Interannual evolution of seasonal thermohaline properties in the Gulf of Trieste (northern Adriatic) 1991–2003

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[1] Temperature and salinity data, collected by conductivity-temperature-depth cruises over the Gulf of Trieste during 1991–2003, were analyzed using different methods. In the first analysis, the evolution within a year of monthly temperatures and salinities at the sea surface and at 10 m depth was examined. Temperature at the surface varies with an annual amplitude of 8.1 ± 0.4°C around 16.5°C, while at a depth of 10 m it varies with an amplitude of 7.0 ± 0.3°C around 15.5°C, the variation being delayed with respect to that at the surface for about 0.4 months. In the second analysis, the interannual variations of seasonal temperatures and salinities were examined. In this northernmost part of the Mediterranean Sea, summer temperatures at the surface between 1991 and 2003 were rising between 0.12 and 0.23°C/year with an error of 0.05°C/year. When the year 2003 with its extremely dry summer period was excluded from the analysis, the trend is reduced to 0.07–0.09°C/year (±0.06°C/year). Winter temperatures, however, demonstrate an increasing trend from near zero to 0.10°C/year ± 0.14°C/year when year 2003 was excluded from the analysis. Similar changes in trends have been observed for air temperatures. Summer temperatures at a depth of 10 m have a more reliable positive trend: 0.22–0.23°C/year (±0.08°C/year). Salinities obtained from the objective analysis show a most pronounced positive trend of 0.28–0.34 year^{-1} (±0.16 year^{-1}). When 2003 is excluded from the analysis, this value decreased to 0.22–0.28 year^{-1} with an error of 0.09 year^{-1}.

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1. Introduction

[2] The northernmost part of the Mediterranean Sea is the shallow (average depth 21 m) rectangular Gulf of Trieste (roughly 20 km × 20 km), which has shallower northern part. It is open to the rest of the northern Adriatic along its western side (Figure 1) where it exchanges water mass [*Mosetti*, 1967]. The first instrumental measurements of the hydrographic properties of the Gulf of Trieste were conducted between 1904 and 1908 by Alfred Merz [*Merz*, 1911]. About a quarter of a century later the densest water mass in the northern Adriatic was recorded at the bottom (22 m) in the southern part of the Gulf of Trieste in the extremely cold winter of March 1929 [*Vatova*, 1929], with a density excess of 30.33 kg/m^3 and salinity of 38.15. This highest density of the Gulf was measured among the 23 stations located in the northern Adriatic, northwards of the Po-river delta. In a review of these early hydrographic readings and of experimental oceanography from after the second World War up to 1999 [*Malačič and Petelin*, 2001] one also finds that at the sea-surface of the Gulf there is a belt of freshwater from the Isonzo (Soča) river along the northern (Italian) coastline. As will be demonstrated, this freshwater belt is present almost the whole year, except during summer. It extends more or less offshore, with an inertial bulge south of the Isonzo river delta. Other rivers that discharge into the Gulf along the eastern (Italian) and southern (Slovenian) coastline play a minor role.

[3] During the years 2002–2003, extensive conductivity-temperature-depth (CTD) surveys were conducted within the framework of the ADRICOSM project (ADRIatic sea integrated Coastal areas and river basin Management system pilot project) in a joint effort by two institutions from countries that share the Gulf [*Malačič et al.*, 2004]. These data were added to the hydrographic database of the Gulf since 1991, just after the first international cruise activity [*Celio et al.*, 1991], when surveys with CTD probes over the Gulf became almost a regular monthly practice. The temperature and salinity fields of ADRICOSM cruises were analyzed and "instantaneous" situations (surveys over 20 stations completed in 8–10 hours) were compared with the "climatological" monthly fields [*Celio et al.*, 2006].

[4] Recent conclusions of the *International Council for the Exploration of the Sea* (*ICES*) [2005] for the year 2004 illustrate the following: sea temperatures in the near-surface

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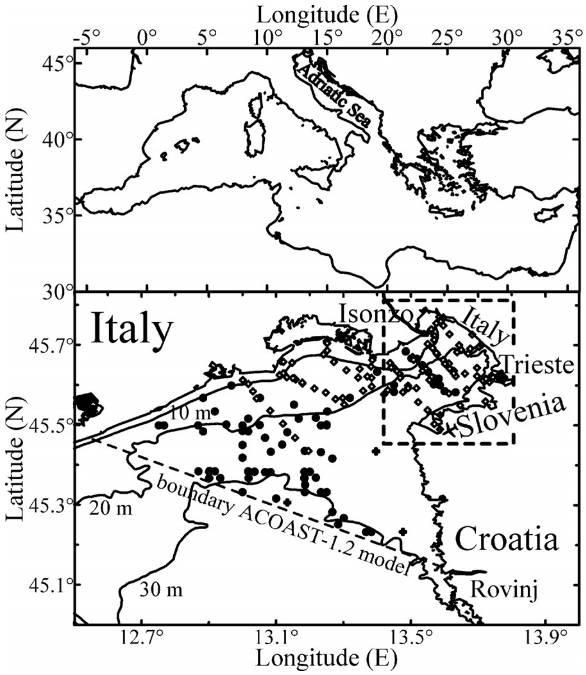

Figure 1. (top) Domain of interest in objective analysis: the northernmost part of the Mediterranean Sea (circle in the northern Adriatic Sea). (bottom) Distribution of CTD sampling stations of Atosmed6 database [*Zavatarelli and Pinardi*, 2003] in circles together with sampling stations of NIB-MBS (Slovenia) and LBM (Italy) in diamonds and RBI.CMR in Rovinj (Croatia, crosses). The dashed line represents the open boundary line of the numerical model ACOAST-1.2, north of which monthly data were analyzed using objective analysis (OA). Trend analysis was conducted for the area inside the Gulf of Trieste (dashed rectangle) which is relatively well covered with sampling stations. The air temperature data collected from the meteorological station, which is located at Portorož airport, are marked with a special symbol.

layer of the northwest Atlantic Ocean (New Foundland and Labrador shelf), the Bay of Biscay, the North Sea, and the Norwegian, Barents and Greenland Seas were above the "long-term mean" and/or above the temperatures in previous years. These regions outnumbered by far the few regions that experienced a decrease in temperature (south of the Scotian Shelf in the western Atlantic). The ICES group also points out the importance of the North Atlantic Oscillation index (NAO) which is a normalized sea level pressure difference between Iceland and the subtropical eastern North Atlantic. Positive NAO means an increased low above Iceland and a high above the Azores, causing warmer and wetter conditions in the eastern North Atlantic that neighbours the Mediterranean Sea. It was determined from the long-term (1921–2000) statistical analysis that interannual changes of annual temperature in the surface layer of the northern Adriatic are related to NAO and solar radiation [*Supić et al.*, 2004], with a zero time lag (measured in years). Salinity and density in the surface layer are also related to the major (Po) river discharge rate, while temperature and salinity near the bottom (30–40 m depth) are related to another index, the Mediterranean Oscillation (MO) index, which measures the normalized surface air-pressure difference between the midnorthern Atlantic (around the point of 25°W, 47.5°N, extending 5° in the W-E direction and 5° in the N-S direction (B. Grbec, personal communication)) and southeastern Mediterranean around 40°E, 30°N [*Grbec et al.*, 2003]. While this correlation was substantial at zero lag, salinity and density near the bottom are significantly related to the river discharge rate at a lag of one year.

[5] Recently, reports appeared in the public media about an increase of the sea-surface temperature of the Mediterranean Sea from 1993 to 2003 of 0.75°C (http://carmenlobo.blogcindario.com/2005/03/00068.html), which data came from a joint study conducted at the University of Alicante (Spain) and NASA (I. Vigo, personal communication). The surface temperature of the Adriatic Sea increased by 0.87°C, this increase was outstripped only by the increase in temperature of the Black Sea (0.94°C) during the same interval of ten years. This deviates for several times from the milder estimates of sea-surface temperature increase of the *Intergovernmental Panel on Climate Change* (*IPCC*) [2001], according to which an increase of less than 0.5°C over a decade is estimated for the surface temperature of the Mediterranean Sea (an increase between 1.3 and 6.3°C over the period of 1990–2100).

[6] In this paper trends of seasonal temperatures and salinities from 1991 to 2003 will be analyzed in light of these findings. Seasons in this paper were chosen as three-month periods: spring is March–May, summer June–August, autumn September–November and winter December–February. A comparison of results will show that in the past decade the trend of increase in sea-surface temperature in the Gulf of Trieste is much stronger than that estimated by the IPCC for the Mediterranean Sea, being closer to the assessment recently released to public.

[7] In a second section, methods will be described. Results will be presented in the third section, and discussion with conclusions will follow the results. In Appendix A there is a review of the standard errors of coefficients and confidence intervals in linear trend analysis.

2. Methods

[8] Objective analysis (OA) was already applied in another study [*Celio et al.*, 2006], in which cruises over the Gulf of Trieste during the years 2001–2003 were studied. Here we shall briefly summarize that in this study the CTD data were analyzed using the interpolation method of objective analysis [*Bretherton et al.*, 1976] in which the error variance is minimized. The input data of the CTD casts were collected during the period 1991–2003 over the area covered by a numerical model of circulation in the Gulf [*Malačič and Petelin*, 2006] with its surroundings (Figure 1). Many simulations using OA showed that results were reasonable when the covariance function, which was applied on detrended data, is supposed in a form $F(r) = [1 - (r/r_0)^2] \exp(-r^2/(2\Lambda^2))$, where r is the distance, with a following set of parameter values: r_0 = 20 km (the zero crossing correlation scale) and Λ = 10 km (the decay length scale). The search radius of the data was chosen to be 15 km. The OA output was generated on a grid of cells that form a square with a length of 0.5 km. Seasonal output values of

temperature and salinity for each year are, however, burdened with an error: mostly because of the lack of data from offshore of the peninsula of Istria. Therefore, for the trend analysis of seasonal values, only the data in the northeastern part of the model domain, which covers the Gulf's interior was chosen (Figure 1, dashed frame). This narrower area is relatively well covered with the cruise data in time (with a monthly period) and space (2–5 km spacing between stations). Numerous OA analyses of temperature and salinity over the Gulf's interior showed that areas in which the OA error of surpassed 20% are limited and confined to the lower left (southwestern) corner of this narrower domain, just outside the Gulf, where data coverage is poor. Data with an error larger or equal to 20% were eliminated from the analysis and the areas with this error were blanked in graphs of the horizontal distribution of quantities.

