THE RECENT EVOLUTION ON THE MID-LATITUDE ATMOSPHERIC PRESSURE AND ITS EFFECTS ON THE LOCAL SEA LEVEL: THE CASES OF THE MEDITERRANEAN AND VENICE IN PARTICULAR.

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Riassunto – Negli anni 2009 e 2010 è aumentata in modo preoccupante la frequenza delle inondazioni di Venezia (le “acque alte”). Questa antica città, assieme alle località della sua laguna, è particolarmente vulnerabile anche rispetto a piccole variazioni del livello del mare. Il livello medio dei due anni mostrava una crescita notevole e costante. La verifica di una analoga situazione in tutto l’alto Adriatico, nonché, progressivamente, di tutto questo mare, dei mari italiani e di tutto il Mediterraneo, creava apprensione, pensando a quanto si prospetta con le variazioni climatiche.
Peraltro, non si osservava alcuna crescita altrettanto decisa della temperatura dell’acqua, nei due anni considerati. Dove invece appariva netta l’origine del fenomeno era nella pressione atmosferica (almeno come indicatore) diminuita dovunque in modo drastico, sempre nel 2009 e 2010. Con molto interesse si è poi accertato che anche sulle coste atlantiche dell’Europa si osservava uno scenario analogo e più dettagliato: dalla latitudine della Manica fino al Marocco la pressione atmosferica è risultata in netta diminuzione nei due anni considerati, in contrasto con le alte latitudini, in decisa crescita. I livelli marini si comportavano, anche nelle stazioni oceaniche, in crescita dove la pressione scendeva, e viceversa.
È ben noto, in generale, l’effetto “barometro invertito”: se su un bacino si instaura un’alta pressione, il livello dell’acqua si abbassa, a spese di altre aree dove, per la pressione minore, il livello si innalza. Usando medie annali si instaura una visuale statistica, che media quindi su diverse situazioni, dando comunque un risultato che non può essere, anche a causa dei molti fattori trascurati, il risultato puntuale che si avrebbe in condizioni statiche.
Il pensiero che, nel caso di Venezia come in altri ambienti, la tendenza osservata continui accentuandosi è particolarmente preoccupante. In realtà si può sempre ricordare che la variabilità interannuale è sempre presente, e per quanto accentuati i fenomeni di due soli anni non possono essere considerati climatologicamente decisivi. Questa speranza mostra di non essere infondata: la tendenza dei primi mesi del 2011 si presenta invertita. La pressione atmosferica, nel periodo da gennaio a maggio, è vistosamente cresciuta e i livelli osservati a Venezia sono diminuiti. Di nuovo, nulla può essere dedotto stabilmente da periodi così brevi.
Un’ultima considerazione distingue, sempre per Venezia, tra effetti generali di crescita del livello medio e possibili accentuazioni delle burrasche (*storminess*) che provocano, in genere per poche ore, le inondazioni della città. Un semplice, anche se rozzo, strumento per distinguere i due fatti consiste nel riportare tutte le “acque

alte” al livello medio dell’anno (come dire, grossolanamente: se il mare non si fosse alzato). In questo caso la frequenza dei livelli estremi non mostra alcun aumento: la crescita del livello medio sembra così essere la principale causa dei periodi di frequenti inondazioni, quale quello degli anni recenti.

Abstract: Two recent investigations merged into a common conclusion. An intriguing increase of the mean sea level in the Mediterranean, up to the year 2010, stimulated the study of possible connections with the atmospheric forcing. At the same time an independent analysis of meteorological data, on the interface between Atlantic Ocean and Europe, showed trends consistent with the Mediterranean observations. Atmospheric pressure appeared as the key parameter for the analysis. The situation in Venice caused remarkable concern, but the short span of the first five months of 2011 prevents from extending the trend into the future.

1. Introduction

There is a widespread concern about climate changes causing, in particular, a general rise of the level of oceans and seas (IPCC, 2007).

A large number of populations live in the vicinity of the sea, with a scarce safety range, and inundations are feared. The present work was indeed started considering the anomalous frequency of floods in the city of Venice in the year 2009, even increasing in 2010. The town is very peculiar not only for its structure and its artistic beauties, but also for its vulnerability, with the street level not quite higher than the water in the many canals (in almost direct connection to the Adriatic Sea). It is well known that a dangerous land subsidence occurred in the 20th century, caused by the extraction of ground water (Gatto and Carbognin, 1981), but it seems no longer active. It is also known that the floods are mostly caused by the particular morphology of the northern Adriatic where Venice (with other towns) is seated: SE wind (the ‘sirocco’) piles up water in the dead-end of the sea. Like all other areas, troubles can also come from atmospheric depressions that are sufficient to locally increase the sea level (Robinson *et al*, 1973; Zampato *et al*, 2006).

