Lecture O10. Forcing of sea level variability

1. Land movements

Glacio- isostatic rebound

Tide-gauges are located on land and land moves. Land moves for various reasons. It can be due to local subsidence, a common problem at deltas and estuaries, or it can be due to recent or past ice-sheet melting. For example, during the last ice-age (about 18,000 years ago), sea level was about 130 m lower. The removal of such a great mass from the ice-sheets meant that the earth's crust started moving upwards rebounding from the weight of the ice. This is still seen in parts of the globe, the Scandinavian peninsula, the northern part of the UK and that of Canada being prime examples. In the Scandinavian peninsula, maximum rates of land rise in excess of 10 mm/yr are known to exist. Far from the area where the ice mass was located, the land moves as an adjustment to these processes, although the rates are much less; for example, in the Mediterranean are less than 0.5 mm/yr. Of course, tectonic movements or ground water extraction can also lead to land moving.

The GIA effect has been modelled by various models. The output of one model (ICE-4G VM2) model is shown below (Peltier, 2002).

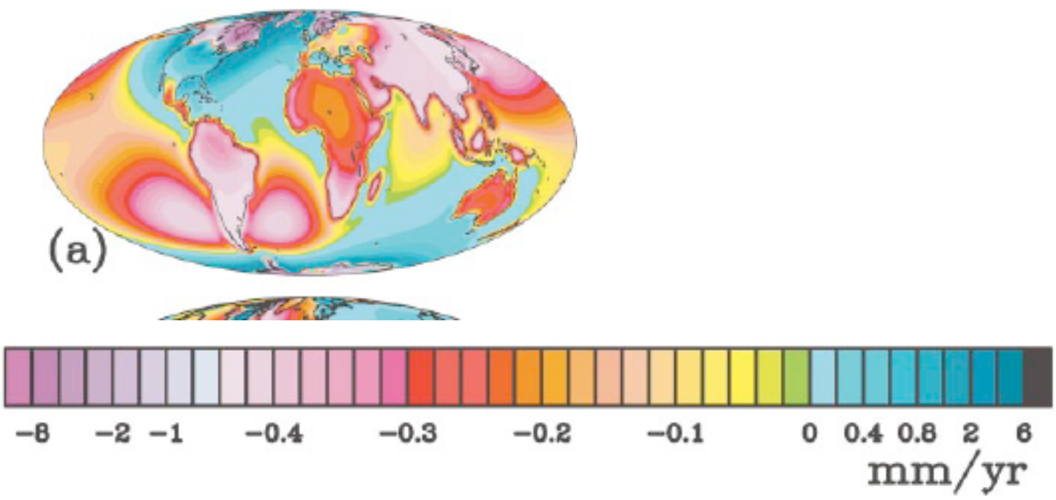


Figure 8 ICE-4G (VM2) model prediction of (*a*) the present-day rate of sea-level rise relative to the deforming surface of the solid Earth, including the influence of rotational feedback; (*b*) same as (*a*) but excluding the influence of rotational feedback; (*c*) the difference

Apart from the global response to ice melting after the last glacial maximum, local effects in the areas near the Alps have been demonstrated. Thus, the southern parts of France have been claimed to experience an upward land movement of between 0.1 and 0.3 mm/yr (Stocchi et al., 2005).

Tectonic movements

The Mediterranean Sea is the place where the African and Eurasian plates collide. This causes significant tectonic movements and, or course, earthquakes. Assessing how much sea level changes due to these processes is again based on earth models. (see, for example, Di Donato et al., 1999).

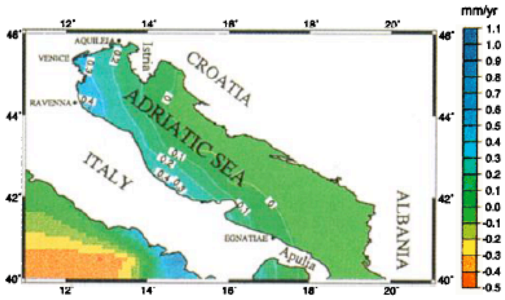


Figure 3. Present-day rate of sea-level change due to active tectonics in the Adriatic.