[9] Two depth intervals for the input data of temperature and salinity were chosen: 0–0.5 m and 9.5–10.5 m, where the data from the first depth interval near the sea-surface will be denoted as the data at 0.3 m depth, while the data from the second interval will be treated as the data at 10.0 m depth. Since there was a relatively small number of data within a certain month of a particular year, the OA analysis gave poor results over some areas, especially north of the town of Rovinj along the Istrian peninsula. Therefore, two kinds of OA analysis were performed. In the first, the OA was applied to all temperature or salinity data at a particular depth interval in a particular month of all years from 1991–2003. The number of source data is between 264 (January) and 650 (June), or 439 ± 123, where the first number is the average and the second the standard deviation of the number of the data within a particular month from the years 1991–2003. The output was recorded on a grid with a space resolution of 0.5 km × 0.5 km, which is the resolution of the coastal numerical model of circulation [*Malačič et al.*, 2004]. Statistical analysis on these "monthly" output values of OA was performed. The second OA was performed on "seasonal" data. The number of source data for this analysis ranges from 765 (winter) to 1379 (summer), or expressed as the average number and the standard deviation: 1087 ± 264. Since the abundance of the source data was sufficient for each particular year within the interior part of the Gulf of Trieste, the OA analysis in this case was performed with the same resolution as in the previous one, separately for each year in the period 1991–2003. On these seasonal data of the OA output, trend analysis was performed. This one was not performed directly on source data because their density varies in space from year to year and the seasonal source data from one year would not match those from another. When the distribution of temperature and salinity in each season over the whole period 1991–2003 at the depths of 0.3 m and 10 m was studied, we noticed that there were many measurement data during each season located around the "typical" positions of the stations. Their values show quite a large range, mostly due to interannual variations. Therefore, the error of the OA method and the number of measurements was reduced by averaging the values and positions of those measurement data with the highest correlations (a maximum of ten), which have the distance between them smaller than 1 km.

[10] In the interpretations of the linear least squares fit of interannual variations of seasonal quantities, $y = a + bx$, where y are seasonal temperatures or salinities and x is time (in years). We will focus only on b, the coefficient of trend. The error estimates of the coefficients of linear fit are described in Appendix A. Here it is sufficient to mention that the coefficient of trend will be given as $b \pm s_b$, where b is its best fit value and s_b the estimated standard error. In Appendix A some ambiguities are resolved which are related to different expressions of standard errors, with and without taking into account weights that are inversely related to the seasonal variances of the data. Envelopes with confidence limits of 95% were added on the graphs of trends. Linear trend analysis was performed with two types of linear least squares estimates. In the first, the data were weighted with $1/s_i^2$, where s_i represents the seasonal standard deviation (SD) of quantity in i-th year. These SD represent horizontal variations of quantities obtained as an output from the OA within a season of a particular year. We shall refer to this trend as the "weighted trend" (WT). In the second trend analysis, the data were not weighted, this trend will be denoted as the "unweighted" trend (UT). Average values of T and S will be referred to as "seasonal" values (e.g., spring temperature).

[11] The spring-summer period in 2003 was anomalously dry and warm, while winter 2002–2003 was colder than usual. This leads us to double the trend analyses of seasonal quantities during 1991–2003. Trend analysis was repeated without taking into account 2003, in order to check if the situation in year 2003 significantly affected the trend since 1991.

[12] Since it is expected that temperatures in the shallow sea are very much influenced by air temperatures, instantaneous air temperatures were collected for the period 1991–2003 at the local Portorož airport in Slovenia (see Figure 1), daily at 7:00, 14:00 and 21:00 hours. However, it makes sense to analyze only the instantaneous data which cover the time interval when cruises were performed during the day (mostly during working hours), therefore only averages of temperatures at 7:00 and 14:00 hours were considered. Seasonal air temperatures were calculated in two ways: firstly, the seasonal mean value in a certain year was calculated out from only those days for which cruise data were available. Secondly, all days were accounted for in the average of a particular season of a particular year. Again, as with the cruise data, weighted (WT) and unweighted trends (UT) have been calculated, with year 2003 included and excluded. Air temperatures from the airport were, of course, not treated with the OA. In this way eight values of coefficient of the interannual trend of air temperature were estimated together with their uncertainties for each season.

3. Results

3.1. Variability of Temperature and Salinity in the Gulf of Trieste Over Time

[13] Table 1 represents statistics of temperature and salinity fields over a larger domain that also covers the area outside the Gulf (Figure 1). Monthly means were extracted to have a general view of the data. In the period 1991–2003, monthly temperatures vary from 9.2°C to 25.0°C at the surface and from 9.2°C to 22.6°C at 10 m depth, with a

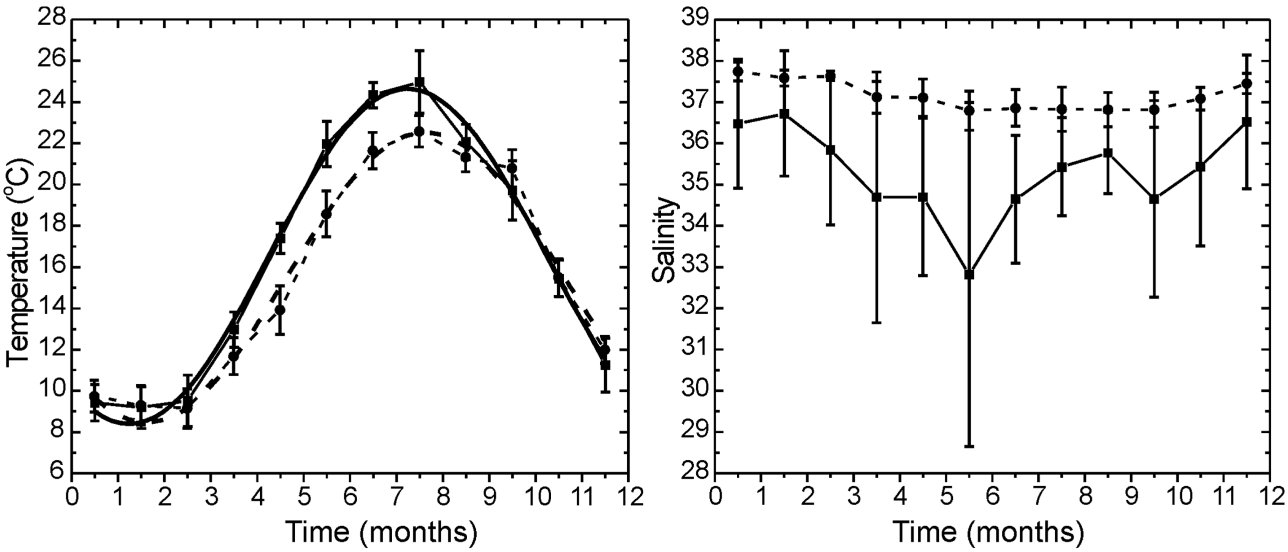

Figure 2. (left) Monthly temperatures and (right) salinities during 1991–2003 at 0.3 m (solid lines with squares) and at 10 m depth (dashed lines with dots) over the area north of the dashed line in Figure 1. The annual trigonometric least squares fits (thick solid and dashed lines) are plotted over the monthly data of temperature. Vertical bars represent the range of two monthly standard deviations; in the least squares fit monthly values were weighted with standard deviations (SD).

mean that is 1°C lower at 10 m depth than that at the surface (16.5°C). This agrees with the trigonometric least squares fit that gives for the annual amplitude 8.1 ± 0.4°C at the surface and 7.0 ± 0.3°C at 10 m depth. The annual signal at 10 m depth is delayed with that at the surface for about 0.4 months. Figure 2 shows monthly temperatures and salinities together with monthly SD. Large SD are mainly attributed to interannual variations of quantities, while linear trends over 13 years represent a small contribution to SD. At the surface, the largest monthly SD of temperature occurs in August (1.5°C), when temperature reaches its highest monthly value of 25.0°C, while the largest monthly SD of salinity is in June (about 4.2), when salinity reaches the lowest monthly mean value of 32.8. A second local minimum of salinity is reached at the surface in October. Salinities at depth fluctuate much less, with a range between 36.5 and 38.5. While it is obvious that temperatures are governed by the annual cycle of solar radiation [*Malačič*, 1991], there is, however, one peculiar deviation from the sinusoidal annual evolution of monthly temperatures: in September temperatures are lower than those of the sinusoidal fit, while in October they are higher. This is present at the surface as well as at 10 m depth and deviations are stronger at the surface. However, the deviations are at the edge or within the range of two standard deviations around the montlhy mean values. The cause of this phenomenon is not yet clear, however, it seems to be related to the autumn advection of water mass and heat from the rest of the Adriatic Sea [*Stravisi and Crisciani*, 1986].

[14] 2003 was anomalously hot and dry during spring–summer period, with extremely low monthly discharges from rivers around the northern Adriatic. The interannual average flow rate of the Isonzo (Soča) river, the major river that discharges into the Gulf of Trieste, is 285 m^3/s, 215 m^3/s, and 181 m^3/s in June, July and August, respectively [*Raicich*, 1996], while in 2003, these flow rates were only 2, 7 and 2 m^3/s (Direzione Regionale dell'Ambiente – Friuli Venezia Giulia), respectively, that is, for two orders of

Table 1. Basic Statistics of Monthly Temperatures T_m and Monthly Salinities S_m at Depths 0.3 m and 10.0 m[a]

	T_m, °C	T_m, °C	SD_T, °C	SD_T, °C	S_m	S_m	SD_S	SD_S
Depth, m	0.3	10.0	0.3	10.0	0.3	10.0	0.3	10.0
⟨ ⟩	16.52	15.54	1.04	0.89	35.31	37.15	1.97	0.35
SD	6.02	5.23	0.29	0.15	1.10	0.36	0.87	0.13
Min	9.19	9.17	0.61	0.67	32.81	36.79	0.99	0.12
Max	24.97	22.60	1.51	1.18	36.72	37.74	4.17	0.53
T_0	16.51 ± 0.28	15.52 ± 0.25						
T_1	8.07 ± 0.38	7.02 ± 0.34						

[a]The statistics of monthly standard deviations (*SD*) from monthly values is added, in which the subscript denotes temperature or salinity. For a comparison the parameters of the trigonometric least squares fit $T_0 - T_1\cos(2\pi(t - t_0)/12)$ of monthly temperatures are added, where a period of 12 months is supposed and where t_0 is the time of monthly minimum (in months) since the start of a year, which equals to 1.24 months for 0.3 m depth and 1.62 months for 10.0 m depth. Monthly terms in the least squares procedure were weighted with a factor of $1/s_i^2$, where s_i is the standard deviation of i-th month. R^2 of trigonometric least squares fits of monthly temperatures equals 0.99 for both depths.

