Sea-level changes and crustal movements recorded along the east Adriatic coast

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Summary. — Sea-level changes in the Adriatic are investigated on the basis of monthly mean sea levels registered at Croatian tide-gauge stations Rovinj, Bakar, Split and Dubrovnik since the beginning of the 1950s. A comparison of sea-level anomalies with air-pressure anomalies recorded simultaneously at Pula, Rijeka, Split and Dubrovnik reveals a statistically significant relationship: a 1 mbar air-pressure change corresponds to a 1.8–2.0 cm sea-level change. The relationship enables sea-level anomalies to be corrected and, consequently, long term sea-level changes to be determined more reliably. A 20-year cycle observed in both the uncorrected and corrected anomalies is interpreted in terms of the global bidecadal signal and its regional manifestation in the Mediterranean. In order to minimize the effects of the bidecadal cycle, trends are analysed over a 30-year sliding window. The procedure reveals that the trends vary along the Croatian coast from ca. 1 mm/a in the North to zero in the South, with deceleration being visible at all the stations during the early 1970s. The finding is interpreted in terms of a) global sea-level rise, b) regional multidecadal sea-level variability, and c) local tectonic movements. Multidecadal sea-level changes are believed to be related to the natural variations observed in the atmosphere above Europe and/or to the anthropogenic changes of the Mediterranean freshwater budget. Tectonic movements bring about a rising of the middle and south Adriatic coast relatively to the north Adriatic coast at a 1 mm/a speed, with the Bakar area being characterized by anomalous crustal motions.

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1. – Introduction

Sea-level rise, which may be expected due to the increased atmospheric concentration of greenhouse gases and related warming of the Earth, became a major subject of concern over the last ten years or so. The first predictions were catastrophic, putting the rise over the 21st century in the 56–345 cm range [1]. Subsequent research has led to a considerable reduction of these values: according to the most recent assessment, prepared by the Intergovernmental Panel of Climate Change, the sea level is projected to be about 50 cm higher than today by the year 2100, with a range of uncertainty of 20–86 cm [2].

Concern over the future has helped to focus the interest of researchers on the past sea-level changes, as they are documented by tide-gauge records. Presently, there is some consensus that the global sea level has risen by between 10 and 25 cm over the past century, mostly due to thermal expansion of sea water and melting of low latitude glaciers [2]. The consensus had to be reached in the face of considerable year-to-year and interdecadal sea-level variability as well as of land movements which are well known to influence relative tide-gauge measurements. Low-frequency sea-level variations and crustal movements may be of the regional, or even local spatial scale, implying that analyses of global sea-level changes have to rely on a number of regional and local studies.

This paper concentrates on relative sea-level variability recorded along the east Adriatic coast. In the second section tide-gauge measurements, performed since the beginning of the 1950s at four Croatian stations distributed along the coast, are presented. The third section focuses on year-to-year variability and its relationship with the meteorological forcing. The results obtained are used to improve an analysis of long-term changes in the fourth section, and in particular to diagnose relative land movements along the Croatian coast. All the findings are summarized and their relevance for a prompt response to the future sea-level changes in the Adriatic is underlined in the final, fifth section.

2. – Data

The present analysis of sea-level changes is based on data collected at Croatian stations which have records extending over at least forty years: Rovinj (1955-), Bakar (1929-1939, 1949-), Split (harbour, 1929-1941, 1954-) and Dubrovnik (1954-). As has been shown recently, in the Mediterranean a record length of at least thirty years is needed in order to compute the sea-level trends with a standard deviation of not more than 0.5 mm/a [3]. Station sites considered in this paper are shown in fig. 1. It is obvious that the Croatian tide gauges form a rather dense network, the densest that could be found in the Mediterranean [3]. Geological [4] and seismological [5] information suggests that the network resolution is adequate for an analysis of crustal movements in the area. At all the network sites float operated tide gauges have been installed and are still in use. Elevation of contact marks above tide-gauge data has been regularly checked, and stability of local bench marks has been periodically controlled. It is estimated that the accuracy of a single, hourly measurement of the sea-surface height equals ± 1 cm. From original values monthly means are computed. The procedure reduces measurement-related errors, but at the same time aliases high-frequency signals (tides, storm surges, seiches ...), which in the Adriatic have typical amplitudes of $O(10\ \mathrm{cm})$, into the monthly data set [6]. Consequently, the accuracy of a monthly mean value is not better than about ± 1 mm.

The monthly mean data have been checked by comparing each station record to a few of its neighbours. This revealed sporadic problems with the data (Rovinj: February-March 1958; Bakar: January-March 1951, February 1983; Split: different datum levels before and after World War II). Moreover, there are breaks in the data records. Thus, the December 1995 value is missing for Rovinj, and measurements were occasionally interrupted at Dubrovnik (in 1954 and 1955, as well as during the heaviest

