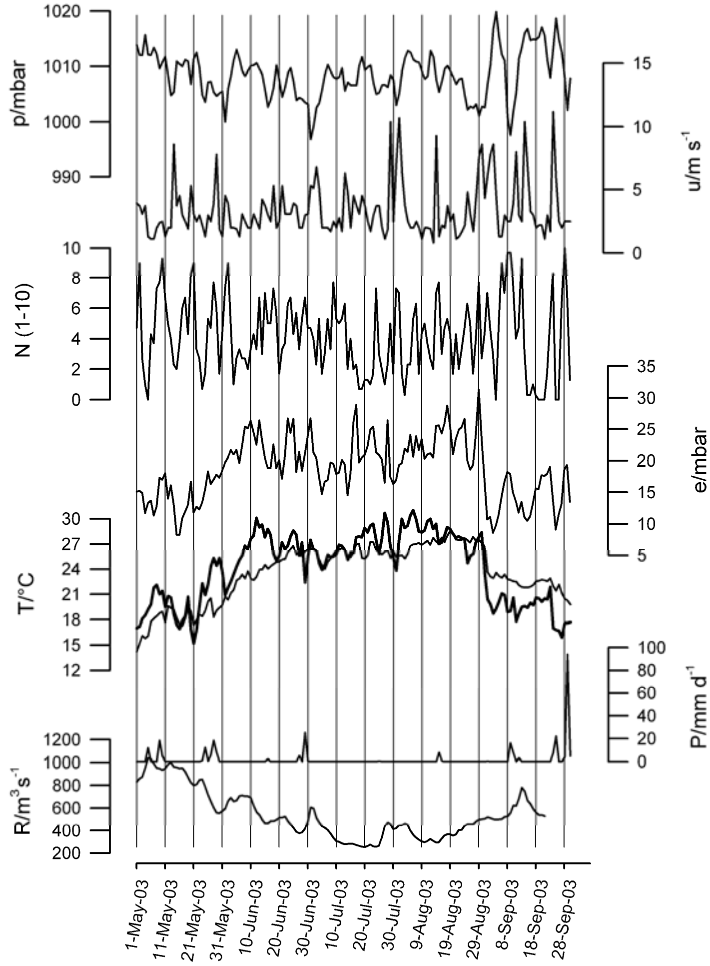

Figure 2 Daily values of meteorological parameters (air pressure p, scalar wind speed u, fractional cloud cover N (0 cloudless, 10 overcast), water vapor pressure e, air (thick line) and sea (thin line) temperature T, precipitation P) at Pula station and of Po river discharge rate R.

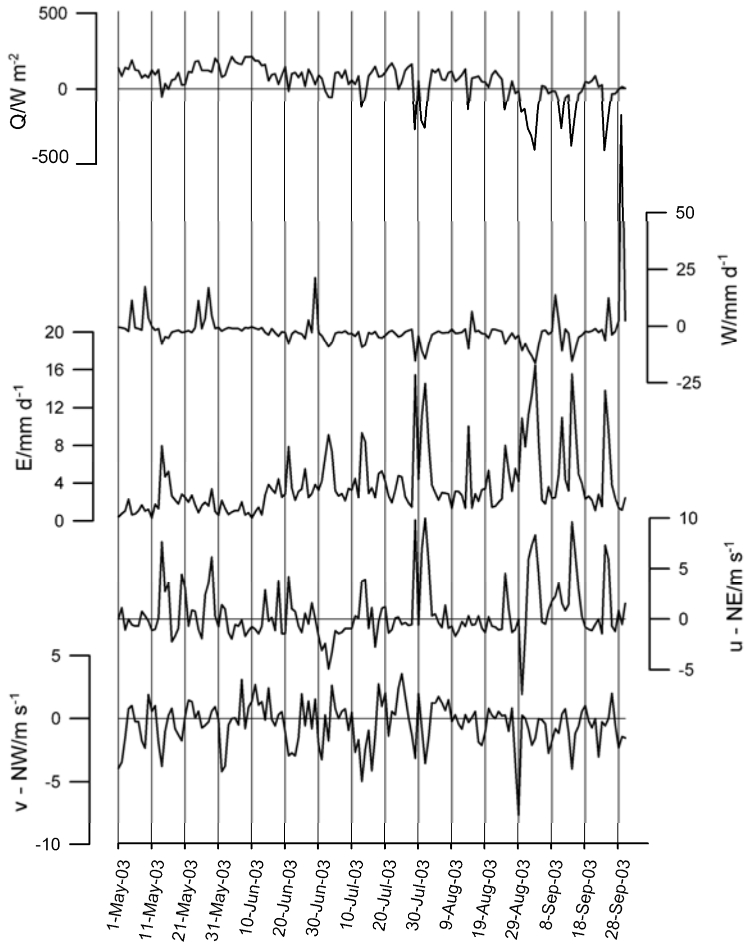

Figure 3 Daily values of total surface heat (Q) and water flux (W) with respect to daily values of evaporation (E) and NE (u) and NW (v) components of wind at Pula station. Positive values of Q and W indicate that the sea is gaining heat and moisture while positive values of u and v indicate winds coming from northeasterly and northwesterly directions respectively.