A careful investigation was started on a large scale, involving, for the above reasons, both the sea and the atmosphere**.**

2. Data and methods

The sea-level data taken at the tide gauges in the various countries are available, more or less quickly. For Venice and its lagoon level values are easily found online thanks to the ICPSM (the tide office of the city), but also thanks to the local branch of the national agency ISPRA. The latter institution also operates and monitors dozens of tide gauges along the Italian coasts. In particular, most of the above tide gauges are coupled with meteorological recorders. The Italian CNR runs various instruments, here mention is given in particular to the Trieste office, with one of the longest records of tides.

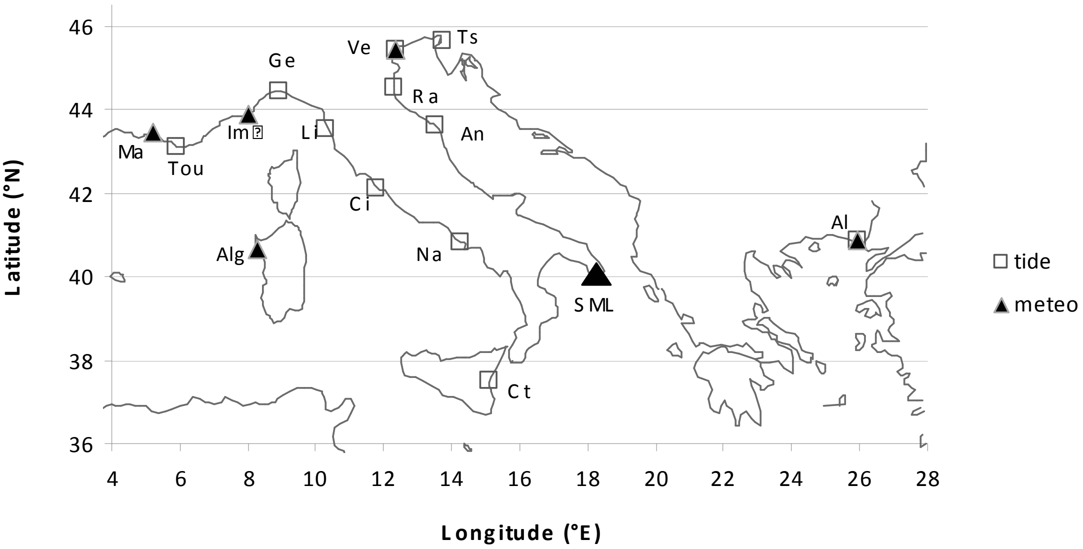
In the proximity of Italy, France is very active through its hydrographic office SHOM (and data are made available through the institution SONEL). The similar services of the Slovenian, Croatian and Greek republics give very useful data.

International institutions take care of making public sea-level information, for example the Permanent Service of Mean Sea Level (PSMSL) based in Liverpool or the SEAS institution. Both can be seen online.

The ICPSM mentioned above collected a valuable data base of tidal records from the various sources, together with a meteorological archive, having in mind the service of tidal forecasting.

For meteorology the data recorded at the tide gauges of ISPRA, as described above, have been very useful for the present investigation. Also the records of the Italian meteorological service (run by the Air Force) were important, together with the Russian Federation meteorological office that makes available data from all countries. A rich private data base of meteorological data concerning the interface of Europe and the Atlantic Ocean (Pirazzoli *et al*, 2010) turned out as essential for the investigation.

Two location maps for the corresponding areas (both for tide gauges and met stations) are given in fig. 1 (a and b), and the contributions from the various sources are specified when they are used in the paper.