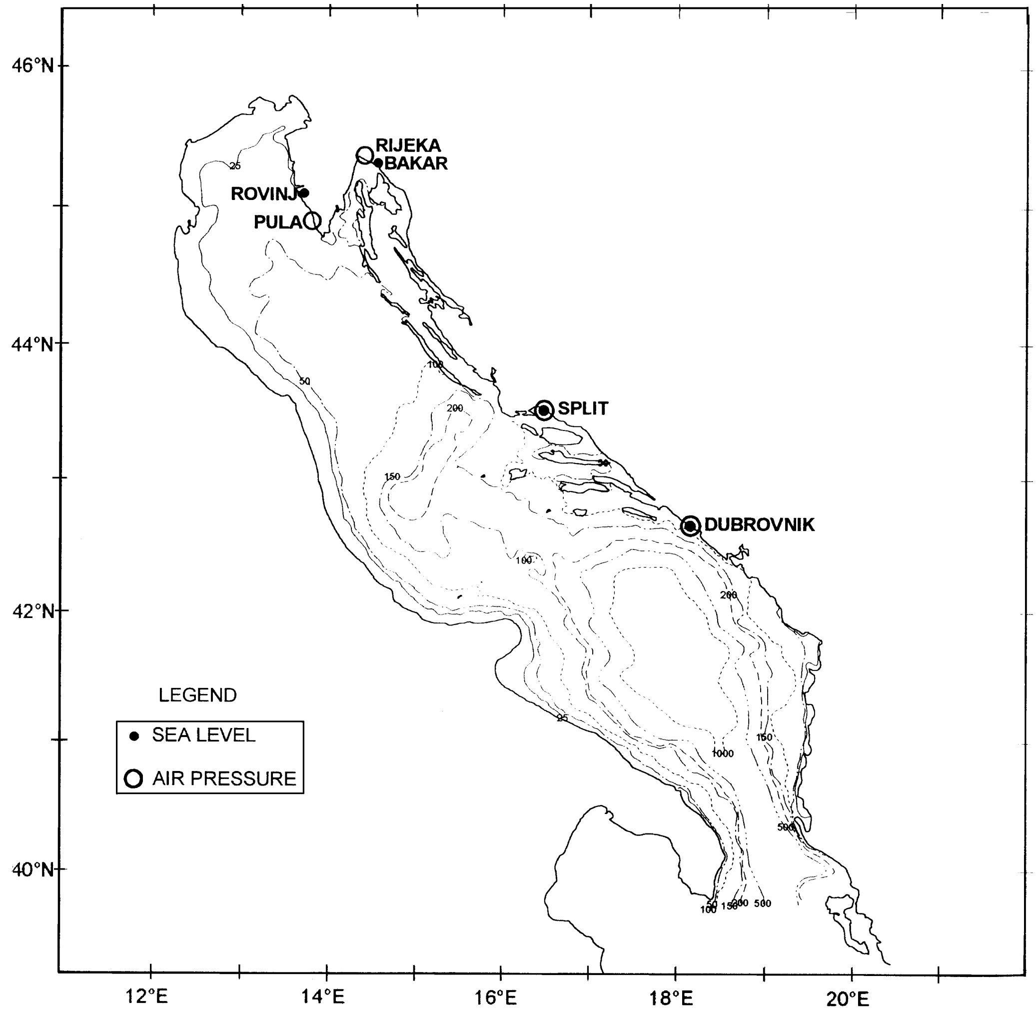

Fig. 1. – Locations of sea-level and air-pressure measuring stations along Croatian coast of the Adriatic Sea.

attacks on this town, between November 1991 and February 1992). Accordingly, input data for the present research were monthly mean sea levels, recorded at Rovinj (June 1955-December 1995), Bakar (April 1951-December 1995), Split (March 1954-December 1995) and Dubrovnik (January 1956-December 1995), with the erroneous or missing values being replaced by using the neighbouring station records (correlation coefficients varied between 0.96 and 0.98, and were significant at the 99% level). Almost all of the original data were previously published in Croatia [7], and were archived by the Permanent Service for Mean Sea Level [8].

For the present investigation air-pressure data, collected in the vicinity of tide gauges simultaneously with sea-level measurements, were also needed. Air pressures, registered at stations Pula, Rijeka, Split and Dubrovnik (fig. 1), were reduced to the mean sea level and were averaged over 1-month intervals. Errors detected by "buddy checking" at Pula (October 1960) and Split (February 1955, December 1995), as well as missing values at Pula (January 1991-October 1992), were bridged by regressing useful data on those collected on neighbouring stations (correlation coefficients in this case surpassed 0.98, being significant at the 99% level).

3. – Fluctuations of sea level

Time series of monthly mean sea levels recorded at Rovinj, Bakar, Split and Dubrovnik show a considerable year-to-year variability. As sea levels at all the stations are fluctuating almost in unison, we have submitted the four time series to Principal Component Analysis (PCA) and have used the first principal component to illustrate the variability (fig. 2). The corresponding eigenvector, determined from the covariance matrix, has components which vary from 0.47 (Dubrovnik) to 0.53 (Bakar), *i.e.* are close to the theoretical value due to a signal having equal strength at four stations. The leading mode accounts for 96% of the total variance. Figure 2 also shows average seasonal course of the first principal component, computed over the 1956-1995 interval and drawn for each year, together with the corresponding standard deviations.

As is already well known [9-13], the Adriatic sea levels are typically low in late winter or early spring, high in late autumn. The average range of the annual cycle amounts to about 10 cm (fig. 2). Theoretical analyses indicate that the seasonal sea-level variability may depend on the air-pressure and wind forcing [14] and on both the isostatic and nonisostatic buoyancy-flux effects [15]. The relative importance of the various forcing mechanisms has yet to be estimated for the Adriatic.