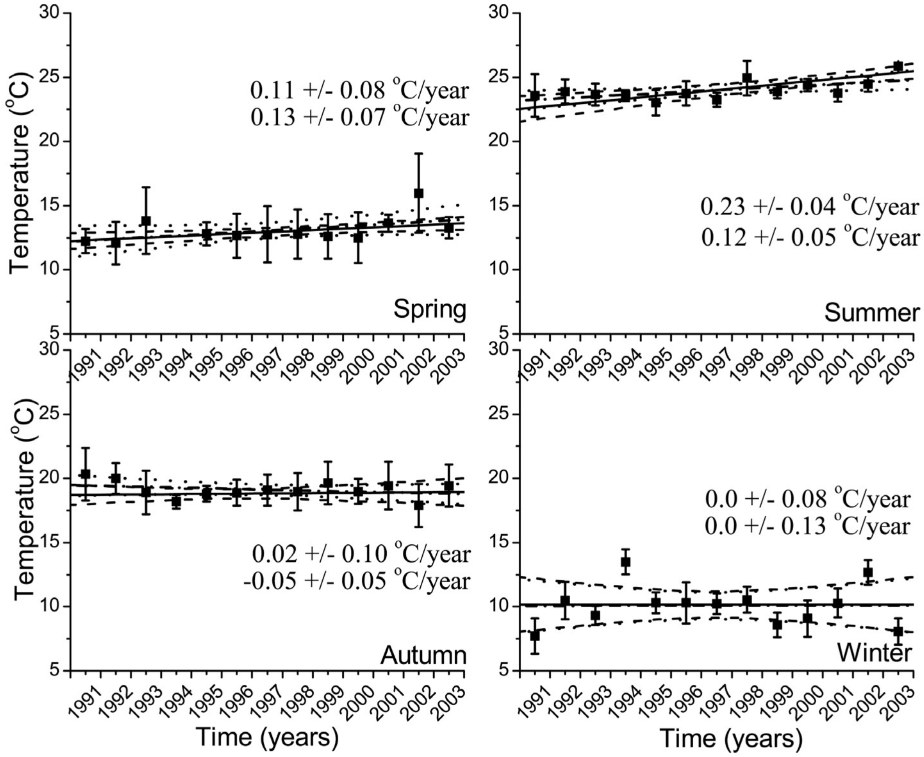

Figure 3. Trends of seasonal temperatures at a depth of 0.3 m. Seasonal average (squares) with 2 × SD (vertical bars) of data output from the OA over the area inside the rectangular domain in the Gulf of Trieste (Figure 1). Linear trends of the seasonal data weighted with SD are marked with solid lines, while dash-dotted lines are trends without weight. The envelopes of 95 % confidence limits for the former trends are in dashed lines, while for the latter they are in dotted lines. Text in the first row in each plot represents the coefficient of trend for the WT (weighted trend), while in the second row is the coefficient calculated for the UT (unweighted trend). Lines related to WT frequently overlap with the lines related to UT.

magnitude lower. This extremely dry period ended during the last three days of August 2003, when the average flow rate of the Isonzo was 24 m^3/s. Therefore, trend analysis with and without year 2003 makes sense.

[15] Interannual variations of seasonal temperatures over the Gulf of Trieste are presented in Figure 3 (0.3 m depth) and Figure 4 (10 m depth), while variations of salinities are in Figure 5 (0.3 m depth) and Figure 6 (10 m depth). Coefficients of trend are given in Table 2. All figures show quite accurately that there is no reliable negative trend – temperatures and salinities are either experiencing a positive trend, or they are without any trend during 1991–2003. Temperatures in spring have a surprisingly close trend for WT and for UT: 0.10–0.13°C/year with an error of 0.08 at 0.3 m depth (Figure 3) and of 0.06 at 10 m depth (Figure 4). Temperatures at 10 m depth are lower than those at 0.3 m by about 1.5°C. Summer temperatures are much higher than those of spring (by about 10°C at the surface and 9°C at 10 m depth) and at the surface they differ from those at 10 m depth by about 2.5°C. Summer temperatures at the surface experience different trends, of 0.23°C/year (WT) and of 0.12°C/year (UT) with an error of up to 0.05°C/year. The difference in the trend between WT and UT analysis is due to relatively large variations of SD from one year to another. However, these values are reduced evidently, especially for WT, when the year 2003 is excluded from the analysis: 0.07–0.09°C/year with an error of up to 0.06°C/year. Summer temperatures at the depth of 10 m have more equilibrated SD's from one year to another (vertical bars on Figure 4), the coefficients of trend in both analysis (WT and UT) are much closer: 0.22–0.23°C/year. Their mean values, however, vary more pronouncedly from one year to another, causing the uncertainty (standard error) of trend to be larger (0.06–0.08°C/year). This trend of temperature at 10 m depth is also a much more stable one than that at 0 m – when the year 2003 is excluded (Table 2), the trend is slightly increased: 0.26 ± 0.09°C/year. Both values of temperature rise since 1991, with and without year 2003, are remarkably high. Autumn temperatures are certainly those for which we may conclude that they do not experience any serious trend. The trend in WT analysis is positive, while that in UT is negative. Both have uncertainties that are larger or equal to the values of coefficients. Winter temperatures at the surface also do not show any reliable trend. However, we cannot conclude the same for winter temperatures at 10 m depth: they vary between 0.02–0.09°C/year, where the upper value (WT) seems more reliable (±0.05°C/year) than the lower value (UT) with an uncertainty of 0.12°C/year, which is six times larger than the value of the coefficient. Therefore, winter temperatures at 10 m depth

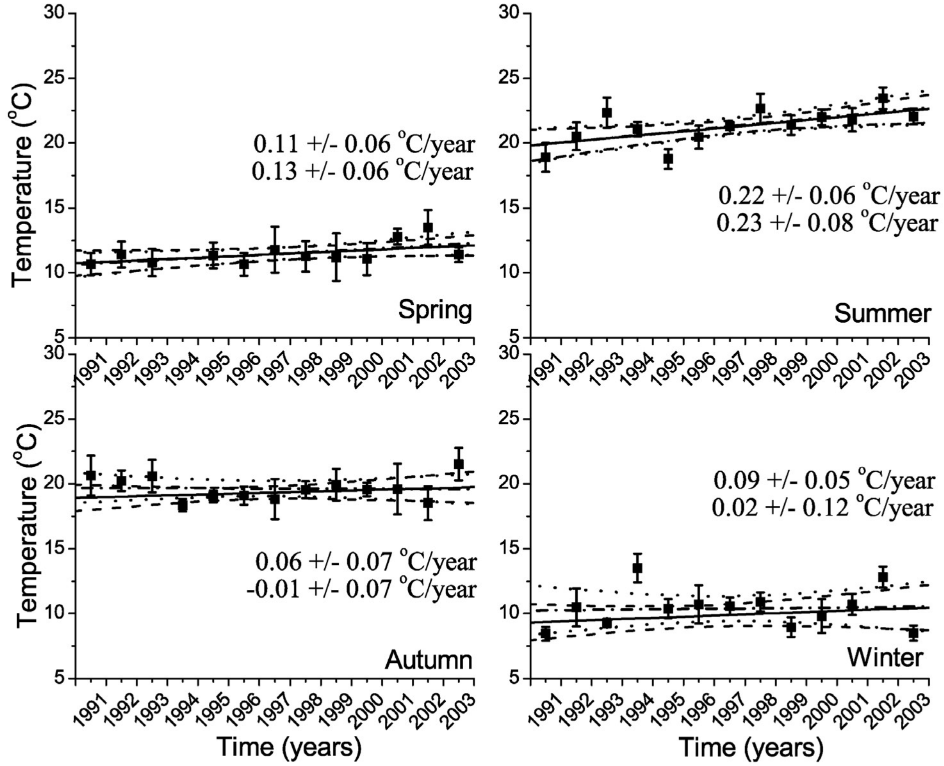

Figure 4. Similar to Figure 3, except for the depth around 10.0 m.

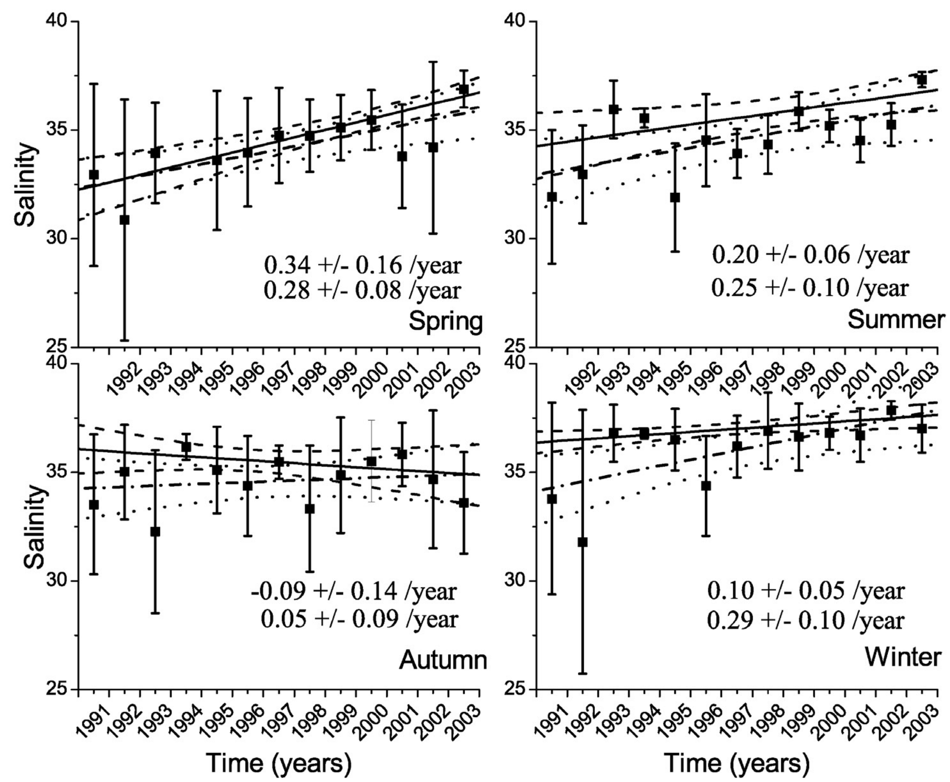

Figure 5. Trends of seasonal salinities at depths around 0.3 m; notations are similar to those in Figure 3.