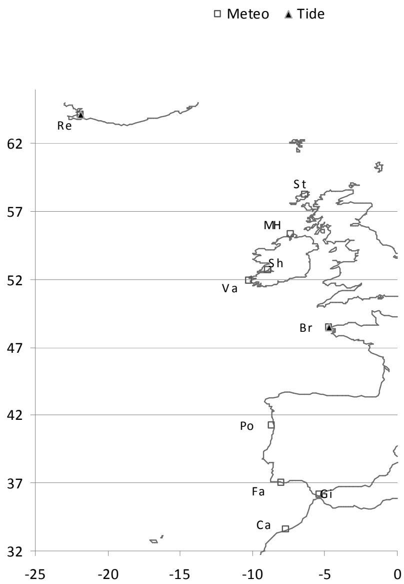


Figure 1 – a) location map, Mediterranean area, b) Atlantic "front" towards Europe; tide-gauge data used are separated from the meteorological measurements.
Symbol meaning: a) Ma, Marseille; Tou, Toulon; Im, Imperia; Ge, Genoa; Li, Leghorn (Livorno); Ci, Civitavecchia; Alg, Alghero; Na, Naples; Ct, Catania; SML, S.M. di Leuca; An, Ancona; Ra, Ravenna; Ve, Venice; Ts, Trieste; Al, Alexandroupolis.
b) Re, Reykjavik; St, Stornoway; MH, Malin Head; Sh, Shannon; Va, Valentia Island; Br, Brest; Po, Porto; Fa, Faro; Gl, Gibraltar; Ca, Casablanca.

For the present work, standard numerical methods were used. The water level at Venice was analyzed in terms of astronomy (Doodson, 1921) and surges, otherwise the only effort could concern the large number of data for synthesis and error control. Common algorithms were used for correlation or least-square modelling.

3. Results

3.a. Reasons for concern

What was described in the introduction is the pathway of the results of the investigation. Indeed, the alarm at the end of 2010 is clearly shown in fig. 2.

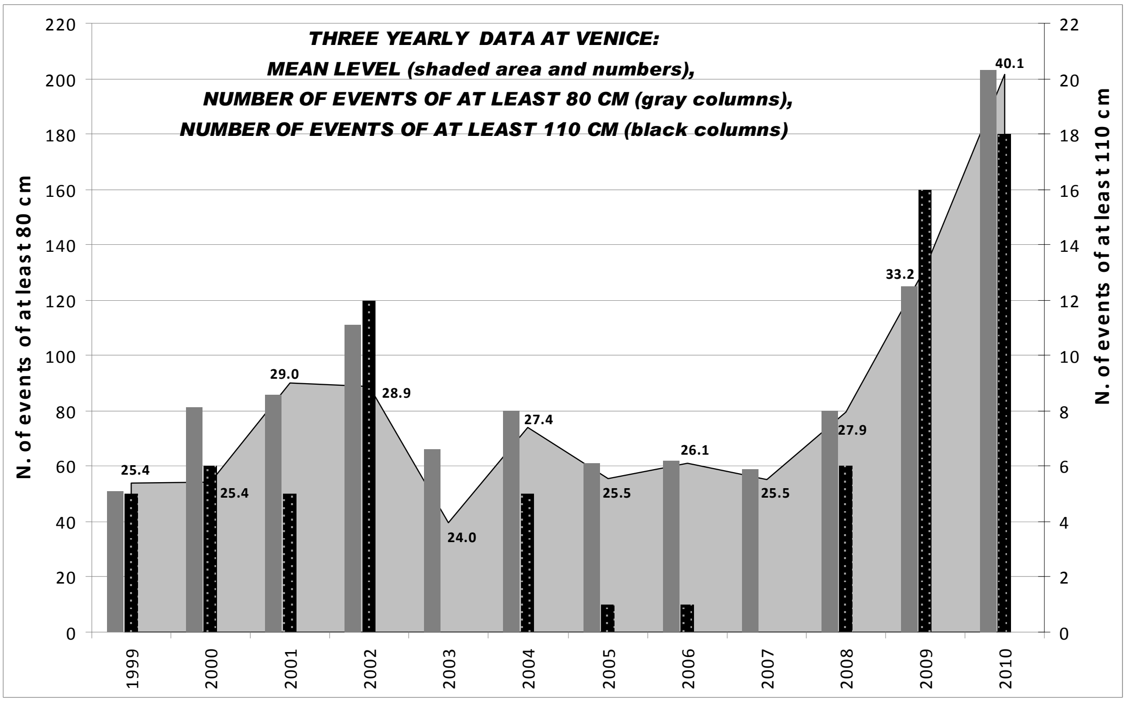


Figure 2 – The Venice concern: the mean sea level rising (shaded area and numbers) and the unpleasant effect: 110 cm level (over the zero of the tide gauge) and 80 cm (the threshold of alert), yearly number of events. Data from the Venetian ICPSM.

In the Venice floods, the damages are slightly different for the various sections of the city. A reference of 110 cm (see the meaning below) is assumed adequate for alarm, since it corresponds to 14% of the streets being inundated, with most shops and first-floor homes, not to mention difficult boat transit under bridges. Also a lower level of 80 cm is a threshold frequently considered, with a large part of St. Mark square being inundated.