Here, departures of monthly mean values from the 40-year averages—*i.e.* anomalies—are of primary interest. Figure 2 shows that there is no regularity in the occurrence of significant anomalies: sometimes the anomalies of different sign follow each other, on other occasions similar anomalies may persist for years. An example of the latter case is a sequence of anomalously low sea levels, recorded between winters 1988/1989 and 1992/1993. Lowering of the winter 1988/1989 sea level was reported for some other parts of the Mediterranean Sea as well [16].

Previous studies indicate that the Adriatic sea-level anomalies may be related to the corresponding air-pressure anomalies [17-19]. In order to check the relationship, we have performed PCA on the monthly mean air pressures recorded at Pula, Rijeka, Split and Dubrovnik. The first mode explains 98% of the observed variance, its eigenvector components vary from 0.46 (Dubrovnik) to 0.53 (Pula), and thus the first principal component, shown in fig. 3, is representative of the air-pressure variability above the Adriatic over the last forty years. Comparison of figs. 2 and 3 reveals that the average seasonal course of sea level is not controlled by air pressure. However, sea-level anomalies obviously mirror air-pressure anomalies. In particular, during five consecutive winters, beginning with 1988/1989, air pressure was anomalously high above the Adriatic, which lowered the sea level.

Significant air-pressure anomalies usually extend over a wide area. Thus, for example, during winter 1988/1989 high air pressure was observed over the whole of Europe and Mediterranean Sea, with the 500 mbar surface being in January up to 200 gp m higher than is usual for this part of the year [17]. Climatological data for the four subsequent winters showed that similar anticyclonic disturbances repeatedly occurred over Europe [20]. How can the persistent occurrence of winter anticyclones above Europe be explained? Meteorological analyses suggest that the atmosphere

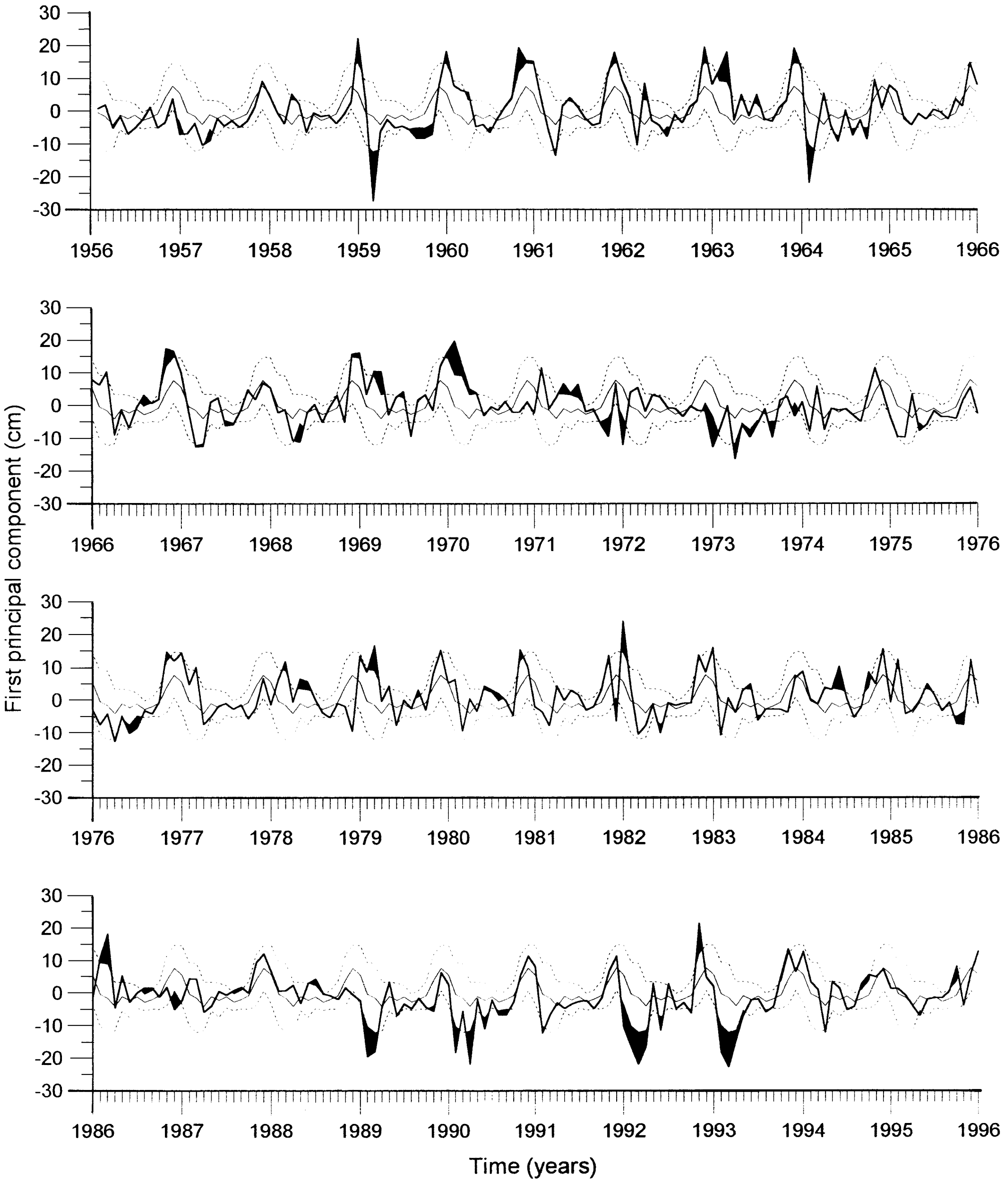

Fig. 2. – The first principal component (thick solid line), determined from monthly mean tide-gauge records originating from Rovinj, Bakar, Split and Dubrovnik, and scaled to give sea levels in real units (cm). Also shown is the seasonal course of the component (thin solid line), averaged over the 1956-1995 interval and drawn for each year, together with the corresponding standard deviations (dashed lines). Significant anomalies are shaded.