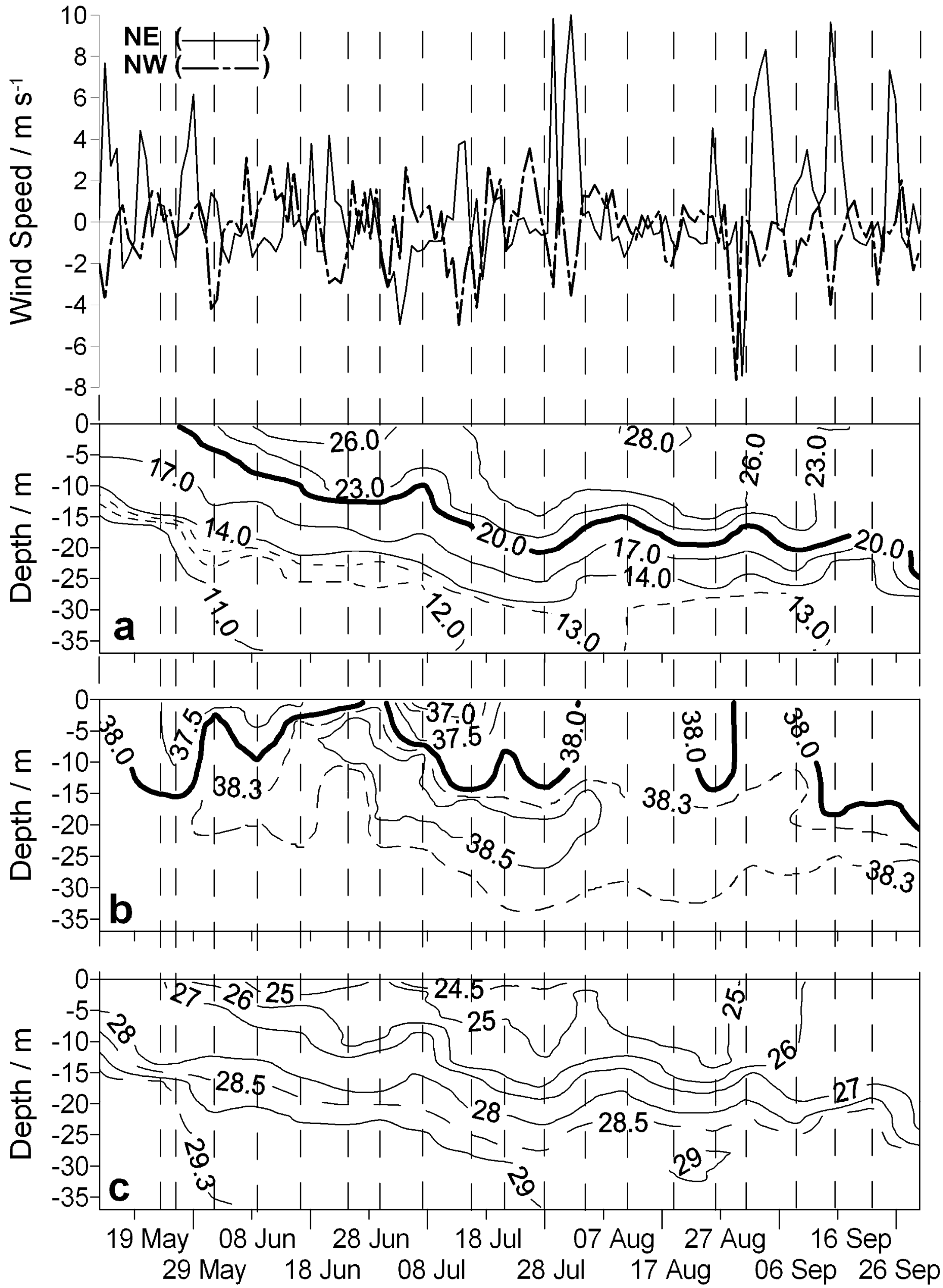

Figure 4 Temporal evolution of (a) temperature, (b) salinity and (c) density at station RV07 and wind components from the northeast (solid line) and northwest (broken line). Dates on which hydrographic data were collected are indicated by vertical lines.

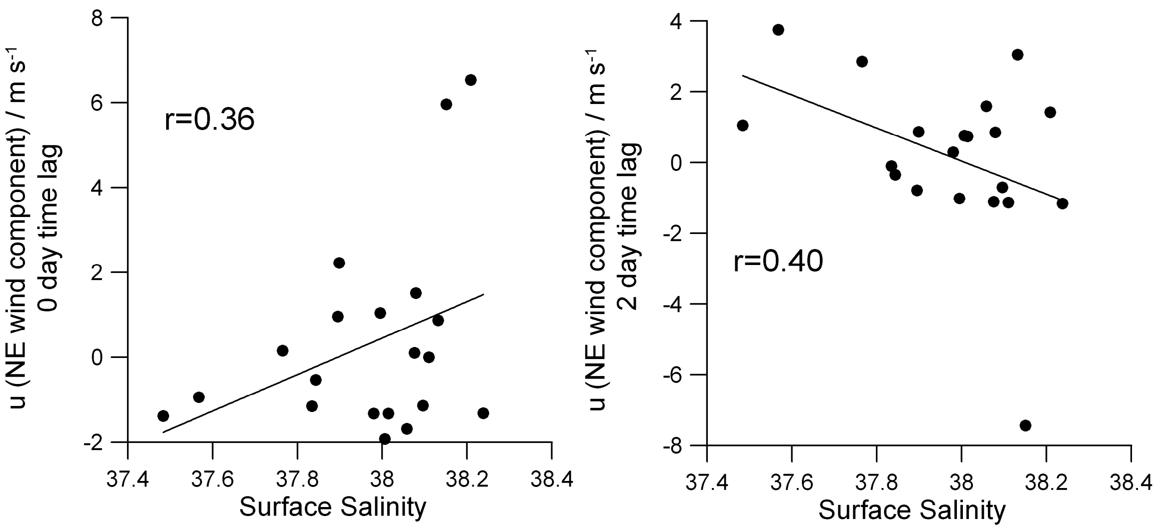

Figure 5 Average surface salinity computed for the entire region for each date in the May-September 2003 interval on which cruises were performed in comparison with NE wind component velocity on the same day and two days before the cruise. Linear fits are also given. (The correlation for a 2 day time lag is high even when the extreme negative (SW) wind component episode is excluded).