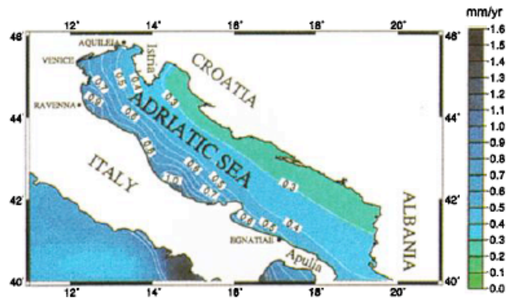


Figure 5. Present-day rate of sea-level change due to GIA and active tectonics.

Water extraction and local subsidence due to it, as well as sediment compaction, is also known to apply to various areas, in particular Venice and the Nile.

Thus, when sea level is measured by a tide-gauge, the measurement is relative to the (local) land sea level rise. As concerns coastal protection, we want to make forecasts and we need to assess how much of this movement is due to the land movement and how much is due to oceanic processes.

An alternative option is to measure directly the land movements by use of GPS analyses. Such an attempt has recently been published (Wöppelman et al., 2007). It appears that around 0.5 mm/yr globally can be attributed to land movements, while around 0.3 mm/yr were found for Marseille and Genova.

2. Direct meteorological forcing

Atmospheric forcing in the form of atmospheric pressure changes and wind can significantly affect sea level. The changes of atmospheric pressure are approximated by the inverse barometer correction (IBC). If the atmospheric pressure changes from P1 to P2 at a place and the atmospheric pressure remains steady elsewhere, then sea level will change by $IBC = -1/\rho g(P2 - P1)$, where ρ is sea water density and g gravity. This results in approximately -1 cm / mbar change.

However, in the Mediterranean Sea, the IBC does not hold for fast changes, because the Strait of Gibraltar constrains such exchanges. Garrett and Majaess (1982) demonstrated the phenomenon in the Mediterranean first. Thus, for pressure signal with period less than 10 days, the Mediterranean Sea does not respond isostatically.

The wind setup can also be estimated empirically and this can be approximated by $n= 0.03*f/g*W_{shelf}*U_{longshore\text{-}wind}$ (Sandstrom, 1980).

Presently storm models provide operational information on directly forced sea level. The output of HIPOCAS and MOG2d are two options presently available in the Mediterranean Sea.