above Europe may be sensitive to sea surface temperature variability, both in the North-West Atlantic [21] and equatorial Pacific [22, 23]. It appears that colder-than-usual surface waters in these areas tend to be associated with positive geopotential

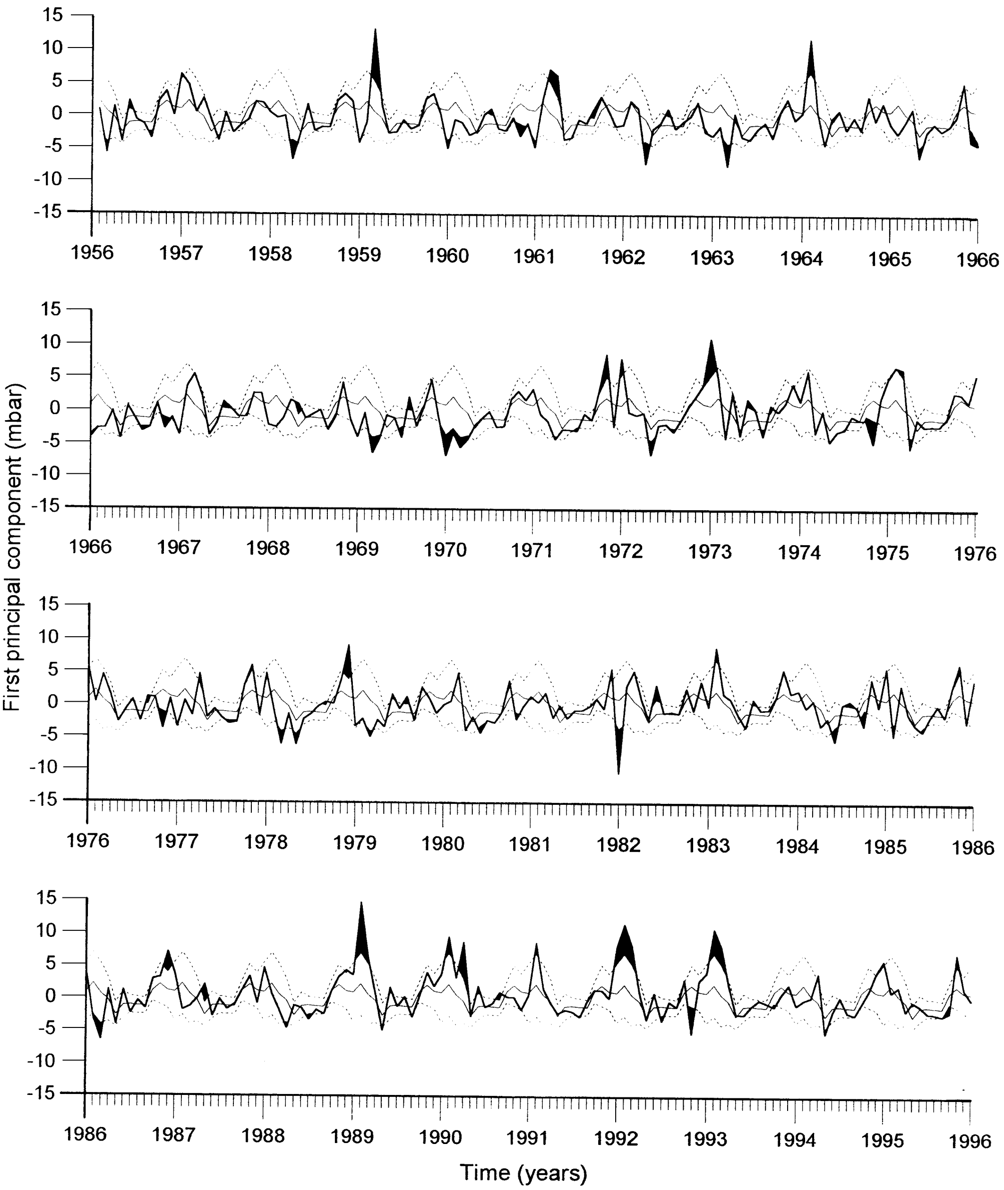

Fig. 3. – The first principal component (thick solid line), determined from monthly mean barograph records originating from Pula, Rijeka, Split and Dubrovnik, and scaled to give air pressures in real units (mbar). Also shown is the seasonal course of the component (thin solid line), averaged over the 1956-1995 interval and drawn for each year, together with the corresponding standard deviations (dashed lines). Significant anomalies are shaded.

height anomalies over Europe. The winter situations singled out here indicate that the European climatic conditions are influenced more by the Atlantic than the Pacific sea surface temperatures [20], but also show that geopotential height anomalies predicted