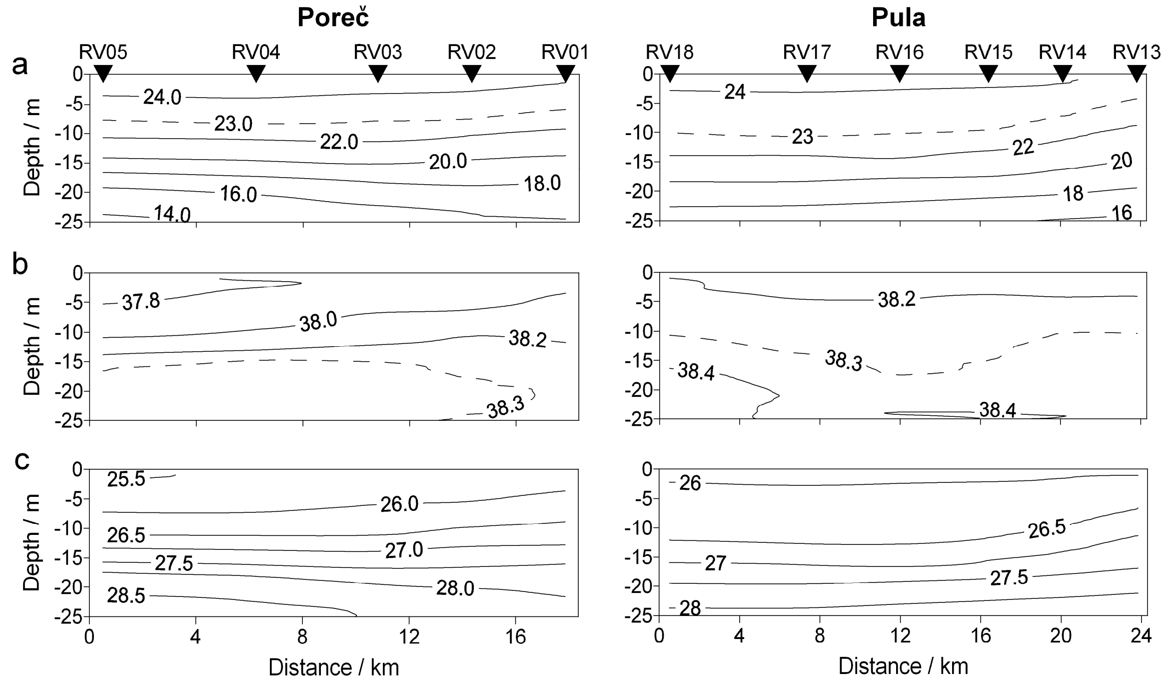

Figure 6 Mean (a) temperature, (b) salinity and (c) σ_t distributions for the May-September 2003 period for the Poreč and Pula sections.