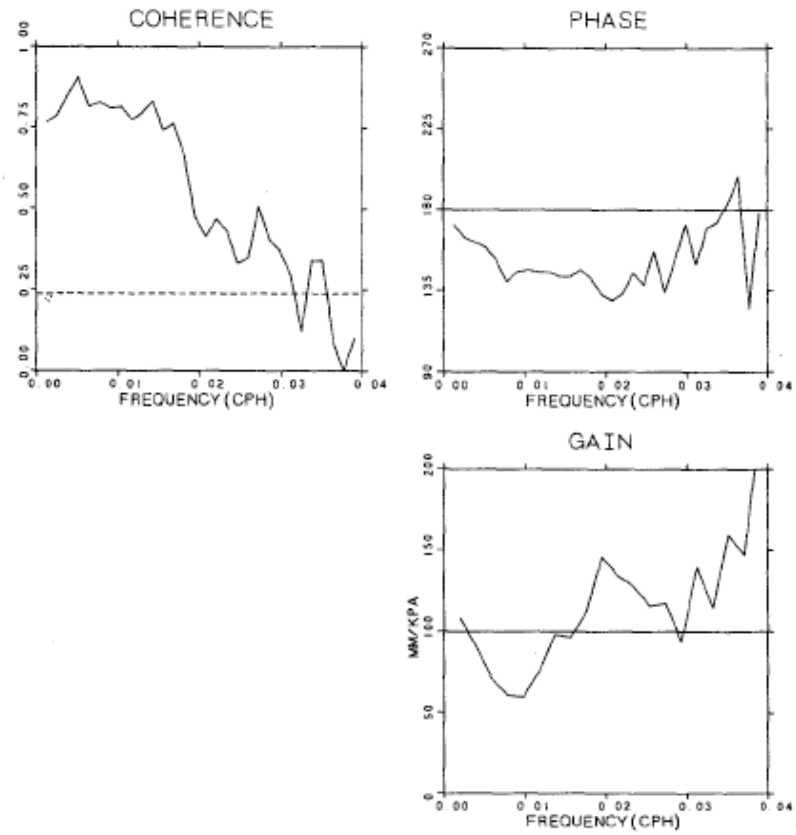
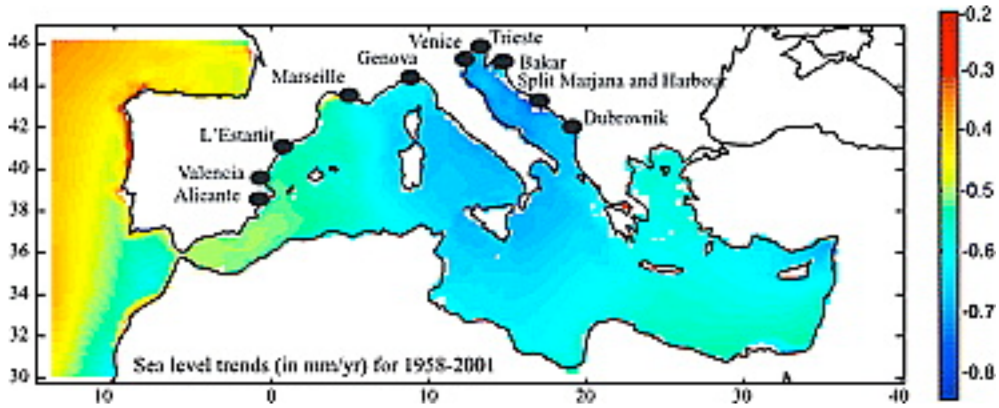


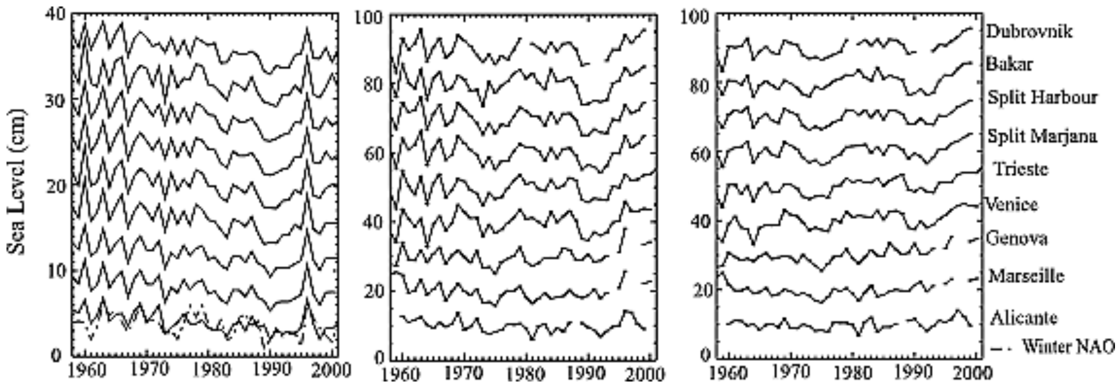
FIG. 6. Coherence, phase, in degrees, and gain for Katakolon sea level and Andravidha atmospheric pressure. The dashed line indicates the level above which the coherence is significant at the 95% confidence level. A Phase less than 180° corresponds to a lag of minus sea level behind atmospheric pressure.