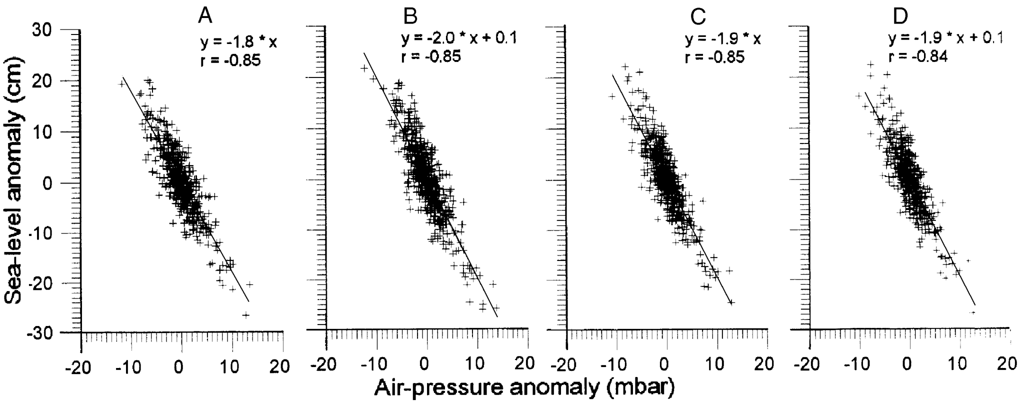

Fig. 4. – Result of the correlation and regression analysis of air-pressure anomalies recorded at Pula (A), Rijeka (B), Split (C) and Dubrovnik (D), and sea-level anomalies registered at Rovinj (A), Bakar (B), Split (C) and Dubrovnik (D). The intervals covered by the data are given in the text.

from the former temperatures [20, 21] underestimate the observed values [17]—as has been observed before [24]. Thus, there are a number of open questions regarding climatic fluctuations [25], but it is firmly established that those occurring over Europe influence the sea level of the Adriatic and Mediterranean Seas.

Visual inspection of figs. 2 and 3 suggests that sea-level and air-pressure anomalies could be correlated and regressed one on the other. It has been found that the maximum correlation coefficient (– 0.86, significant at the 99% level) is obtained with a zero time lag between the anomalies. Regression analysis has led to a somewhat surprising result: a 1.0 mbar increase (decrease) of air pressure corresponds to a 1.9 cm lowering (rising) of sea level. In order to check this finding and to allow for possibly different response of sea level at various stations to air-pressure forcing, we have repeated the correlation and regression analysis for each meteorological/oceanographic station pair (Pula-Rovinj, Rijeka-Bakar, Split, Dubrovnik). The results, shown in fig. 4, confirm the inverted-barometer overshoot documented previously by mode-to-mode analysis. There are two possible interpretations of the finding: either there is a resonant transfer of energy from the atmosphere to the Adriatic Sea, or the sea level responds not only to air pressure but to some other forcing agent (*e.g.*, wind) coherent with it. The first possibility may probably be ruled out, as at the large temporal scales considered, with the low phase speeds involved, coupling of the atmosphere and Mediterranean Sea should be off-resonant [26]. The second possibility deserves a serious consideration, as low (high) air pressure above the Adriatic is usually associated with the southern (northern) winds, and thus both meteorological agents contribute to the rising (lowering) of sea level. However, we shall not probe this possibility further here, because long time series of wind stress, which would be needed for a multiple correlation and regression analysis, are not available, and numerical simulations involving both the air pressure and wind forcing of the Mediterranean and Adriatic are beyond the scope of the present paper. Although not useful for testing theoretical models, the regression considered may still be used for diagnostic and prognostic purposes. In particular, we shall use the obtained relationships to correct sea level for year-to-year atmospheric forcing, and thus to eliminate possible local meteorological influences on sea-level changes.

4. – Sea-level changes

The sea-level trend can in the simplest way be determined by performing a linear least-squares fit on the annual mean values computed from a tide-gauge record. Such a procedure leaves, however, many problems open. Thus, the trend may be contaminated by meteorologically induced variability. Moreover, it could depend on the length of the sea-level record, *i.e.* may be influenced by a nonlinear process. Consequently, we opt here for a somewhat different approach.

Let us model the monthly mean sea level Z at a particular station as

$$Z(t) = a[P(t) - G_P(t)] + G_Z(t) + R_Z(t)\,, \tag{1}$$

where P is the monthly mean air pressure at the station, G is the monthly sea level or air pressure averaged over the forty-odd years, a is the regression coefficient determined in the previous section (ranging from 1.8 cm/mbar at Rovinj, via 1.9 cm/mbar at Split and Dubrovnik, to 2.0 cm/mbar at Bakar), whereas R is a residual value. Denoting by $\langle\ \rangle$ a low-pass filter, the simplest version of which is a 12-month moving average, we can compute the smoothed sea-level anomaly as

$$\langle Z(t) - G_Z(t)\rangle = a\langle P(t) - G_P(t)\rangle + \langle R_Z(t)\rangle\,. \tag{2}$$

Such an anomaly may be controlled by local meteorological processes (captured by the first term on the r.h.s. of (2)) but also by regional atmospheric variability unrelated to the local air pressure, isostatic and nonisostatic buoyancy-driven phenomena, pole and nodal tides, global sea-level rise, crustal movements, and, of course, measurement errors (all of which are represented by the second term on the r.h.s. of (2)). Alternatively, we may compute the smoothed and corrected sea-level anomaly as follows:

$$\langle Z(t) - G_Z(t)\rangle - a\langle P(t) - G_P(t)\rangle = \langle R_Z(t)\rangle\,. \tag{3}$$

In the remainder of this section both uncorrected and corrected anomalies, defined by (2) and (3), respectively, will be described and used to analyse the sea-level trends.