The zero level (to give a meaning to 110 cm) is a reference fixed on the structures (it was the mean water level in 1897) so that variations of the observed mean do not change it, and, so to say, the troubles of 110 cm are the same at every time (but more or less frequently).

Fig. 2 shows also the increase of floods in 2009 and even worse in 2010. This in spite of a very low solar activity: reference is made to a recent hypothesis of correlation of sunspot numbers and surge aggressions (Pirazzoli and Tomasin, 2008, Zanchettin *et al*, 2009, Barriopedro *et al*, 2010) and in the years considered the Sun was very quiet (*http://sidc.oma.be/sunspot_data*). An obvious search for more convincing causes was started.

3.b. Searching for causes

A first hypothesis was a new sinking of Venice (Brambati *et al*, 2003, Carbognin *et al*, 2005) or maybe something wrong only in the tide gauge. But the data from Trieste were the same, and this "twin city of Venice" in the Northern Adriatic suffers no subsidence. Increase in the sirocco wind along the Adriatic? Definitely not, since the mean sea-level rise appeared all along the Italian stations (fig. 3). Clearly, tide gauges selected in order to avoid a common dependence on wind direction exhibited the same behaviour of mean sea level, so one can say that in the central Mediterranean, at least, the sea level had increased in 2009 and 2010. More clearly: on a short time scale, Venice sometime experiences a higher mean level with respect to Trieste if the 'bora' wind (NE) dominates. But considering different tide gauges at a very large scale, it is unlikely that all dominant winds change just to exhibit the same effect on mean levels.

Indeed, data from French Mediterranean and Greek stations showed, in the same fig. 3, that all the Mediterranean was involved.

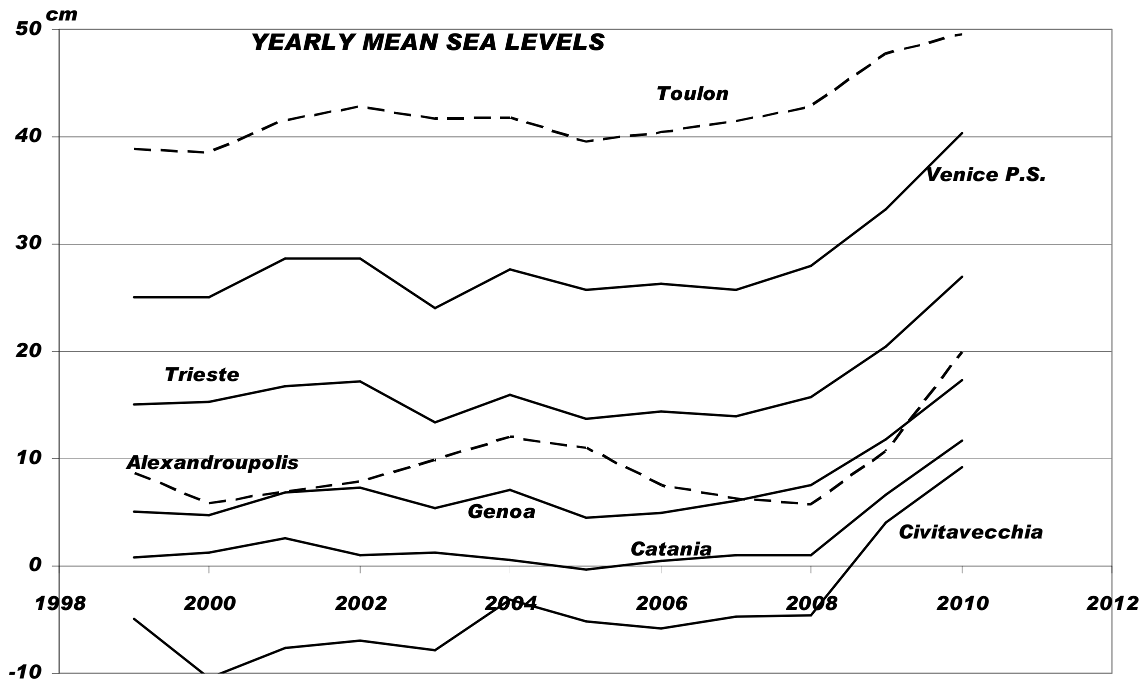


Figure 3 – The rise of mean sea level in many stations of the central Mediterranean (Italian tide gauges) and also both at west (Toulon) and at east (Alexandroupolis). Data from ISPRA (Italian stations), SHOM/SONEL and PSMSL.