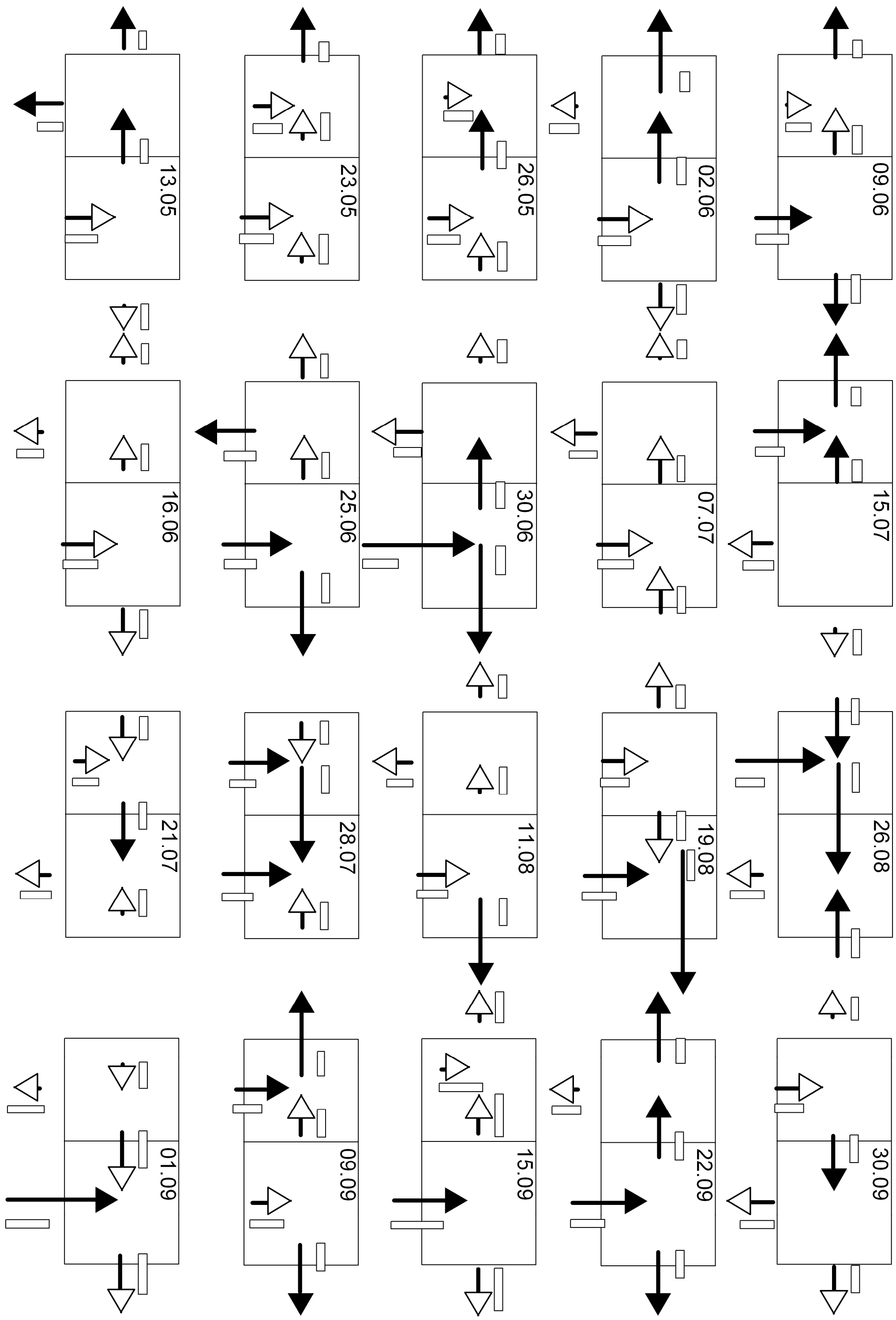

Figure 7 Total geostrophic transports (arrows) and error estimates (bars) for the Poreč, Rovinj, Pula, FN and FS sections on individual cruise dates. Arrow heads are white when the estimated error is greater than transport.

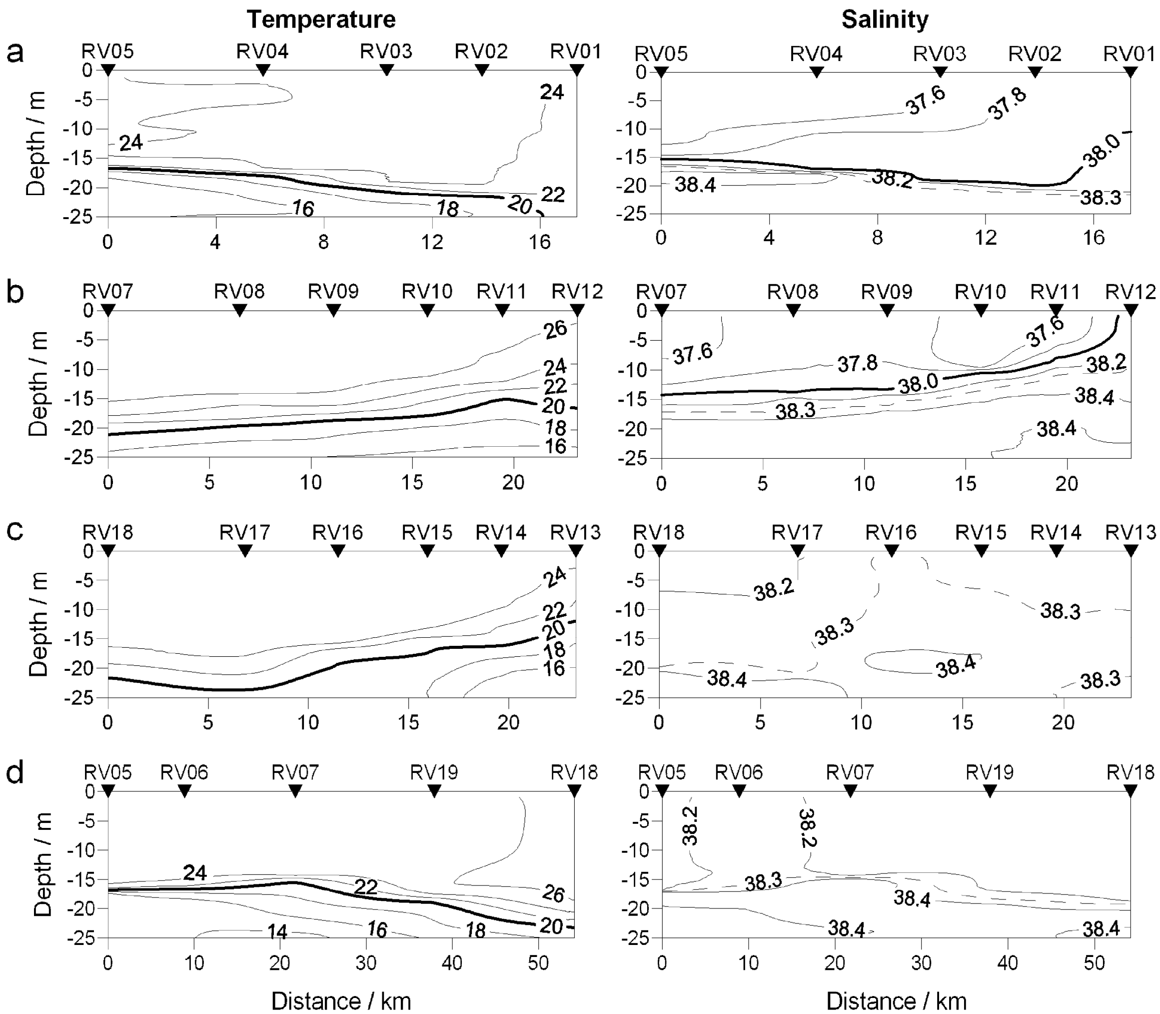

Figure 8 Temperature and salinity distribution at the (a) Poreč (09 September), (b) Rovinj (28 July), (c) Pula (30 June) and (d) Frontal (01 September) sections for dates on which mass transports were very large.