Figure 5 shows the two types of anomalies for the Croatian tide-gauge stations. Obviously, the removal of local meteorological effects considerably reduces variance (by between 53 and 67%). In the time series thus obtained a rather weak pole tide (of about 14 month period) may be observed. More important is an oscillation having a 20-year period. It has already been observed in the Adriatic, at Trieste [27, 28] and Bakar [18] stations. The oscillation does not represent the nodal tide: by fitting a cosine series with a period of 20a to the smoothed and corrected sea-level anomalies of fig. 5, we have obtained the amplitude (~ 2 cm) and peak years (around 1963 and 1983) which depart significantly from theoretical values for the equilibrium nodal tide [29]. On the other hand, the oscillation may be related to the bidecadal signal which has been observed globally and which manifested itself in the Mediterranean area in the low air pressure [30-32] that occurred in the early 1960s and 1980s simultaneously with the high air [30, 33, 34] and sea surface [31, 32, 35] temperatures; moreover, low salinity was recorded in the East Mediterranean in the beginning of 1980s [36]. All the factors conspired to rise the Mediterranean and Adriatic sea level at the time. Consequently, the bidecadal cycle visible in both the uncorrected and corrected time series of fig. 5

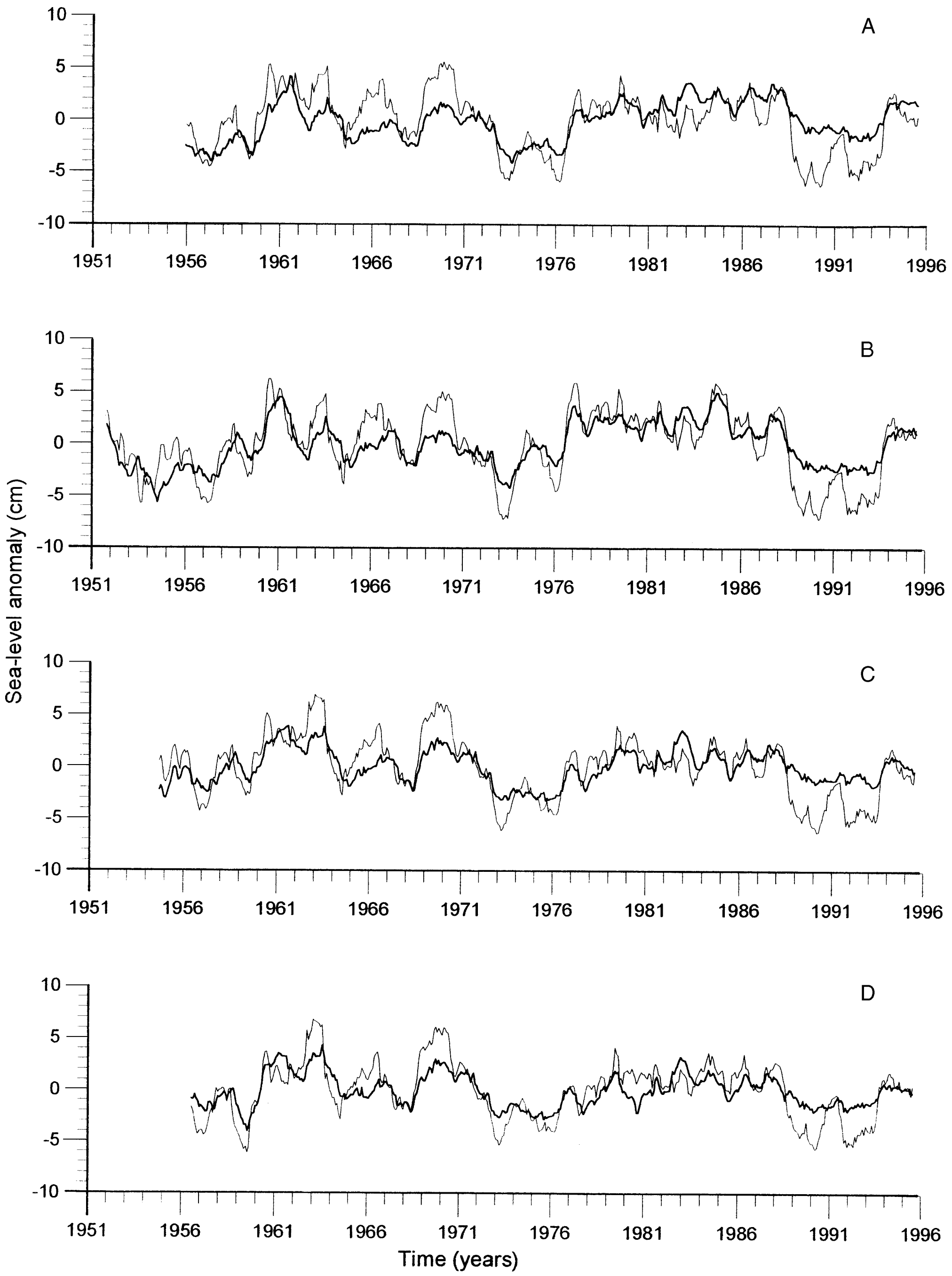

Fig. 5. – Sea-level anomalies for Rovinj (A), Bakar (B), Split (C) and Dubrovnik (D), smoothed by 12-month moving average (thin line), and after being corrected for the local meteorological effect (thick line).