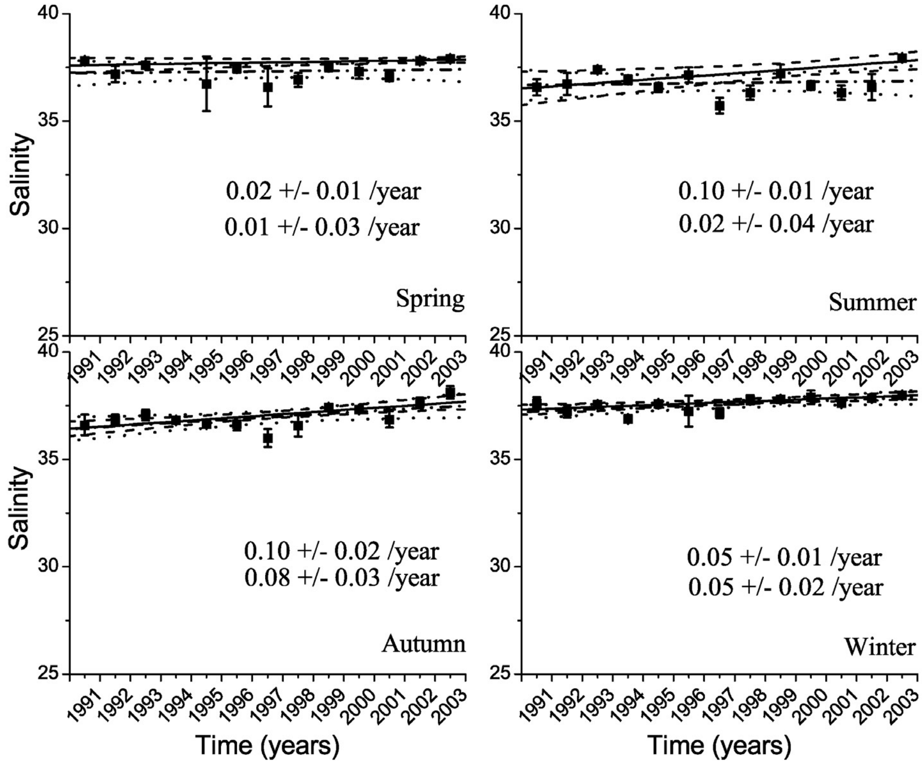

Figure 6. Similar to Figure 5, except for the depth around 10.0 m.

experienced a linear trend in 1991–2003 below 0.09°C/year and above 0.02°C/year. However, in contrast to the summer situation, the trend of winter temperatures increases when year 2003 is excluded from the analysis, up to 0.11 ± 0.14°C/year at the surface, and up to 0.11 ± 0.12–0.23 ± 0.06°C/year at a depth of 10 m.

[16] Salinities show much more interannual variability in SD than temperatures. The largest is at the surface in the winter–spring period (Figure 5), while the lowest at 10 m depth (Figure 6) is in winter. At this depth salinities approach a value of 38 for the year 2003 in all seasons. They are without any reliable trend at the surface in autumn.

Table 2. Coefficients of the Trends of Seasonal Temperature (b_T) and Salinity (b_S) Between 1991 and 2003 for Each Season at Depths 0.3 m and 10.0 m[a]

		Temperature				Salinity			
		WT		UT		WT		UT	
Season	Depth, m	b_T, °C/year	R^2	b_T, °C/year	R^2	b_S, year^{-1}	R^2	b_S, year^{-1}	R^2
Spring	0.3	0.11 ± 0.08	0.52	0.13 ± 0.07	0.25	0.34 ± 0.16	0.75	0.28 ± 0.08	0.55
		0.13 ± 0.10	0.58	0.16 ± 0.08	0.29	0.20 ± 0.25	0.40	0.22 ± 0.09	0.43
	10	0.11 ± 0.06	0.31	0.13 ± 0.06	0.34	0.02 ± 0.01	0.18	0.01 ± 0.03	0.01
		0.19 ± 0.08	0.61	0.16 ± 0.06	0.46	−0.01 ± 0.01	0.04	−0.01 ± 0.04	7E-3
Summer	0.3	0.23 ± 0.04	0.67	0.12 ± 0.05	0.40	0.20 ± 0.06	0.40	0.25 ± 0.10	0.36
		0.09 ± 0.06	0.38	0.07 ± 0.04	0.24	−0.03 ± 0.09	0.01	0.19 ± 0.11	0.23
	10	0.22 ± 0.06	0.45	0.23 ± 0.08	0.42	0.10 ± 0.01	0.44	0.02 ± 0.04	0.01
		0.26 ± 0.07	0.45	0.26 ± 0.09	0.43	−0.07 ± 0.03	0.26	−0.03 ± 0.04	0.07
Autumn	0.3	0.02 ± 0.10	0.01	−0.05 ± 0.05	0.10	−0.09 ± 0.14	0.10	0.05 ± 0.09	0.03
		−1E-3 ± 0.11	3E-5	−0.08 ± 0.05	0.18	−0.05 ± 0.16	0.03	0.11 ± 0.09	0.12
	10	0.06 ± 0.07	0.07	−0.01 ± 0.07	8E-4	0.10 ± 0.02	0.64	0.08 ± 0.03	0.36
		0.02 ± 0.08	5E-3	−0.09 ± 0.06	0.20	0.09 ± 0.02	0.60	0.06 ± 0.04	0.20
Winter	0.3	8E-5 ± 0.08	3E-8	2E-3 ± 0.13	3E-8	0.10 ± 0.05	0.43	0.29 ± 0.10	0.44
		0.11 ± 0.09	0.05	0.10 ± 0.14	0.05	0.11 ± 0.06	0.47	0.32 ± 0.11	0.45
	10	0.09 ± 0.05	0.07	0.02 ± 0.12	3E-3	0.05 ± 0.01	0.62	0.05 ± 0.02	0.40
		0.23 ± 0.06	0.39	0.11 ± 0.12	0.08	0.04 ± 0.01	0.29	0.05 ± 0.02	0.30

[a]Winter includes the months of December–February, spring March–May, summer June–August and autumn September–November. Linear least squares fits were conducted for weighted trend analysis (WT) with a weighted average (weighting factor $1/s_i^2$, where s_i is the seasonal standard deviation in year i), as well as for the unweighted trend (UT) analysis without weighted average. A second analysis was also conducted in which the year 2003 was omitted; the resulting values are written below the results that include the year 2003. R^2 is the square of the coefficient of linear correlation, and 2E-3 stands for 2 10^{-3}.

Table 3. Coefficient of Trend of Seasonal Standard Deviations of Temperature (b_{SDT}) and of Salinity (b_{SDS}) in the Period 1991–2003[a]

	Season	Depth, m	b_{SDT}, °C/year	R^2
SD temperature	summer	0.3	−0.06 ± 0.02	0.37
			−0.05 ± 0.03	0.27
		10	−0.03 ± 0.02	0.15
			−0.02 ± 0.02	0.10
			b_{SDS},/year	R^2
SD salinity	spring	0.3	−0.20 ± 0.09	0.37
			−0.18±0.10	0.26
	autumn	10	−0.002 ± 0.01	0.004
			−0.003 ± 0.01	0.007

[a]Only those seasons and depths were chosen for which significant (major) value of b_T and b_S were found for seasonal temperatures and salinities, respectively. Results of a second analysis in which the year 2003 was omitted are written below the results that include the year 2003. There was no weighting in linear fits.

Similarly to temperatures, autumn salinities have one negative trend (WT) of −0.09 year^{-1} with a large uncertainty (0.14 year^{-1}), and a positive trend (UT) of 0.05 year^{-1} with a smaller uncertainty (0.09 year^{-1}), which is twice the value of the coefficient. Salinity experienced a trend with the highest trend in spring: between 0.28 year^{-1} (UT) and 0.34 year^{-1} (WT), but only at the surface. The trend for spring salinities during 1991−2002 is around 0.2 year^{-1} (Table 2) with a large error of 0.25 year^{-1} (WT) which is similar to 0.22 year^{-1} (UT), which is more stable (±0.09 year^{-1}). The trend of salinity in spring at 10 m depth is ten times smaller (0.01−0.02 year^{-1} with uncertainties 0.01−0.03 year^{-1}) and is hardly a reliable one. The trend of salinities in spring at the surface is followed by the trend of salinities in summer (0.20−0.25 year^{-1}) and winter (0.10−0.29 year^{-1}), with an uncertainty of up to 0.1 year^{-1}. However, when 2003 is taken out of the analysis, summer salinities at the surface experience a slightly negative, unreliable trend (−0.03 ± 0.09 year^{-1}) in WT analysis, and a positive one (0.19 ± 0.11 year^{-1}) in UT analysis, which is about 25% lower than that for the period 1991–2003. This clearly indicates that the year 2003 seriously affects trend analysis of salinities in spring, as well as salinities in summer. At the depth of 10 m (Figure 6) the trend differs substantially from UT (0.02 ± 0.04 year^{-1}) to WT (0.1 ± 0.01 year^{-1}) for salinities in summer, while there is a perfect match between them (0.05 ± 0.02 year^{-1}) during the winter period.

[17] Table 3 summarizes important figures about the interannual variability of the standard deviations (SD) of temperatures and salinities. A surprising conclusion is that there is most certainly no increase in SD of seasonal quantities: there is the largest decrease of SD of temperature in summer: −0.06 ± 0.02°C/year, and of SD of salinity in spring (−0.2 ± 0.09 year^{-1}), both at the sea-surface. While the R^2 value of these most important trends never exceeds 0.37, showing a relatively poor linear correlation, other trends of SD are most certainly not worthy of mention.

[18] Changes of temperature and salinity over a 10 year period, according to calculated trends in Table 2, are simplified in Table 4, which also presents the impact of these trends on density, looking "globally" over the whole Gulf of Trieste. During spring and summer the density significantly increases at the surface, and slightly decreases at the depth of 10 m. This reduces the vertical density difference over 10 m depth from 2.77 to 0.67 kg/m^3 in spring and from 2.57 to 1.18 kg/m^3 in summer. During autumn, the density at the surface seems to remain steady, however, at the depth of 10 m an increase of salinity of 1 over a decade leads to an increase of the difference of densities along the vertical from 1.72 to 2.49 kg/m^3 over an interval of 10 m depth. During winter there is only a trend of salinity at the surface (of 2 over 10 years) and an increase of temperature of 0.5°C and of salinity of 0.5 at 10 m depth. Overall, during winter the mean stratification was reduced to zero over 10–13 years inside the interval 1991–2003, during autumn it was increased, while during spring and summer it was decreased.

[19] The results of the trend analysis of air temperatures at Portorož airport (see Figure 1 for the location) are summarized in Table 5. Trends of air-temperatures estimated only from the data taken from the set of cruise days show significantly lower R^2, except for the winter season, where trends in the WT analyses are much more susceptible to this narrowing of the set of days to cruise days than in the UT analyses and also have larger uncertainties. Further discussions about this effect will be addressed later.