Atmospheric pressure has been the dominant parameter of sea level variability in the Mediterranean Sea over the last few years. The trends of the output of HIPOCAS can



be seen in Figure 1 of Tsimplis et al. (2005) above. Moreover (Figure 2, see below), it can be seen that the variability is reproduced. Note that the NAO index is very well correlated with the signal of the model.

Tsimplis and Josey (2001) have shown that it is the increase in sea level pressure during the winters that caused the sea level reduction in the Mediterranean during 1960-1993.



3. Steric sea level changes

When the oceanic temperature increases the oceans expand. When salinity increases, then sea level contracts. The changes are in general assessed on the basis of the Equation of Stated for Sea Water, an empirical relationship. In general, the equation of state of sea water is non-linear, so that the exact amount of each of these contributions will depend on the exact values of T, S and pressure.

The estimated values have been calculated by Tsimplis and Rixen (2002).

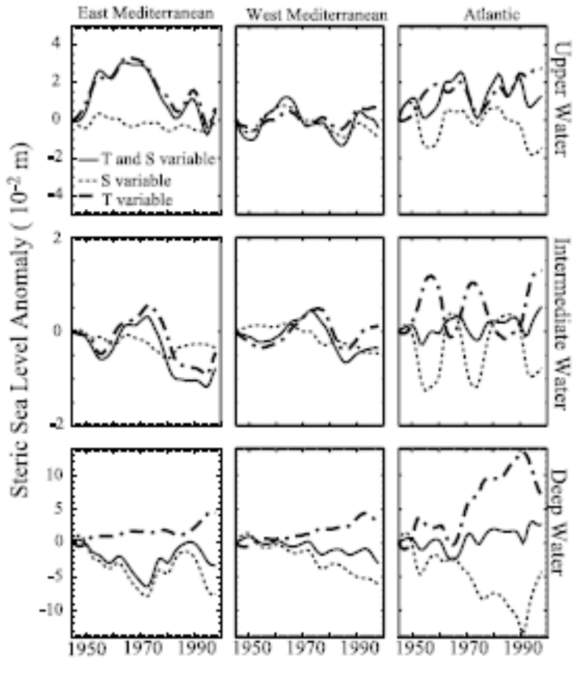


Figure 2. Steric sea level anomalies with time for the Eastern Mediterranean, the Western Mediterranean and the Atlantic sector. The variability due to temperature variation alone and the salinity variation alone has been calculated by keeping the other variable (i.e. S and T respectively) constant at their 1945 value.

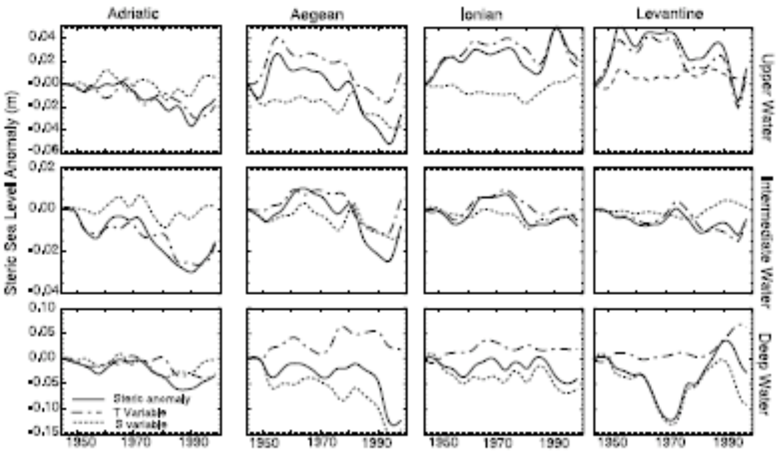


Figure 3. As Figure 2 but for the smaller areas shown in Figure 1.

Significant changes in the steric sea level signal can be seen for specific layers. However, which part of such signals is transmitted to coastal tide-gauges is still unclear.