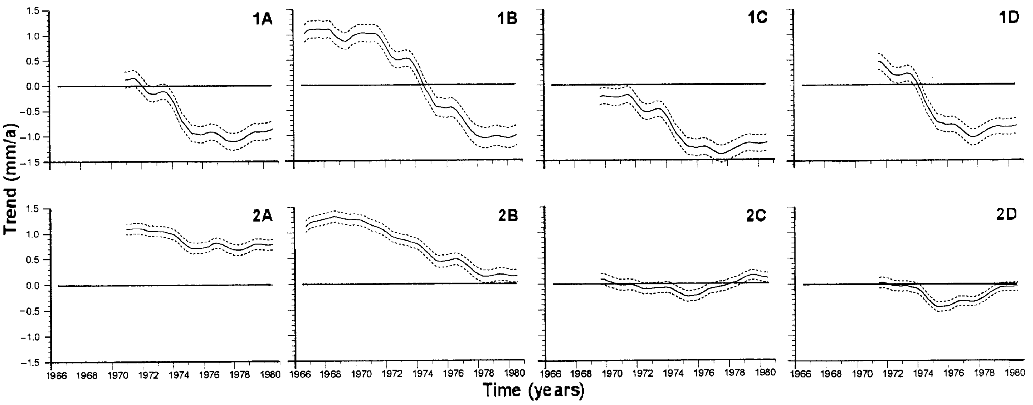

Fig. 6. – Trends and corresponding standard errors, determined by regression analysis over a 30-year sliding window and attributed to the median year. The analysis was performed on smoothed sea-level anomalies originating from Rovinj (A), Bakar (B), Split (C) and Dubrovnik (D), without (1) and after (2) correcting for the local meteorological effect.

may be attributed partly to the air pressure (and possibly wind) forcing and partly to the steric influence and related nonisostatic water-flux effect, which in turn represent regional manifestations of the global bidecadal signal.

Possible nonlinearities in the time series have been allowed for by computing sea-level trends over various sliding windows. Results for 10-year spans were considerably influenced by the bidecadal oscillation just described. On the other hand, the 30-year sliding window provided results more amenable to interpretation. Figure 6 shows trends and corresponding standard errors, computed from uncorrected and corrected smoothed anomalies originating from Rovinj, Bakar, Split and Dubrovnik stations. A simple analysis, performed on a synthetic time series comprising oscillation of the 20-year period and observed amplitude, showed that even the trends computed over the 30-year sliding window may be contaminated by the bidecadal oscillation, but also indicated—in accordance with a previous finding [3]—that the incured error does not surpass ± 0.2 mm/a and that it is thus similar to the standard errors marked in the figure. The regression coefficients determined from uncorrected anomalies (first row in fig. 6) agree reasonably well with the trends already published for the Croatian coast [37-40], if the time intervals for which trends were previously determined are taken into account. Moreover, the deceleration visible in the figure resembles findings from some other Mediterranean stations possessing longer tide-gauge records [41, 42]. By least-squares fitting a second-degree polynomial to uncorrected anomalies we have obtained accelerations ranging from -0.04 mm/a^2 (Rovinj, Split) via -0.06 mm/a^2 (Dubrovnik) to -0.09 mm/a^2 (Bakar). The fit is marginally better than a simple linear approximation to the data.

From the limited time series available one cannot decide whether the deceleration observed is due to changing trends or is related to oscillations whose periods are significant in comparison to, or longer than, the data span. The removal of local meteorological effects reduces the variability of regression coefficients and standard errors (second row of fig. 6), implying that the deceleration may at least partly be attributed to the local atmospheric forcing. Yet, even in the corrected relative sea-surface speeds the deceleration remains visible at all the stations during the early 1970s. While this may be due to the multidecadal thermal variations observed in the North Atlantic and at the surrounding meteorological stations [43], it is tempting to connect it also to anthropogenic control of major rivers feeding the East Mediterranean, control which culminated in 1964 when the Aswan Dam was completed [44]. Man-induced reduction of freshwater input into the Mediterranean brought about changes of the thermohaline properties and circulation in the area (see [45], and references cited therein), and could be responsible for the lowering of sea surface throughout the region.

The trends of fig. 6 show considerable variability between the four stations considered. In order to present the local variability as clearly as possible, we have computed trend differences for all the possible station pairs and have displayed them in fig. 7. Uncorrected values do not show a consistent pattern. Corrected values, however, suggest that over the last forty-odd years the middle and south Adriatic coast (Split, Dubrovnik) was rising relatively to the north Adriatic coast (Rovinj) at a 1 mm/a speed (lower left part of fig. 7). As the postglacial isostatic submergence in the area occurs with an almost uniform speed (ca. 0.4 mm/a [46]), the spatial variability should be ascribed to local tectonic movements. Geological and seismological data support the conclusion: it has been found that the Adriatic Platform rotates around a point in its northern part while colliding with the Dinarides [4] and that consequently vertical crustal displacements are greater and accompanied by stronger and more frequent earthquakes in the middle and south Adriatic than in the north Adriatic [5]. Tide-gauge data indicate that speed of the north-south tilting of the Croatian coast is of