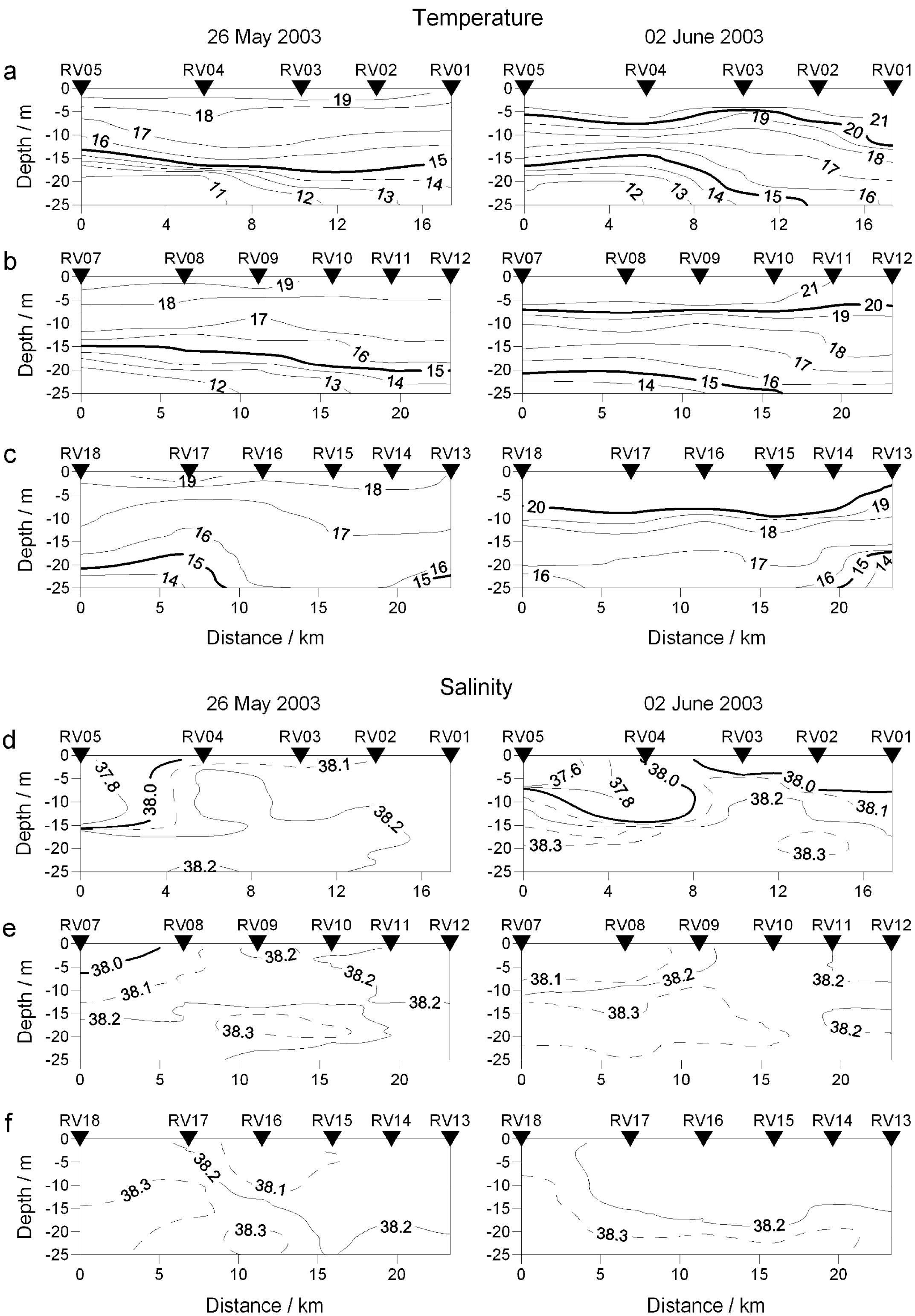

Figure 9 Temperature and salinity distribution for the Poreč (a, d), Rovinj (b, e) and Pula (c, f) sections on 26 May and 02 June.