The nightmare, in these years, is the climatic projection of sea-level rise, related to global warming (Beckeley *et al*, 2007, Grinsted *et al*, 2009, Pardaens *et al*, 2010). It was important that at the ISPRA stations not only sea-level data but also water temperature measurements were provided. Regardless of the questionable location of the instruments, frequently inside harbours and not in the open sea, whatever doubt one can have about the information, a common, similar-instrument result was the absence of substantial increases in water temperature in the last two years, and maybe some decrease (fig. 4). The same stations give also the air temperature, these did not show any step up either (and this is not reproduced here).

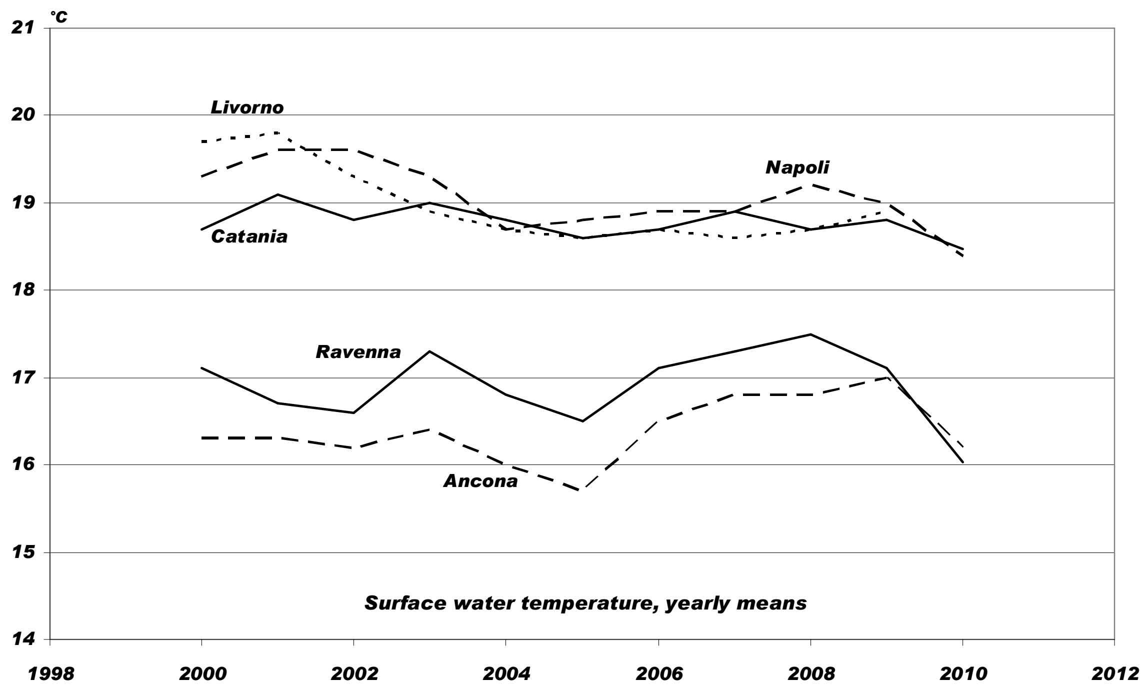


Figure 4 – Surface water temperature, yearly mean values, at five Italian stations in the different basins (from ISPRA).

The atmospheric effect is then considered. The wind, whose effect on the coasts strongly depends on the direction, has been already discarded above. Could one imagine, for each station, an increase of the specific cross-shore wind? The measurement of the atmospheric pressure is indeed very reliable, and it gave an answer to the doubts: in the same central Mediterranean area it appeared to have dropped, as a yearly average, exactly in the two years considered (fig. 5). Similarly, the pressure measurements both at the Western and Eastern Mediterranean gave the same result (Marseille and Alexandroupolis, in the same fig. 5).