4. Oceanic Circulation

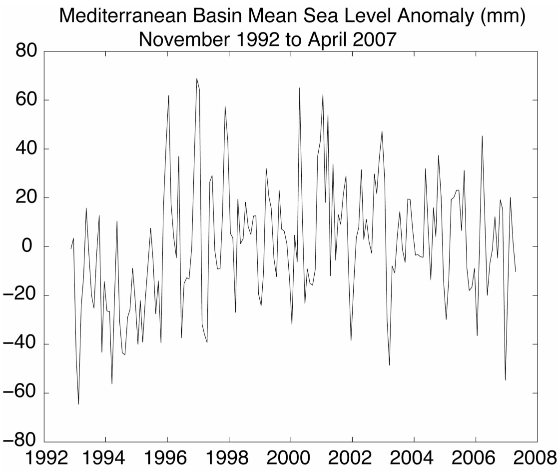
Oceanic circulation is also important. This is only recently started being explored on the basis of 3d models.

5. Why is sea level in the Mediterranean Sea rising faster during the last few decades?

Before the 1960s the Mediterranean Sea was increasing with rates comparable with the global values. However, between the 1960s and the 1990s, sea level in the Mediterranean Sea was either not changing, or in some places reducing. The main reason for this was an increase of atmospheric pressure over the Mediterranean during winters. This was caused with a meteorological pattern called the North Atlantic Oscillation. About 2-4 cm of sea level retreat took place during these three decades.

During the 1990s, high rates of sea level rise have been observed in the Mediterranean Sea and especially in the eastern Mediterranean Sea. These sea level rise rates were many times higher than the sea level rise rates calculated for the whole of the 20th century and sea level rose by about 5-7 cm during the period 1993-1999 in the eastern Mediterranean Basin. These sea level rise rates have now been reduced and the Mediterranean Sea level appears to have been almost stable as satellite altimetry indicates.

Increased sea level rise was also observed all around the world during the last decade, which has been documented as the warmest on record.



6. Is the observed sea level rise due to warming?

Globally, we are certain that during the 1990s heating of the atmosphere and concurrent heating of the upper parts of the ocean appears to be the primary cause of increased sea level rise with smaller contribution by ice-sheet melting. In the Mediterranean Sea, in addition to these effects, important changes in the oceanic circulation led to the additional sea level increase.

However, a decade is a short period for climate studies; thus, we cannot be certain that what happened in the 1990s is linked with climate change and it is not natural variability at decadal scales.

As concerns the period before the 1990s, only about a third of global sea level rise is attributable to heating of the oceans. The other two thirds are partly due to ice-sheet and glacier melting, but because of uncertainties in the measurements we are do not have a certain answer to this question. For the Mediterranean Sea, as explained, local atmospheric changes led to a long period of sea level reduction between 1960s and early 1990s.

7. How much will sea level rise in the Mediterranean Sea in the future?

This is far from a straightforward question. As explained, there are several forcing parameters, internal and external, to the Mediterranean that need to be taken into account. In addition, if the question relates to coastal protection for a specific location, local, regional and global land movements must also be considered. Predicting how important each of the forcing parameters is going to be in the future is not an easy task and involves the use of expert judgement rather than concrete scientific results.

Under climate change scenarios, the warming of the atmosphere depends on the amount of the greenhouse gases emitted, as well as the natural variability of the coupled atmosphere-ocean system. In turn, anthropogenic emissions depend on human population, standards of living, economic development and technology, all of which are interlinked and inter-dependent. Running models for the future with all the possible combinations of these parameters is well beyond our present capability and is also arguably not very useful. Instead, selected sets of assumptions, described as scenarios, have been used and these provide the basis for estimates of projected in the future greenhouse gas forcing. These values are then used to drive numerical models from which we get estimates of how the future will look. We have some confidence in these estimates for the 21st century, but our confidence is diminished as we move further from the 100-year benchmark.