[20] During spring the trend of 0.05 ± 0.35°C/year in the WT analysis when only cruise days are considered is much lower than the 0.16 ± 0.41°C/year when all days were considered, and it is even further lowered to 0.02 ± 0.38°C/year when year 2003 is excluded. Most trends of air temperature in spring support the statement that trends of air temperature in spring (0.13 ± 0.13 – 0.18 ± 0.45°C/year) are close to and less accurate than those in the sea (0.12 ± 0.08°C/year). Interannual trends of air temperatures in summer depend upon the inclusion/exclusion of year 2003: they range from 0.04 ± 0.07°C/year (UT, no year 2003, only cruise days) to 0.15 ± 0.34°C/year (WT, all days). Winter temperatures have trends between 0.07 ± 0.36°C/year (WT, all days) and 0.24 ± 0.11°C/year (UT, cruise days, no year 2003). All trends are positive, except for autumn, when trends are weak and burdened with a relatively large error.

3.2. Variability in Space

[21] Space distribution of temperature and salinity that results from the OA is shown on Figures 7–10 for spring to winter seasons, respectively. Temperatures in spring do not show any significant organized pattern that would draw

Table 4. Density Excess (γ) of Seasonal Values of Temperatures and Salinities and Its Change Δγ Over a Period of 10 Years According to Variations of Temperature ΔT and Salinity ΔS[a]

Season	Depth, m	$\langle T \rangle$, °C	$\langle S \rangle$	γ, kg/m^3	ΔT, °C	ΔS	Δγ, kg/m^3
Spring	0.3	13.1	34.2	25.75	1.0	3.00	2.12
	10	11.5	37.3	28.52	1.0	0.15	−0.08
Summer	0.3	24.0	34.5	23.26	1.5	2.20	1.21
	10	21.3	36.8	25.83	2.2	0.60	−0.18
Autumn	0.3	19.1	34.6	24.69	0.0	0.00	0.0
	10	19.7	37.0	26.41	0.0	1.00	0.77
Winter	0.3	10.1	36.0	27.72	0.0	2.00	2.56
	10	10.4	37.6	28.96	0.5	0.50	0.30

[a]In calculations of the density at depth 0.3 m, pressure was supposed to be equal to 0.0 dbar, while that at 10 m depth of 10.0 dbar, the uncertainty of pressure for 0.3 dbar has no significant influence.

Table 5. Coefficients of the Trend of Air Temperature b_{Ta} Between 1991 and 2003 at Portorož Airport (See Figure 1 for the Location)[a]

		Air Temperature			
		WT		UT	
Season	Days	b_{Ta}, °C/year	R^2	b_{Ta}, °C/year	R^2
Spring	ALL	0.16 ± 0.41	0.55	0.14 ± 0.05	0.44
	NO 2003	0.18 ± 0.45	0.60	0.17 ± 0.05	0.50
	CRUISE	0.05 ± 0.35	0.02	0.17±0.11	0.17
	NO 2003	0.02 ± 0.38	3E-3	0.13 ± 0.13	0.09
Summer	ALL	0.15 ± 0.34	0.31	0.15 ± 0.07	0.28
	NO 2003	0.06 ± 0.38	0.12	0.06 ± 0.06	0.09
	CRUISE	0.13 ± 0.33	0.20	0.13 ± 0.08	0.19
	NO 2003	0.05 ± 0.37	0.05	0.04 ± 0.07	0.04
Autumn	ALL	0.06 ± 0.44	0.11	0.05 ± 0.05	0.09
	NO 2003	0.10 ± 0.49	0.25	0.09 ± 0.06	0.21
	CRUISE	0.01 ± 0.46	2E-3	−0.01 ± 0.06	8E-4
	NO 2003	−0.05 ± 0.53	0.07	−0.06 ± 0.05	0.11
Winter	ALL	0.07 ± 0.36	0.05	0.09 ± 0.09	0.08
	NO 2003	0.11 ± 0.40	0.09	0.13 ± 0.10	0.13
	CRUISE	0.09 ± 0.37	0.06	0.13 ± 0.11	0.11
	NO 2003	0.19 ± 0.40	0.22	0.24 ± 0.11	0.33

[a]For a particular day the average of air temperatures at 07:00 and 14:00 was considered as the representative air temperature during the "working hours" when cruises were conducted. In the second column, "ALL" denotes all days in each season for each year, for which representative air temperatures were accounted in the calculation of seasonal average and standard deviation. "CRUISE" denotes that the seasonal averages and deviations of air temperatures were calculated out only from days for which the cruise data were available, regardless of the distribution of stations at sea during a particular cruise. "NO 2003" means that the data from year 2003 were not considered in the analyses. Winter includes the months of December–February, spring March–May, summer June–August and autumn September–November. Linear least squares fits were conducted with a weighted trend analysis (WT), as well as with unweighted trend analysis (UT), similar to the analysis of the data obtained from the OA of cruise data (Table 2).

particular attention. The range of temperatures at 10 m is not that much lower than that near the surface, although they are lower for a few degrees °C and they do increase towards the southern entrance to the Gulf. Salinities at the surface show a gradient of salinities towards lower values along the northwestern coastline of the Gulf that is orthogonal to the coastline. This results from the outflow of the Isonzo (Soča) river. Salinities at 10 m depth are horizontally quite homogeneous. Since there is little outflow during summer, the freshwater influence is confined to a small bay eastward from the Isonzo river mouth (Figure 8) and to a strip along the northern coastline. Temperatures at 10 m depth are lower in the centre of the Gulf: a situation is even clearer at 20 m depth (not shown). During autumn (Figure 9) lower salinity is present along the northwestern coastline due to river input which is similar to the situation in spring. Since during this season periods of convective overturns of free and forced convection are intercalated with periods of pronounced and relatively short bursts of river outflow, as well as with periods of warming by solar radiation, distributions of temperature and of salinity at the depth of 10 m are patchy, reflecting pronounced local variations on a scale smaller than 5 km. During winter (Figure 10) a clear signal of river outflow is again manifested by lower surface salinity, which spreads over the Gulf even more than in spring. The "patchiness" is less pronounced than during autumn. Lower winter temperatures at the surface also reflect a colder river effect along the northwestern coastline. The effect of temperature, however, now opposes that of salinity from two points of view. Firstly, colder temperatures cause double diffusive processes to be frequent in winter near the northern coastline [*Turner*, 1973] when there is a lower salinity at the surface. Secondly, lower freshwater temperatures reduce the horizontal gradients of density and pressure caused by lower salinity along the coastline. This leaves behind a lower horizontal gradient of surface sea-level and, consequently, creates lower velocities of the freshwater that leaves the Gulf of Trieste along the north-western coastline in a quasi-geostrophic equilibrium, than in case of "neutral temperature" of the river freshwater. At the depth of 10 m there seems to be a colder water mass lying in the central and northern part of the Gulf (the isoline of 10°C), roughly similar to the situation noticed in summer. This colder pool of water mass in the central part is leading to the densest water mass in winter in the central part of the Gulf.

4. Discussion With Conclusions

[22] Since seasonal temperatures near the sea-surface in spring are lower for about 10°C than those in summer (Figure 3), where the relatively low values of SD do not cover the difference between the two, an error is expected. However, it follows from Figure 2 that summer months are placed exactly around the peak of temperatures, while spring months are indeed lower by 10°C. Although one may think that this shows a wrong choice of months for seasons, the analysis here conducted still gives a valuable insight in trends.

[23] We may summarize that in summer sea temperatures experienced the largest linear variations over the period 1991–2003 near the sea-surface, and even more at 10 m depth, of at least 0.2°C/year, causing summer temperatures to increase by more than 2.6°C from 1991 to 2003. Summer temperatures are followed in trend by spring (0.1°C/year) and winter temperatures (less than 0.09°C/year) at both depths, while autumn temperatures do not show any significant trend. The rise of salinities up to 0.3 year^{-1} is a value that is seriously affected by the year 2003, and the value of 0.2 year^{-1} (1991–2002) for spring at the surface sounds more solid estimate. This means an increase of 2.6 over 13 years, indicating a trend of interannual decrease of freshwater input during spring. At the surface the trend of salinities in spring is followed by the trend of summer and winter salinities at the surface, with a similar value of coefficient: 0.1–0.3 year^{-1}.

[24] Contrary to temperatures, salinities at 10 m depth have much smaller trend than that at the surface, it is the smallest during spring (0.01–0.02 year^{-1}) and the largest during summer and autumn (0.08–0.1 ± 0.03 year^{-1}), which is a surprise, since there is no trend of salinities in autumn at the sea-surface. All results also show that any other kind of trend (a nonlinear one) would not be detectable over the measured period. The variability of temperature and salinity did not increase in time, there was a relatively weak trend of decrease of SD of summer temperature at the surface (−0.06 ± 0.03°C/year), and a stronger and more variable trend of a decrease of SD of salinity in spring, around −0.2 ± 0.1 year^{-1}. We may also conclude