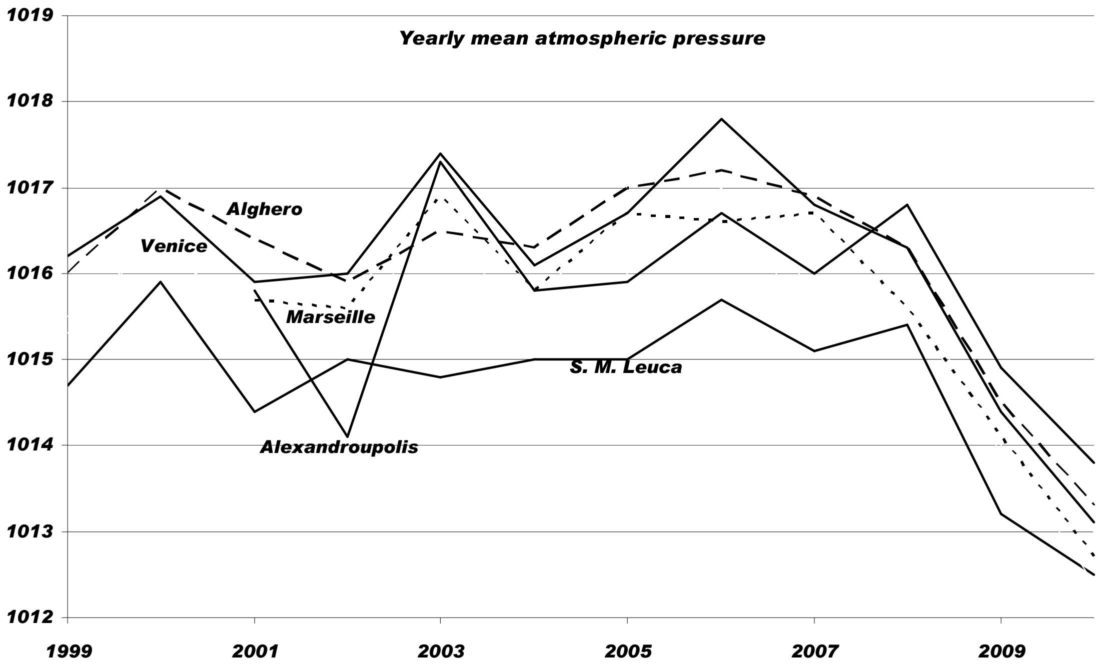


Figure 5 – Atmospheric pressure, yearly mean values at three Italian stations and two sites, east and west (Alexandroupolis and Marseille). Data from Italian Air Force and Russian Met Service.

What to deduce? A change in the trajectory of cyclones, maybe, or some kind of general "lighter" pattern in this area. The "inverse barometer effect" is well known, in static conditions a change of one hPa causes an opposite change in water level of one centimetre (Beretta *et al*, 2005, Raicich, 2010). Here the condition is not static but statistic, whatever it can mean: regardless of many other considerations (wind, temperature, salinity…) one can take yearly mean sea level at a site (like Venice) and the corresponding value of pressure, finding an empirical relation using least-square method (level in cm, pressure in hPa):

$$msl = 82.27 - 3.35 \times (press - 1000.0).$$

It means that a one-hPa change gives a change of 3.35 cm (standard deviation: 0.36 cm) in the mean water level. Or, in the limits of the 12 years considered (1999 through 2010), one finds the remarkable correlation *c* as -0.93 between the two numbers. This concerns Venice, but similar values were found for the other sites, with the top figure of Leghorn (Livorno), of c = -0.99. The observations used come from ICPSM in the Venice case, otherwise from ISPRA.

3.c. Atlantic similarities

At this point, another research emerged in addition to the above considerations. Following an investigation on the meteorology along an Atlantic front, so to say, i. e. the interface between the north of the ocean and Europe, concerning the wind evolution in the last decades (Pirazzoli *et al*, 2010), a new study was developed on the atmospheric pressure along the front. The past analysis, from Iceland to the Bay of Biscay, showed certain structures for wind at the different latitudes; now, using pressure and extending the data base both in time (up to the last years) and in space (down to Morocco), a significant detail came out. The zonal belt centred in the Mediterranean was affected, in the last years, by the same decline in atmospheric pressure (fig. 6a). This extended northward, since even at Brest there was a decline, whilst the northern part of the Atlantic coasts exhibits an increase (fig. 6b). Some way, the North Atlantic Oscillation, or NAO index (Hurrell and Deser, 2009) is expected to appear more and more negative in this period. The mean sea level shows, in these areas, variations that are consistent with the pressure change (fig. 7, Brest and Reykjavick), a result rather convincing. Spending some more word about NAO, it is clear that in the literature there are many definitions of it, outlining particular seasons or else. Since we restrict here to yearly means of the different parameters, the yearly values are of interest, and there is no surprise finding a dominant negative figure for the two years at the authoritative site *http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/month_nao_index.shtml*.

All this, is it part of a longer trend? In what follows it does not clearly seem so, even considering the very short time scale of the analysis.