There are a number of important points one should remember about these estimates: First, that the future is not, to a very large extent, determined. That is we have options available. Second, that none of the scenarios are predictions. They should be considered as exercises to be used for policy determination. Clearly, if all of the options gave us the same answer, then there would not be much to do apart from adapting to the expected changes. Third, one should remember that the global models do not, in general, have the appropriate resolution to give information at local scales and many they do not include a realistic Mediterranean Sea. Finally, there are processes not yet well understood which are parameterised in the model. The extent that these can cause errors cannot be assessed by the model outputs themselves.

Having all the above issues in mind, let's come back to the question posed: The global and regional (higher resolution models) indicate that the Mediterranean Sea will become warmer and saltier. Warmer means expansion and saltier means contraction of sea level. The temperature and salinity changes may have consequences for the ecosystems, but here we only consider sea level. The overall range of the global models is very large: -40 cm to 20 cm, for the changes due to internal causes in the Mediterranean Sea. However, looking at the temperature-related changes alone, the range goes up to 60 cm. The reason why one may wish to look solely at the temperature-related changes is because the salinity in the global models is not well described, due to the way the Strait of Gibraltar is parametrised.

One cannot choose a "best model" and the above range is the best estimate for the range of uncertainty we have for the internal forcing parameters. One should then take into account the external to the basin forcing parameters. The global thermal expansion of the oceans due to ice melting is in the range between 20 – and 60 cm. However, there is significant uncertainty regarding the rapid dynamical changes in the ice flow, which may lead to faster increases of ice melting and larger sea level rise.

The above may sound complicated and confusing. We consider a range of values between -20 cm to 60 cm as the one that should be taken into account. However, we think that the Mediterranean Sea will experience lower sea level rise than the global ocean due to the increases in salinity. It must be made clear that this is our expert judgment rather than most previous statements which are based on studies and facts.

As already mentioned, land movements should also be taken into account. Some of them are long-term motions; however, the redistribution of the water mass by ice-sheet and glacier melting is expected to cause regional and global effects which will differ in the future. We do not presently have the skills to predict them accurately.

It is clear that coastal protection schemes should balance the cultural and economic importance of the area against the costs of adopting higher or lower levels of protection.

The following projection comes from one model and one scenario. Thus, it is only provided as indicator of the spatial variability of the projected changes rather than a best estimate.