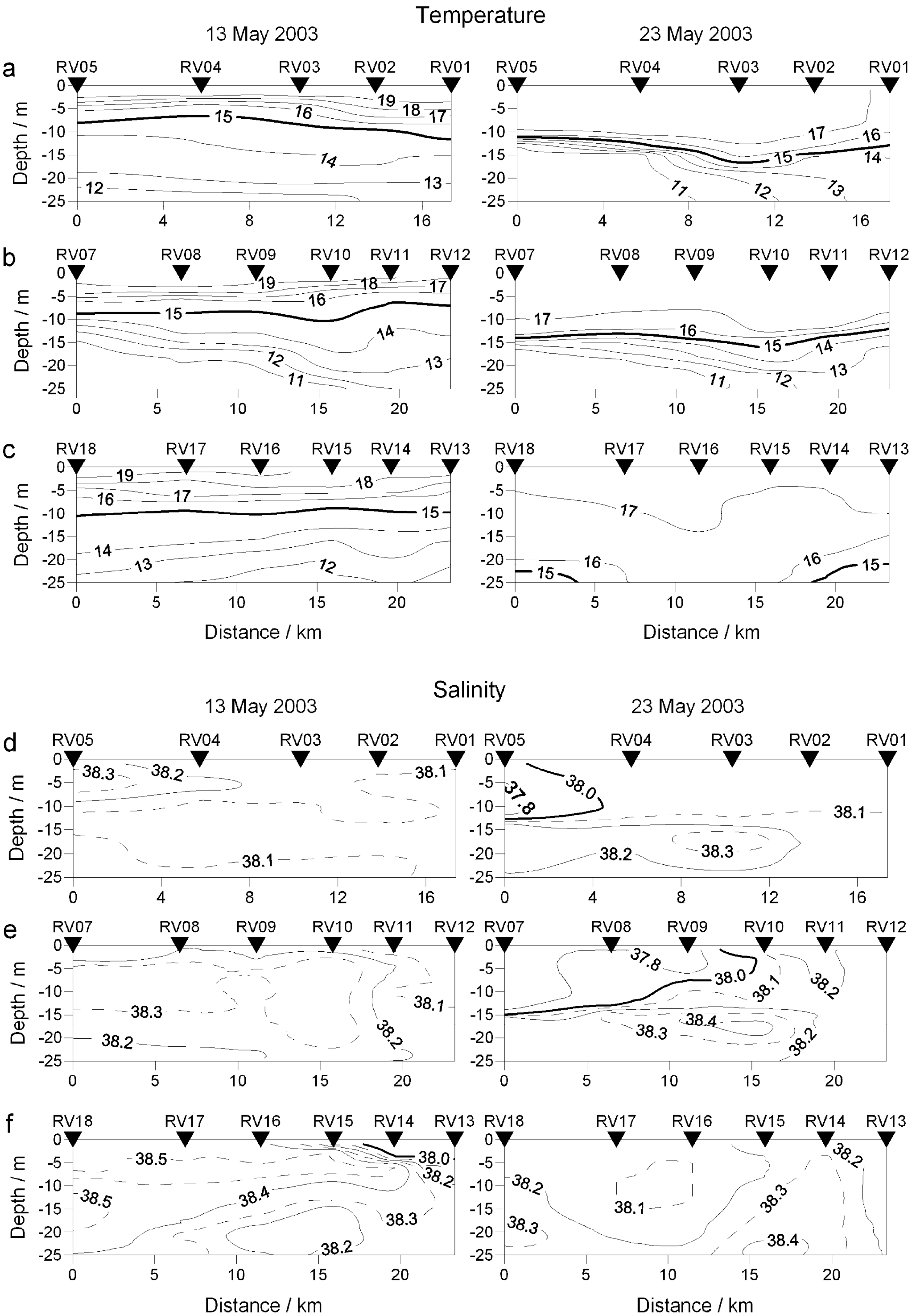

Figure 10 Temperature (°C) distribution at the (a) Poreč, (b) Rovinj and (c) Pula sections and salinity distribution at the (d) Poreč, (e) Rovinj and (f) Pula sections before (13 May) and after (23 May) a bora episode.