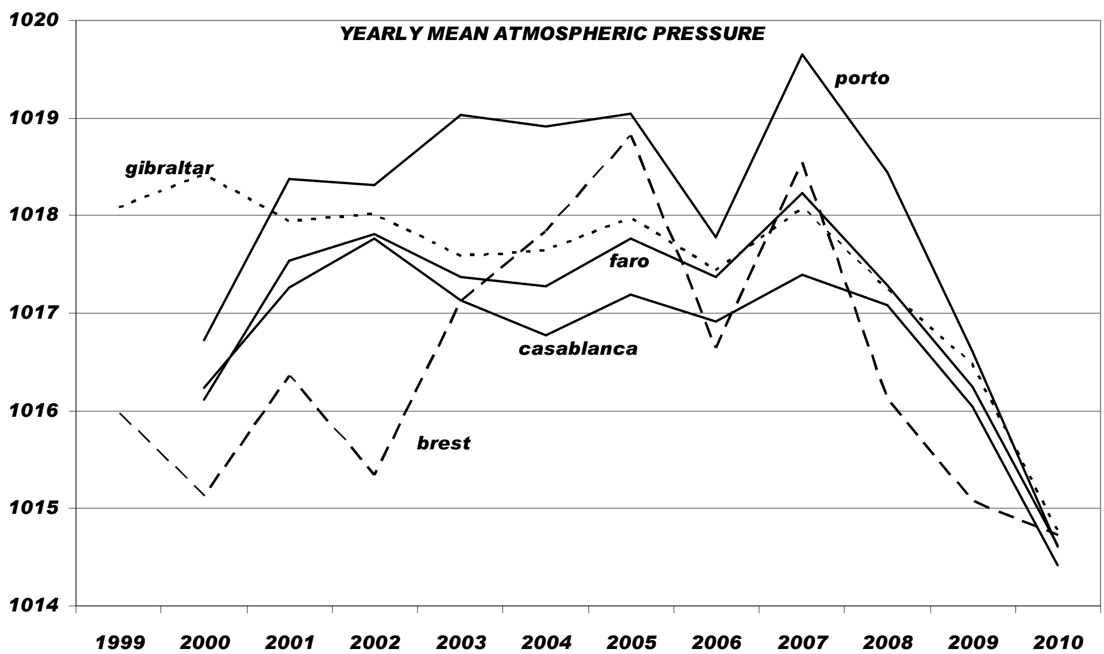


Figure 6a – Pressure means at Atlantic stations, decreasing values from Brest to Casablanca. Data from Russian Met Service.

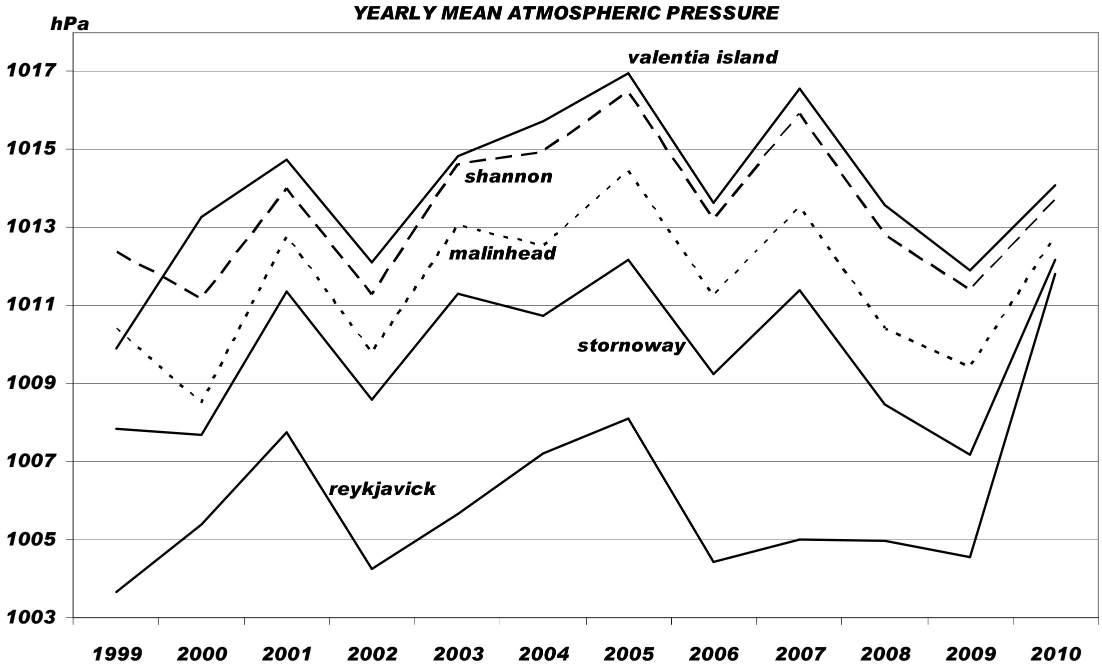


Figure 6b – Pressure means at Atlantic stations, increasing values in the northern part. Data from Russian Met Service.