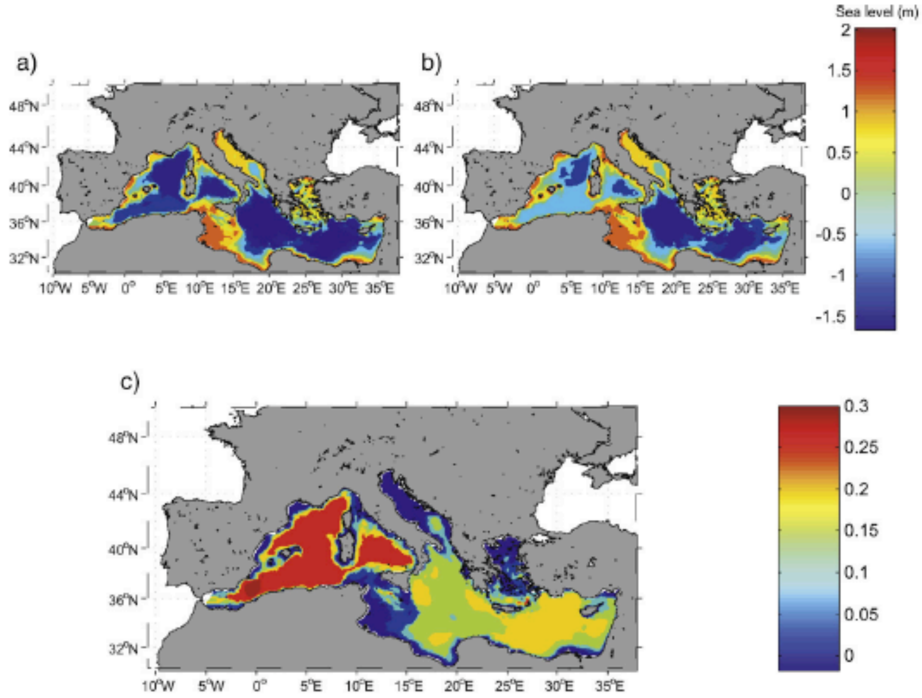


Fig. 6. Steric sea level for the periods 1961–1990 (a) and 2070–2099 (b) and their differences (c).

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Station Name	Variance (cm^2)	%Var Atm.	Obs. Trend	Atm. Trend	Ste. Trend	Residual trend	Res. PGR corr.
S.J. de Luz	8.84	19.73	1.7± 0.7	-0.7± 0.2	-0.1±0.3	2.7±0.6	2.6±0.6
Santander	13.45	20.92	1.6± 0.5	-0.4± 0.1	-0.3±0.3	2.4±0.6	2.4±0.6
Coruña	12.42	31.18	1.9± 0.5	-0.3± 0.2	-0.4±0.3	2.5±0.5	2.6±0.5
Vigo	19.00	25.41	1.7± 0.6	-0.2± 0.2	-0.4±0.3	2.5±0.5	2.6±0.5
Cascais	7.64	30.66	0.0± 0.4	-0.5± 0.1	-0.7±0.7	1.2±1.0	1.2±1.0
Cadiz	19.78	14.82	4.5± 0.7	-0.6± 0.1	-0.9±0.5	5.8±0.9	5.7±0.9
Tarifa	13.45	-11.73	-1.3± 0.5	-0.6± 0.1	0.3±0.1	-0.8±0.6	-0.7±0.6
Ceuta	8.09	9.81	0.6± 0.4	-0.6± 0.1	0.5±0.2	0.4±0.5	0.6±0.5
Malaga	21.28	14.17	4.1± 0.7	-0.6± 0.1	0.2±0.1	4.3±0.6	4.5±0.6
Alicante	2.14	36.53	-0.7± 0.3	-0.7± 0.1	0.1±0.1	0.0±0.3	0.0±0.3
Marsella	6.94	40.51	-0.0± 0.4	-0.7± 0.2	0.1±0.2	0.6±0.3	0.6±0.3
Genova	6.81	46.76	-0.3± 0.4	-0.9± 0.2	-0.4±0.2	1.6±0.4	1.7±0.4
Venecia	14.92	29.34	0.3± 0.4	-0.9± 0.2	-0.1±0.1	1.2±0.3	1.4±0.3
Trieste	9.00	48.56	0.3± 0.4	-0.8± 0.2	-0.1±0.1	1.0±0.3	1.2±0.3
Rovinj	8.64	44.89	-0.2± 0.4	-0.8± 0.2	-0.2±0.2	0.8±0.4	0.9±0.4
Bakar	13.17	44.57	0.2± 0.5	-0.8± 0.2	-0.2±0.1	0.9±0.4	1.1±0.4
Split I	10.31	42.69	-0.2± 0.5	-0.9± 0.2	-0.5±0.1	0.9±0.4	1.0±0.4
Split II	9.33	45.72	-0.4± 0.4	-0.9± 0.2	-0.5±0.1	0.8±0.3	1.0±0.3
Dubrovnik	8.50	42.82	0.2± 0.4	-0.9± 0.2	-0.9±0.2	1.7±0.3	1.8±0.3

Table 2. (Marcos and Tsimplis 2008) Values of variance of yearly observations, variance explained by the atmospheric and steric contributions and observed, meteorologically-induced and steric sea level trends for the period 1960-2000. Steric trends are calculated using MEDAR database for the Mediterranean stations and Ishii for the Atlantic ones. Trends are in mm/year.

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