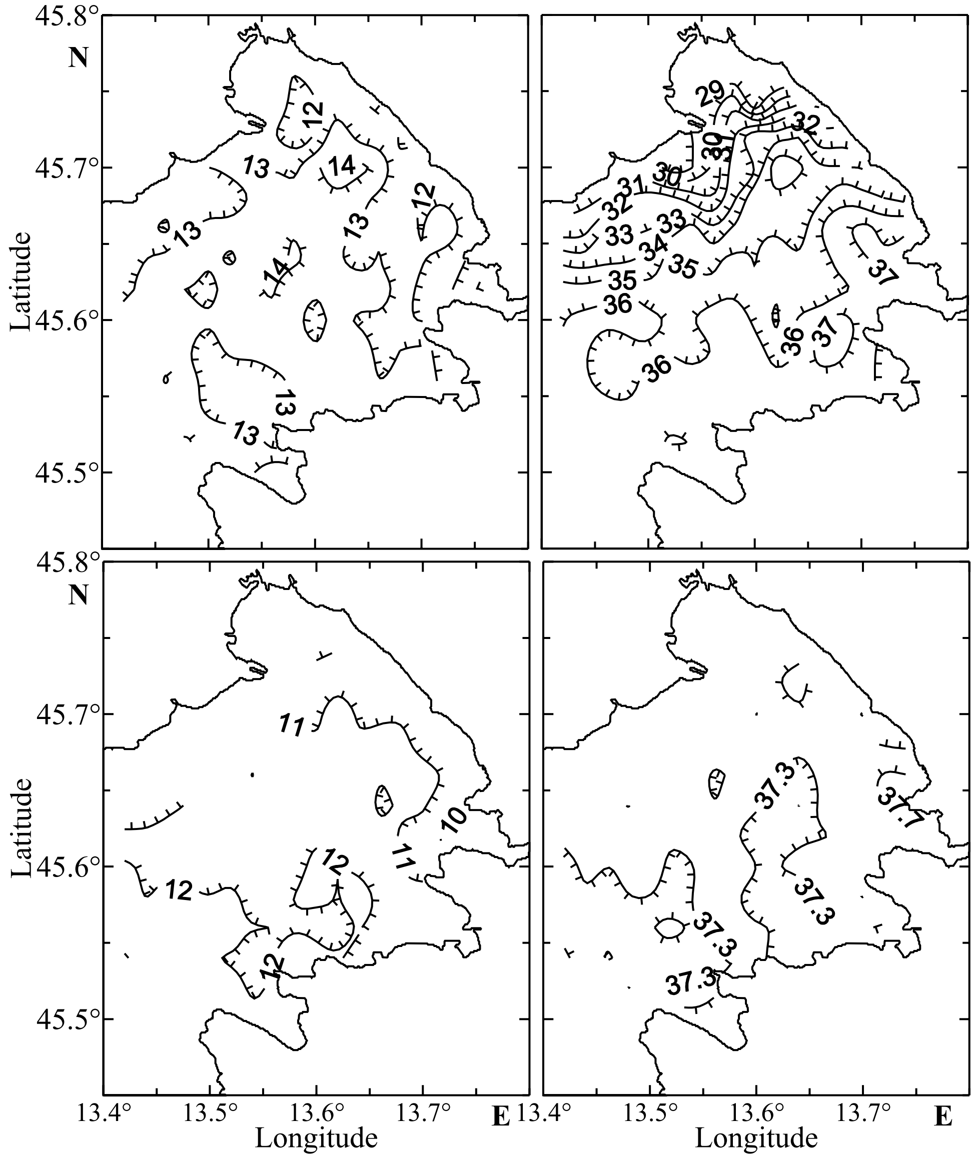

Figure 7. Distribution of (left) temperature and of (right) salinity at (top) 0.3 m depth and (bottom) 10 m depth during the spring period. The distributions results from the OA of the data (see text). The isolines of temperature are in steps of 1.0°C, while those of salinity in steps of 1.0 (0.3 m) and of 0.4 (10 m).

that the relatively short time series does not provide enough data to make any affirmative conclusions about the interannual variability. However, it seems (Figures 3–6) that all seasonal quantities are susceptive to the oscillations on a timescale of 4–6 years, that composes the gross part of the variability of mean values within seasons.

[25] Space distribution of temperature and salinity during the anomalous summer of 2003 was treated elsewhere [*Celio et al.*, 2006]. The usual (climatic) offshore increase of salinity in the north eastern corner of the Gulf (Figure 8), where the belt of freshwater along the northwestern coastline starts, was absent in the summer of 2003. Instead, the highest salinity (37.99) in the Gulf of Trieste was recorded at a location just a few miles eastward of the mouth of Isonzo, where freshwater influence is usually the strongest. However, it usually follows from horizontal distributions of quantities, that lower salinities are related to the outflow of the Isonzo river in the spring, autumn and winter periods and that during summer and winter a denser water mass is formed in the central part of the Gulf.

[26] A word about the anisotropy of the horizontal distributions of temperature and salinity, especially at the sea-surface seems appropriate. Figures 7–10 demonstrate that along the Gulf's axis the variations of salinity at the surface are smaller than those across it, leading to the conclusion that the correlation of quantities along the Gulf's axis would have a larger range than the correlation of quantities across the Gulf. Therefore, the anisotropy of fields should also be taken into account in the OA in the future and its effect on trend analysis should also be examined.

[27] The trend in sea-surface temperature deviates from the conclusions of the IPCC that during winter the variability of temperature (in the atmosphere) "will likely de-

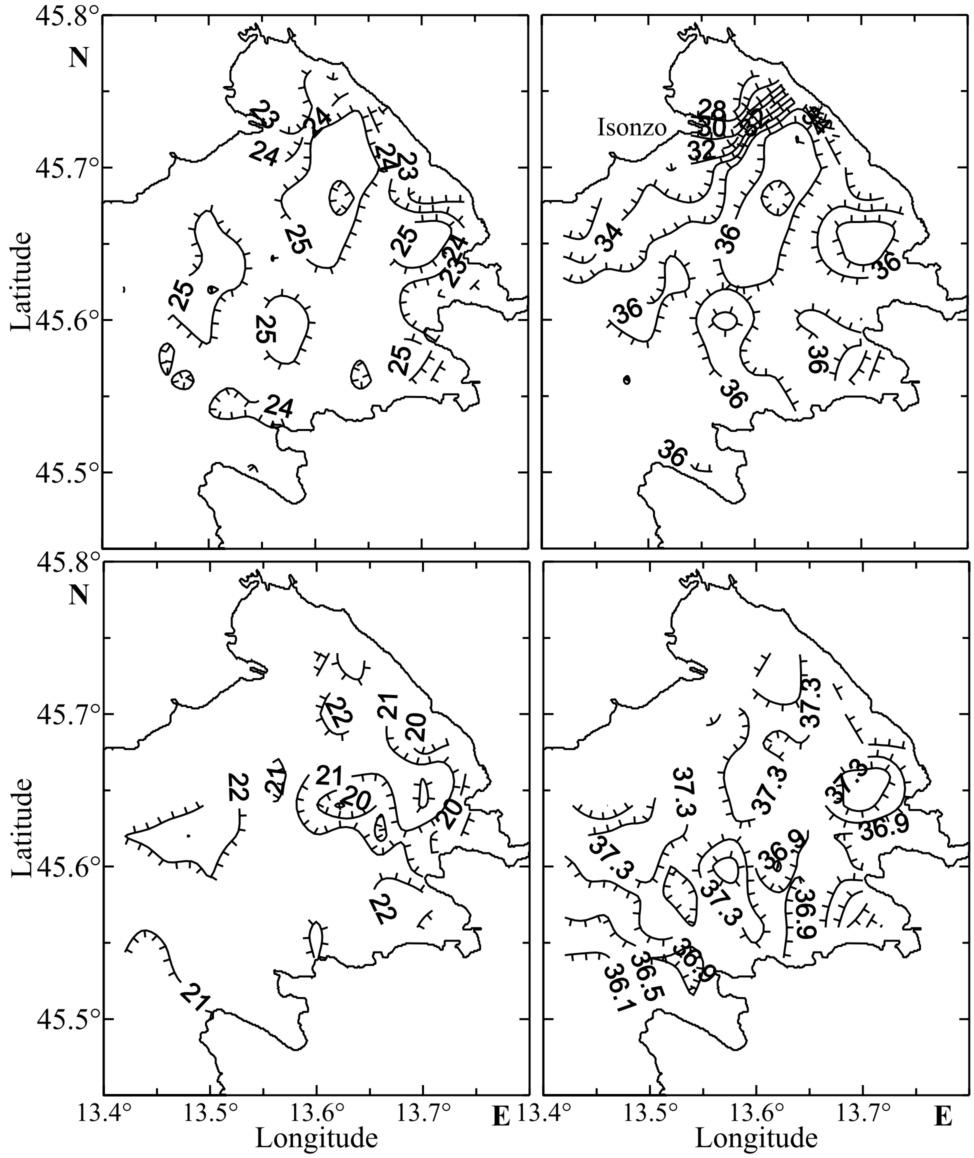

Figure 8. As in Figure 7, but for the summer period.

crease'' [*Giorgi et al.*, 2001], while during the summer period this variability should increase in midlatitude northern hemisphere land areas; we may consider that the area around the northern Adriatic falls in this category. Globally averaged surface (air) temperature is supposed to increase: 1.4–5.8°C from 1990 to 2100 [*IPCC*, 2001, p. 13]. However, over the Mediterranean sea the trend of surface (air) temperature increase [*Albritton et al.*, 2001] is predicted to be in excess of 40% (''much greater than average warming,'' Figure 21 on their page 69), which means an increase between 1.3 and 6.3°C over the period of 1990–2100 (less than 0.5°C over a decade). This was projected with different numerical simulations that take into account different scenarios of sulfur dioxide input and fossil fuel emissions, where the long lived CO_2 and N_2O are ''the dominant determinants'' in climate change over a longer period (century). Looking at trends of historical data in the period 1950–2003 that show a realistic situation in the nearest past, the increase in sea-surface temperature is estimated to be about half that of the mean land surface air temperature [*Albritton et al.*, 2001]. From 1976 to 1999 there was an increase of 0.15°C/decade (their page 26) in land surface anomalies of temperature, giving about 0.08°C/decade of increase in global surface sea-temperature, according to the estimate of the IPCC. Although in this paper the analyses were conducted on sea-surface temperature and salinity which were grouped in seasons, we may certainly conclude that trends in sea-surface temperature over the Gulf of Trieste revealed in our study are for an order of magnitude higher than those found on a global level within the period 1991–2003, which was mostly covered by the period of analysis of the IPCC (1976–1999). They are much closer to recent findings of satellite observations about the warming of skin sea-surface temperature of the Mediterranean and Adriatic Seas (I. Vigo, personal communication).

[28] We also have to take into account that cruises were performed mostly in clement weather. This means a bias towards higher values of temperature (potentially greater