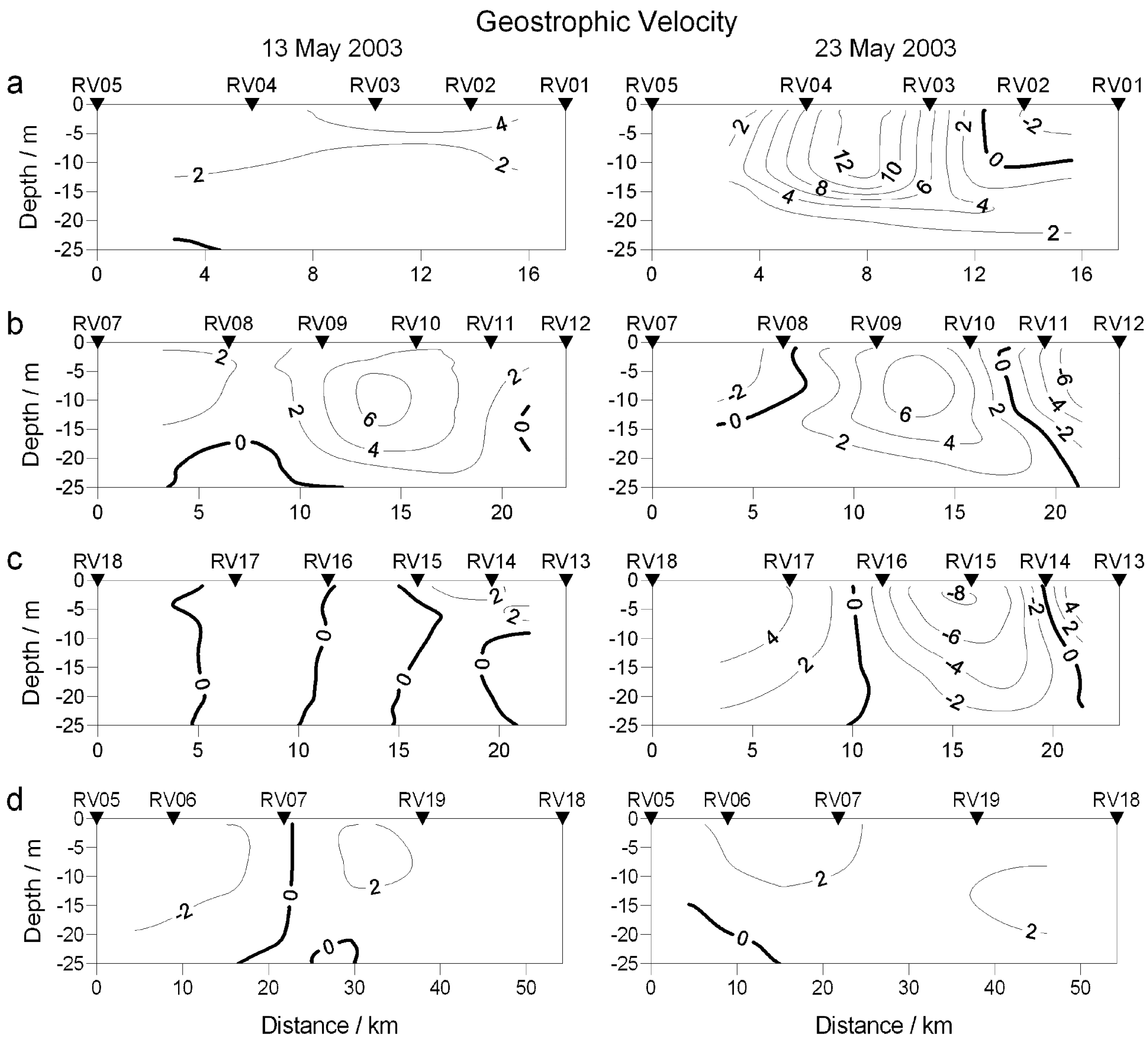

Figure 11 Geostrophic velocities (cm s^{-1}) at the (a) Poreč, (b) Rovinj, (c) Pula and (d) Frontal sections on 13 May and 23 May. For the Poreč, Rovinj and Pula sections, positive values indicate a northward flow into the northern Adriatic while at the Frontal section positive values indicate eastward flow towards the Istrian coast.

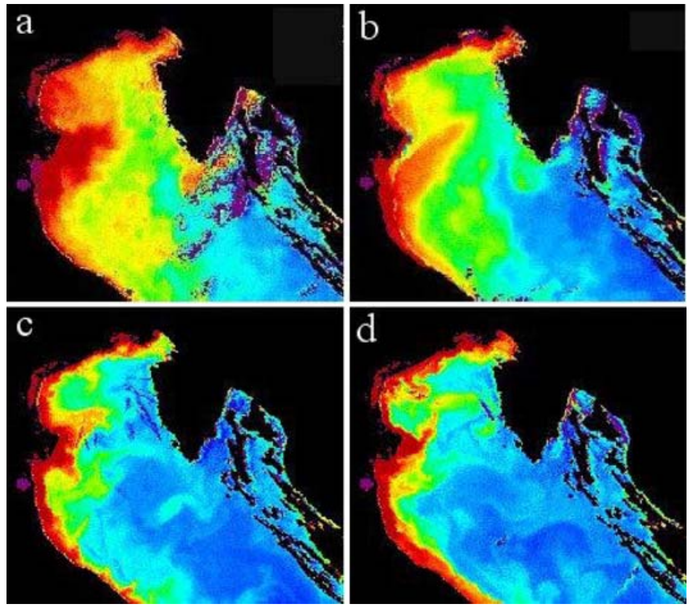

Figure 12 SeaWiFS satellite images of chlorophyll *a* on (a) 13 May, (b) 15 May, (c) 20 August and (d) 27 August. Concentrations range logarithmically from approximately 0.05 mg m^{-3} (blue) to 5.0 mg m^{-3} (red).