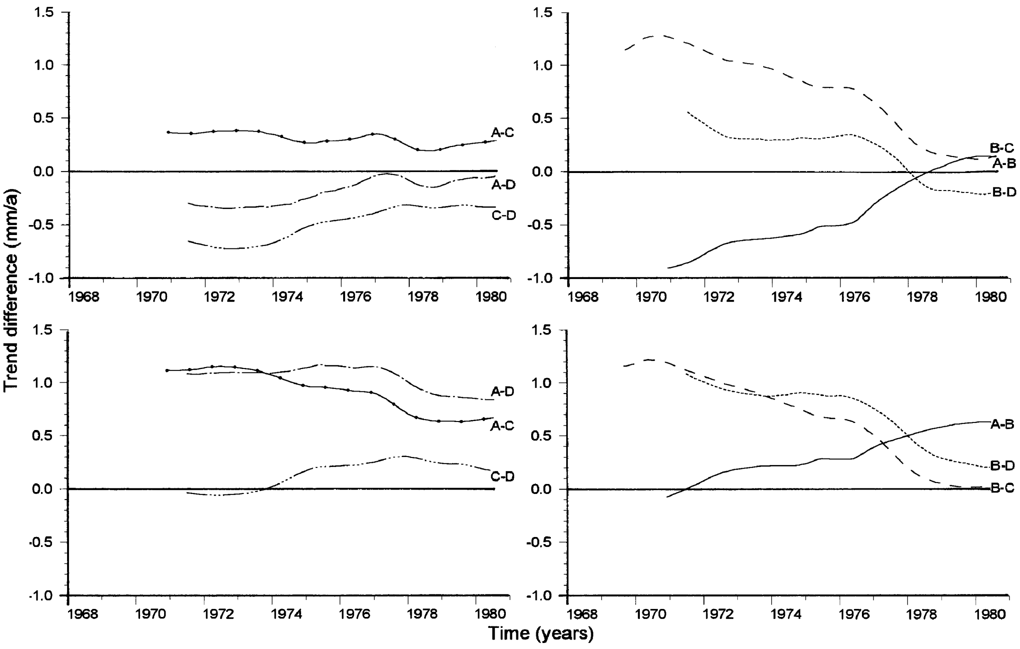

Fig. 7. – Differences of trends shown in fig. 6, computed for all possible pairs of stations Rovinj (A), Bakar (B), Split (C) and Dubrovnik (D), without (top) and after (bottom) correcting for the local meteorological effect.

$O(1\ \text{mm/a})$—a quantification which may be of some interest to other geoscientists investigating the phenomenon.

The lower right part of fig. 7 shows that the Bakar area departs from the simple dynamics just described: the local crustal movements accelerated upwards during the interval over which tide-gauge measurements were performed at Bakar. There is at least one further indication that there is something special about Bakar: it has been observed that the depths of tidal notches are two times greater in the vicinity of Bakar than farther away [47]. The finding has been interpreted in terms of greater submergence of the Bakar area over the last few thousand years. Whereas more recent crustal movements give origin to a local decrease of the relative sea-level rise, they are obviously as limited in space as were earlier vertical motions. We hypothesize that tide-gauge measurements have documented the start of a crustal lift which represents a relaxation after the previous intensive submergence of the Bakar surroundings.

5. – Conclusion

The results of the previous section show that the Croatian tide-gauge records contain no evidence as yet for any acceleration related to the greenhouse effect. This, however, is hardly surprising, bearing in mind the enormous inertia of the atmosphere-sea system and consequently the small accelerations observed up to now worldwide. Without providing original findings on the problem of global sea-level rise, the present analysis has led to several useful conclusions regarding regional and local variability observed since the 1950s. Year-to-year fluctuations of the Adriatic sea level could be correlated with the simultaneous variations of air pressure, a 1 mbar increase (decrease) of atmospheric pressure resulting in a 1.8–2.0 cm lowering (rising) of sea surface. The 20-year cycle observed in the Adriatic has been interpreted in terms of the global bidecadal signal and its regional manifestation in the Mediterranean. Tectonic processes have been found to bring about a rising of the middle and south Adriatic coast relatively to the north Adriatic coast at a 1 mm/a speed, with the Bakar area being characterized by anomalous crustal movements. Finally, multidecadal variability of the Adriatic sea surface has been related to the natural variations observed in the atmosphere above Europe and/or to the anthropogenic changes of the Mediterranean freshwater budget.

Probably, the most important finding is the one on relative crustal movements along the east Adriatic coast, as it appears that for the first time both the direction and speed of these movements have been diagnosed. The finding has been made possible by the continuous operation of the rather dense network of Croatian tide gauges over more than forty years, a feat unparalleled in the Mediterranean. The results suffer from the land-sea level ambiguity in the tide-gauge records, as do all the findings based on tide-gauge measurements alone. It is to be hoped that the ambiguity will be resolved through novel geodetic measurements which are presently initiated along the east Adriatic coast.

The tide-gauge network established in the east Adriatic may prove to be even more useful in the future. Although the present relative sea-level trends vary along the Croatian coast from 1 mm/a in the North to zero in the South, and are thus far smaller than trends observed at some Italian stations in the Adriatic Sea [48, 49], the predicted 50 cm global rise over the next century would be troublesome to the coastal population. As in the Adriatic the rise may be further amplified by regional and local variability, the results already obtained and their future improvements—based on the continuous, possibly modernized, tide-gauge measurements—appear to be necessary for adequately planning the development of the Croatian coastal area.

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