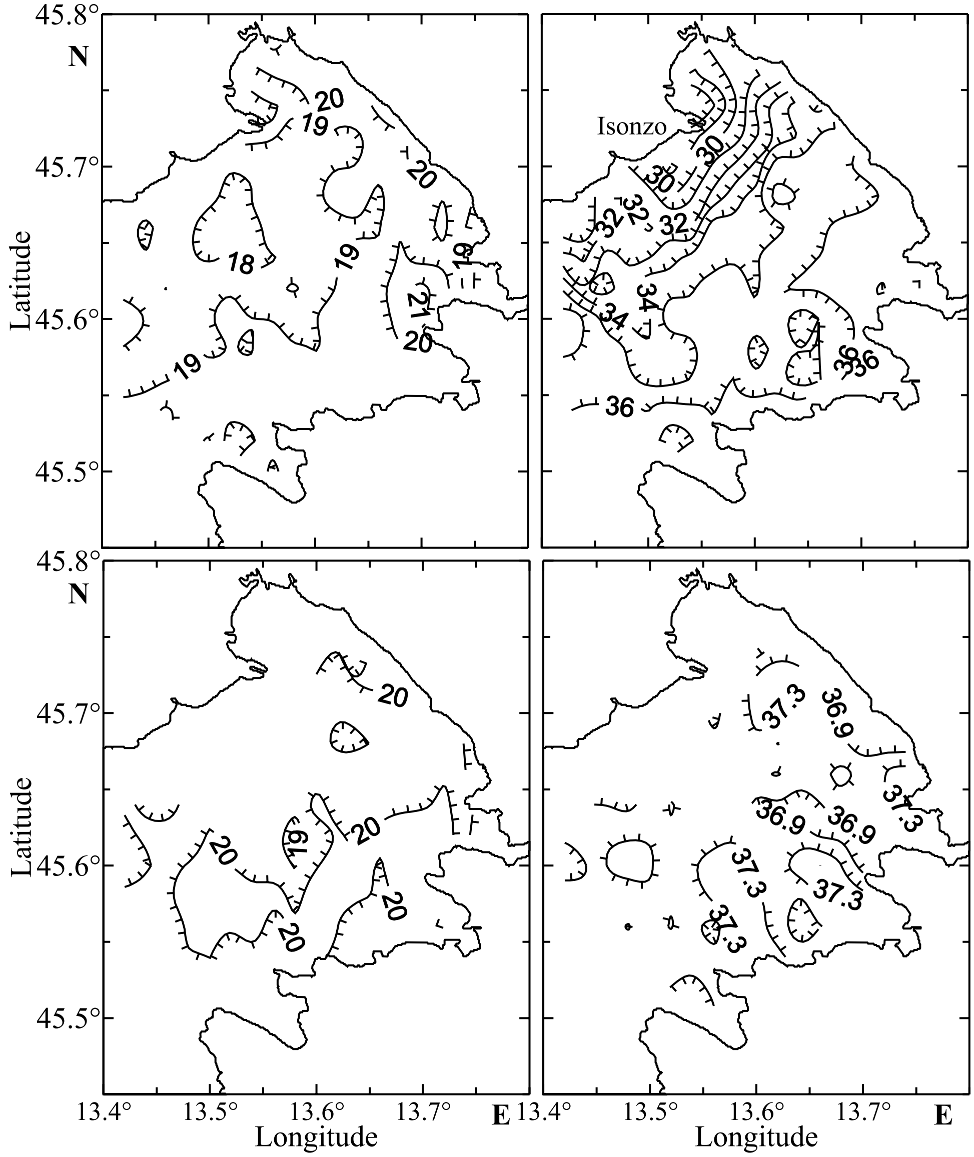

Figure 9. As in Figure 7, but for the autumn period.

solar radiation) and also of salinity (heavy weather is usually related to precipitation and larger river discharges). However, this bias towards higher values is present in each year, and trends here obtained may still manifest a real situation.

[29] Trends of sea temperature in the Gulf of Trieste have to be observed also in light of trends of air temperature. Since for the latter only the time series at one location were chosen, there was no treatment with OA of air temperature data. Major differences between the trends of seasonal air temperature (Table 5) and sea temperature, pretreated with the OA (Table 2) are in the following: In WT analysis the trend of sea temperature at the surface in summer (0.22 ± 0.06°C/year) is larger than that of air temperature (0.13–0.15 ± 0.34°C/year) when year 2003 is included, and also holds when this year is excluded from the analysis (0.09 ± 0.06°C/year in the sea against 0.05–0.06 ± 0.38°C/year in the air). However, for UT, trends are much closer: 0.13–0.15 ± 0.08°C/year (air) against 0.12 ± 0.05°C/year (sea), or 0.04–0.06 ± 0.07°C/year (air) against 0.07 ± 0.04°C/year (sea) when year 2003 is excluded. We have to keep in mind that sea temperatures at the depth of 10 m have a much more reliable and larger trend than those at the surface (0.22–0.26 ± 0.09°C/year).

[30] Another major difference noted between the trends of air and sea temperature is for the winter period: while in the sea the (positive) trend is feeble with large deviations (due to variations in time and space), the trend of the rise of winter air temperatures is much stronger: 0.07–0.13 ± 0.36°C/year when all trend analyses are considered. The trend of winter air temperatures is even stronger when year 2003 is excluded from the analysis (0.11–0.24 ± 0.40°C/year). A similar situation also holds for spring when all days were accounted for in the analysis. This clearly indicates that winter 2003 was not warmer, as was the summer, but was colder that "expected," according to trend analysis. Sea temperatures qualitatively follow air temperatures: trends of winter temperatures increase substantially if year 2003 is excluded from the trend analysis (Table 2).

[31] The reasons for the differences in trends between air and sea temperatures most certainly deserve further en-

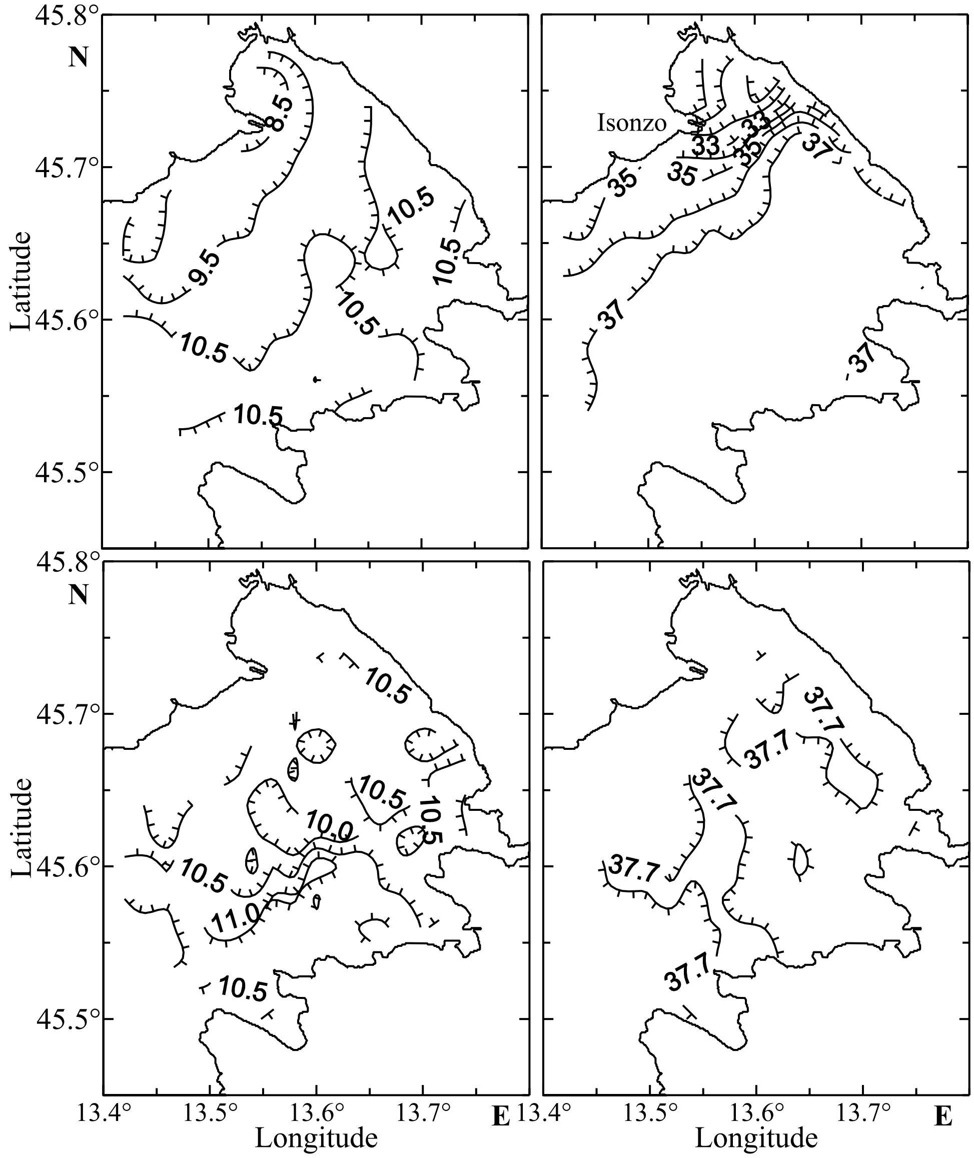

Figure 10. As in Figure 7, but for the winter period. The isolines of temperature are in steps of 1.0°C (0.3 m) and of 0.5°C (10 m), while those of salinity are in steps of 1.0 (0.3 m) and of 0.4 (10 m).

hanced attention in the future. So far, we can only draw an overall conclusion that in the interval 1991–2003 the summer sea temperatures experienced a larger interannual positive trend than air temperatures at one place inside the domain of the Gulf of Trieste, and that most trends are for an order of magnitude larger than those written in the IPCC report [*Albritton et al.*, 2001]. Summer trends of temperatures near the sea surface and in the air increase when year 2003 is included in the analysis, while winter trends of the same significantly decrease.

[32] An estimate of the bias effect on trends of seasonal sea temperatures due to irregular time intervals between cruises could be inferred from the trend analysis of air temperatures. As seen from Table 5 the interannual WT of air temperatures during spring changes significantly. It falls from 0.16 ± 0.41°C/year when all days were considered to only 0.05 ± 0.35°C/year when only cruise days were considered, with a very low R^2 (0.02). A similar result follows when year 2003 is excluded. However, the results of UT analysis for spring differ to a lesser degree. The trend of winter temperatures, when year 2003 is excluded and only cruise days are considered, is nearly doubled against the trend when all winter days were considered. The other two seasons (summer and autumn) do not show large deviations in trends when only cruise days are considered in the analysis as opposed to those when all days are included. Care in interpretation is appropriate, since during cruise days the number and position of the sampling stations differ significantly from one cruise day to another.

[33] Trends of temperature and salinity cause trends of density. The vertical gradient of density over top 10 m (more than half of the water column) during 1991–2003 was significantly reduced in winter, spring and summer, while it looks to be increased during autumn. Coefficients of vertical mixing was likely increased during these three seasons [*Fischer et al.*, 1979], unless the vertical shear of

currents would decrease significantly. The eddy coefficients of the vertical exchange of momentum, heat and matter depend on gradient Richardson number [*Mellor and Yamada*, 1982; *Munk and Anderson*, 1948]. Reviews of different expressions for the vertical eddy coefficient K are also given elsewhere [*Henderson-Sellers*, 1984; *Zhang*, 1994], most of these expressions relate K with N^2 as $K \sim N^{-2q}$, where the bulk stratification frequency $N = [-(g/\rho_0)(\delta\rho/\delta z)]^{1/2}$ with $\delta\rho = \rho_0 - \rho_{10}$ the density difference between surface and the depth of 10 m, $\delta z = 10$ m and $g = 9.8$ m/s^2 and where $q = 1.0$ for cascading turbulence and equal to 0.5 for shear induced turbulence [*Welander*, 1968]. On an annual timescale, seasonal variations are mostly governed by the temperature signal [*Malačič*, 1991] due to solar radiation and it has been demonstrated by analyzing the data of temperature and salinity in the years 1986–1989 that K in the Gulf of Trieste could be expressed as a sum of a constant term and a term that is inversely proportional to the vertical gradient of temperature, which needs to be replaced by N^2. K varies at the surface, reaching a minimum of 1.7 10^{-4} m^2/s in summer, while near the bottom it is constant, around 2.5 10^{-4} m^2/s. It follows from Table 4 that during 1991–2003 the bulk buoyancy frequency during spring and summer changed in 10 years from about 0.05 s^{-1} to 0.02 s^{-1} (spring) or 0.03 s^{-1} (summer) while during autumn N increased from 0.04 s^{-1} to 0.05 s^{-1}. It remains an open question how mean vertical shear over a depth difference of 10 m follows N on a seasonal timescale. An increase of the vertical density gradient during autumn means a decrease of the vertical exchange of gasses and unless there is no important increase in the vertical shear of currents, events of bottom anoxia [*Malej and Malačič*, 1995] may become more persistent and more frequent.