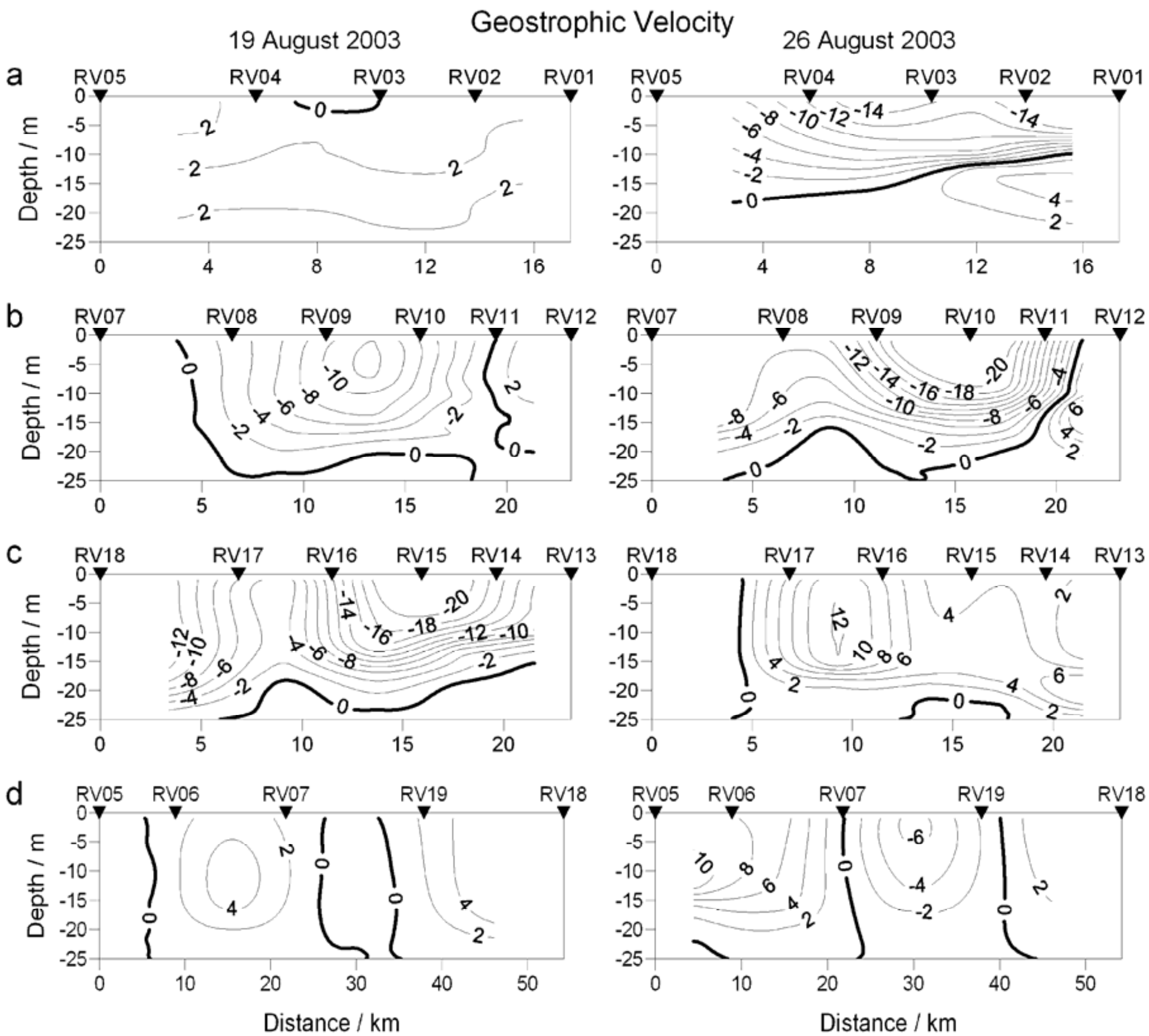

Figure 13 Geostrophic velocities (cm s^{-1}) for the (a) Poreč, (b) Rovinj, (c) Pula and (d) Frontal sections on 19 August and 26 August. Geostrophic velocity directions as in figure 11.

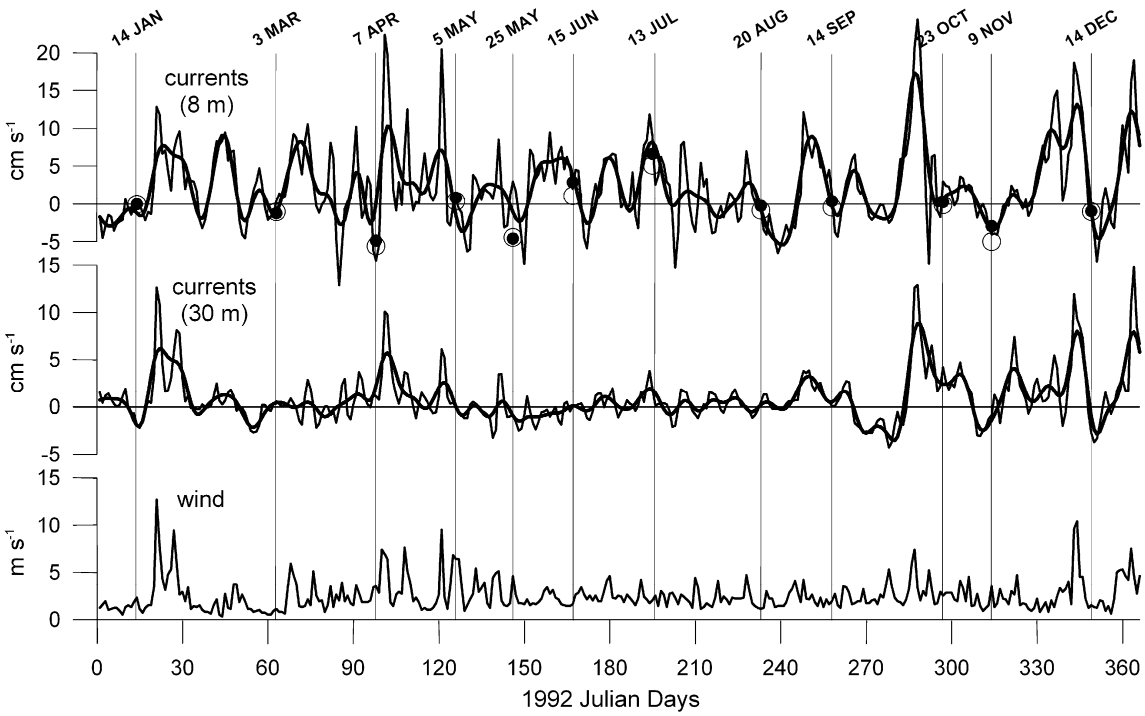

Figure A1 (Appendix) Along-shore component of daily averaged (solid line) and ten-day filtered (heavy solid line) surface (8 m) and bottom (30) currents at station RV07 and daily values of wind speed at Pula (modified from *Krajcar et al.*, 2003). Surface (8 m) geostrophic currents relative to 30 m (filled circle) and 20 m (empty circle) are given in comparison with measured currents.