[34] The present study does not make any predictions of variations of seasonal temperature and salinity in the shallow Gulf of Trieste in the future, nor does it explain the trends over the last decade. Interannual variations of seasonal temperature and salinity are influenced by many agents, such as the circulation of the Mediterranean [*Pinardi et al.*, 2003] and of the Adriatic Sea [*Zavatarelli and Pinardi*, 2003], where variations on a scale of several years were noticed. These variations also depend on interannual variations of atmospheric forcing and river inputs, which deserve a special study. Variations on a timescale of 3–5 years seem to be important, and a 10–13 year period merely covers two to a maximum of three periods of these oscillations that could hardly be filtered out properly in order to see any clear long-term trend within a decade.

Appendix A

[35] Suppose that we denote with y_i a dependent variable (e.g. a seasonal value of temperature), that was calculated as a mean value from the output of objective analysis of the data collected over the Gulf of Trieste at a certain depth interval within a particular season for a year x_i ($i = 1\ldots N$, N = 12 or 13, the number of pairs (x_i, y_i) in years 1991–2003). We will refer to y_i as a "measurement." We also have an estimate s_i^2 for the variance σ_i^2 of y_i. Let us take in the linear least squares procedure for the weight factors $w_i = 1/s_i^2$. One can show that the minimization of $\sum w_i(y_i - \alpha - \beta x_i)^2$ with respect to the expected ("true") parameters α and β, where the sum of terms is over an index $i = 1\ldots N$, leads to their estimates [*Press et al.*, 1992]

$$a = (SySxx - SxSxy)/\Delta, \quad b = (SSxy - SxSy)/\Delta, \tag{A1}$$

with $S = \sum w_i$, $Sx = \sum w_i x_i$, $S_y = \sum w_i y_i$, $Sxy = \sum w_i x_i y_i$ $Sxx = \sum w_i x_i^2$ and $\Delta = (S\ Sxx) - (Sx)^2$. The estimates a and b can be written in another form. One considers that $\Delta = \sum w_i \sum w_i (x_i - \bar{x})^2$ and that $SSxy - SxSy = \sum w_i \sum w_i (x_i - \bar{x})(y_i - \bar{y})$. By exposing S in the expression for b in (A1) and by adding and subtracting a term like $Sx\ Sy/S$ in the nominator and $(Sx)^2/S$ in the denominator one yields for a and b - the trend coefficient:

$$a = \bar{y} - b\bar{x}, \quad b = \sum w_i(x_i - \bar{x})(y_i - \bar{y}) \Big/ \sum w_i (x_i - \bar{x})^2, \tag{A2}$$

where $\bar{x} = Sx/S$, similar holds for $\bar{y}$. This form, usually without weights, is the one most recognized [*Draper and Smith*, 1998].

[36] The analysis of the propagation of uncertainties [*Dunn*, 2005; *Taylor*, 1997] shows that the standard error (or deviation) σ_a of parameter a depends on random deviations y_i from the expected value with a variance σ_i^2 and if they are independent from one i to another, then: $s_a^2 = \sum(\partial a/\partial y_i)^2\ s_i^2$, which also holds for s_b^2. It follows from the derivatives $\partial a/\partial y_i$ and $\partial b/\partial y_i$ of the estimates a and b that

$$s_a = \sqrt{Sxx/\Delta} \text{ and } s_b = \sqrt{S/\Delta}$$

[*Press et al.*, 1992], or written in another form

$$s_a = \sqrt{1 \Big/ \sum w_i + (\bar{x})^2 \Big/ \sum w_i (x_i - \bar{x})^2}$$
$$\text{and } s_b = 1 \Big/ \sqrt{\sum w_i (x_i - \bar{x})^2}, \tag{A3}$$

which is not that much applied, although correct. Caution needs to be shown because expressions from various sources differ with the definitions of weights: in NAG (Numerical Algorithms Group) they applied dimensionless weights as $w_i = \sigma^2/s_i^2$ (see routine g02cac at http://www.nag.co.uk/numeric/cl/manual/html/G02/g02_conts.html), where σ^2 denotes the (unknown) variance of y around the least squares solution, which is estimated with

$$s^2 = \sum (y_i - a - bx_i)^2/(N-2), \tag{A4}$$

where $N - 2$ is the number of degrees of freedom and where weights are actually $w_i = s^2/s_i^2$. NAG multiplied the terms inside the sum of (A4) with weights w_i. However, if $w_i = s^2/s_i^2$ then this change of (A4) leads to an erroneous result. In any case, applying $w_i = s^2/s_i^2$ in (A3) leads to similar forms:

$$s_a = s\sqrt{1 \Big/ \sum w_i + (\bar{x})^2 \Big/ \sum w_i (x_i - \bar{x})^2}$$
$$\text{and } s_b = s \Big/ \sqrt{\sum w_i (x_i - \bar{x})^2} \tag{A5}$$

that are "recognized" by NAG [*Draper and Smith*, 1998], as well as by the OriginLab corporation in their "Origin" software. Again, the form (A5) cannot be applied for $w_i = \sigma^2/s_i^2$ (or $w_i = s^2/s_i$), as one might wrongly conclude, with weights inside the sum of (A4). However, if weights represent frequencies of occurrence, or are based on some other criteria, then there are no problems. The expression (A3) can be considered as a more general one, without these difficulties. When weights are defined as $w_i = \sigma^2/s_i^2$ and when the variance of the data s_i^2 is not known (or is deliberately omitted as in our case), then for this UT analysis it is taken that $s_i^2 = s^2$, meaning that $w_i = 1/s^2$ which gives for s_a and s_b

$$s_a = s\sqrt{\sum x^2/\Delta} \text{ and } s_b = s\sqrt{N/\Delta} \tag{A6}$$

as written in *Taylor* [1997] and *Draper and Smith* [1998].

[37] The envelopes of the 95% confidence intervals around the linear best fit rely on the uncertainty $s(\hat{y})$ of the best fit value $\hat{y}$ around the true (or expected) mean, which is approximated by the overall mean $\bar{y}$. Both are related to each other by $\hat{y} = \bar{y} + b(x - \bar{x})$. Since it is supposed that the covariance between pairs of measured (dependent) quantities is zero: $\mathrm{cov}(y_i, y_j) = 0$ $(i \neq j)$, which also means that they are linearly independent, it can be shown that the covariance $\mathrm{cov}(\bar{y}, b) = 0$ [*Draper and Smith*, 1998]. It follows again from the theory of propagation of errors that the variance $s_{\hat{y}}{}^2$ is composed of two parts:

$$s_{\hat{y}}^2(x_0) = s_{\bar{y}}^2 + s_b^2(x_0 - \bar{x})^2 \tag{A7}$$

where the argument is held fixed $x = x_0$. The first part represents the uncertainty of the calculated average around the true average. The second part grows with the distance from $\bar{x}$ as $(x_0 - \bar{x})^2$, with a rate proportional to the uncertainty of the coefficient of trend, as expressed in (A3). Since $\bar{y} = Sy/S$, where only $Sy = \sum w_i y_i / \sum w_i$ is a function of y_i, it follows that the variance

$$s_{\bar{y}}^2 = \sum(\partial\bar{y}/\partial y_i)^2 s_i^2 = \sum(w_i/S)^2 s_i^2 = 1/S, \tag{A8}$$

in which $S = \sum 1/s_i^2$. This becomes a more familiar expression $s_{\bar{y}}{}^2 = s^2/N$ if individual deviations s_i are unknown and replaced with s from (A4) [*Taylor*, 1997]. Summing up squares of uncertainties in (A8) and (A3) in (A7) yields

$$s_{\hat{y}}(x_0) = \left[\frac{1}{S} + \frac{(x_0 - \bar{x})^2}{\sum w_i(x_i - \bar{x})^2}\right]^{1/2}, \tag{A9}$$

where, similar to (A5), the right-hand side of the expression (A9) is multiplied by s if the weights $w_i = s^2/s_i^2$ are considered (as in NAG). If again, $s_i = s$ from (A4), then a familiar result for the UT analysis follows

$$s_{\hat{y}}(x_0) = s\left[\frac{1}{N} + \frac{(x_0 - \bar{x})^2}{\sum(x_i - \bar{x})^2}\right]^{1/2}. \tag{A10}$$

The envelopes of the 95% confidence limits in trend analysis with the linear best fit rely on the Student-t probability distribution of quantities around their best fit values [*Draper and Smith*, 1998]. While (A10) represents the "standard error" (notation for the estimate of the standard deviation) of the predicted mean value of fit for a given x_0, the individual observation y_i varies about the true mean value (estimated by $\hat{y}$) with a variance σ_i^2, estimated by s_i^2, that is independent of $s_{\hat{y}}{}^2$. Therefore, the "total" variance of the individual observation y_i is composed of a sum of $s_i^2 + s_{\hat{y}}{}^2$ and its standard error is

$$\left[s_i^2 + \frac{1}{S} + \frac{(x_0 - \bar{x})^2}{\sum w_i(x_i - \bar{x})^2}\right]^{1/2}. \tag{A11}$$

If individual variances s_i^2 would be unknown (or deliberately forgotten) and would again be replaced by s^2 (UT analysis) from (A4), then the variance of individual (or future) measurement yields as [*Draper and Smith*, 1998; *Dunn*, 2005]

$$s\left[1 + \frac{1}{N} + \frac{(x_0 - \bar{x})^2}{\sum(x_i - \bar{x})^2}\right]^{1/2}. \tag{A12}$$

Expressions (A11) and (A12) form a hyperbolic dependence of the standard error on $(x_0 - \bar{x})$. The symmetric student-t distribution $t(N - 2, 1 - \alpha/2)$, where $N - 2$ is the number of degrees of freedom, rules the probability (of $1 - \alpha = 95\%$), for which the estimated value differs from the true value for t standard errors. Therefore, one gets the 95% confidence intervals for mean $\hat{y}$ with $s_{\hat{y}}$ from (A9) or (A10) by

$$\hat{y}_0 \pm t(N - 2, 1.975)s_{\hat{y}}. \tag{A13}$$

Confidence intervals for individual measurement y_i are obtained by replacing $s_{\hat{y}}$ in (A13) by (A11) or (A12). From the Student-t distribution $t(N - 2{,}1.975)$ acts as a constant value in the cases here considered, being either 2.201 (N = 12) or 2.228 (N = 13).

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