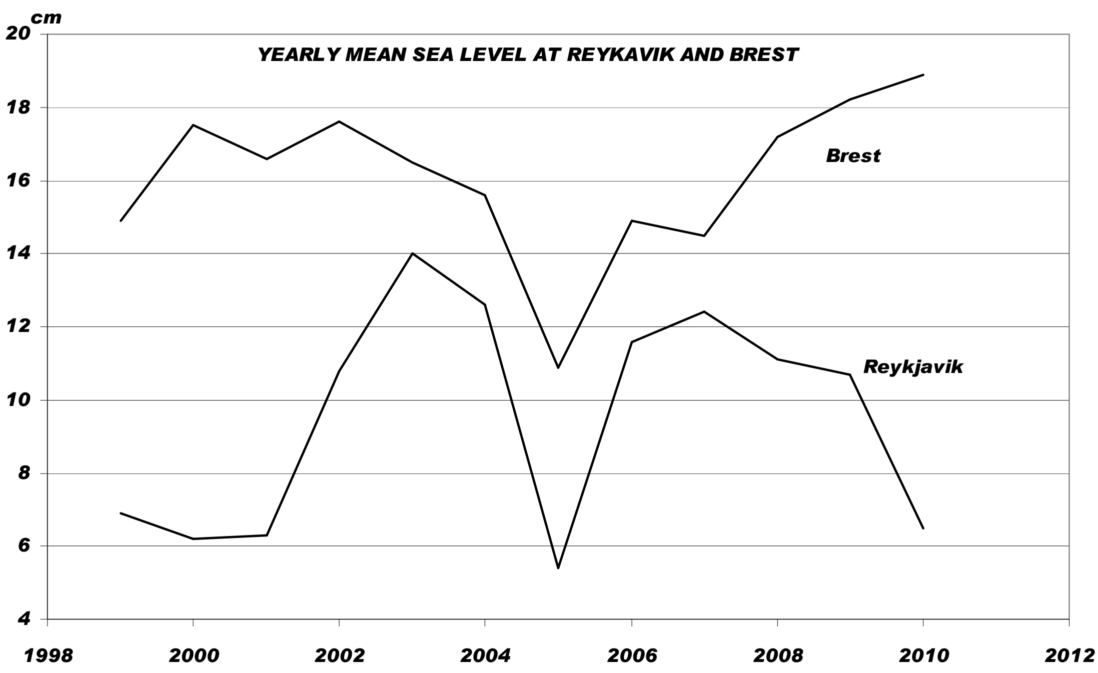


Figure 7 – Mean levels at Brest and Reykjavik, with opposite trend with respect to pressure, after PSMSL.

3.d. Sea level and storms, the sensitive condition of Venice

It was already stressed that the variations of sea level are of particular interest for the city of Venice, like for the other towns in and around its lagoon. Here the streets and the buildings have a very low safety range, partly due to the long-term lowering of the area.

Clearly, if the situation observed in 2009-2010 were to continue, and even to worsen, Venice would be in real danger. The question arises about what is the real menace, either the simple mean sea level or the frequency of surges. The two things are clearly related (every surge increases the statistical mean level), but a rough distinction between them is obtained by referring the observed levels to the mean sea level of the same year. The occurrence of floods becomes definitely flat in time, after such correction, thus putting the blame on the mean sea-level rise in the Adriatic, more than on a storminess increase that is not observed at all. For a similar analysis over the second half of the 20th century, one can see Canestrelli *et al*, 2001.

A feeble reason for hope comes from the records of the last few months: from January to May, 2011, the trend has reversed, with higher pressure and lower levels at Venice. For a more significant estimate, the same short period of five months was considered in the last decade, thus confirming a kind of bounce of the atmospheric pressure and correspondingly of the mean level (fig. 8). It is obvious that five months are not very much in order to deduce a better climatic trend, but indeed also the two frightening years were not sufficient to be climatologically significant for experts. Was it a flying nightmare for Venice? In terms of years, something similar (but reversed) occurred around 1990 (fig. 9): should an observer have deduced that the sea level in the Mediterranean had started a negative trend, he would have been disproved by the years that came later. Again, a temporary increase in atmospheric pressure seems to have caused that phenomenon. For what concerns surge frequency, some hope comes also from (a part of) the literature (Troccoli *et al*, 2011).

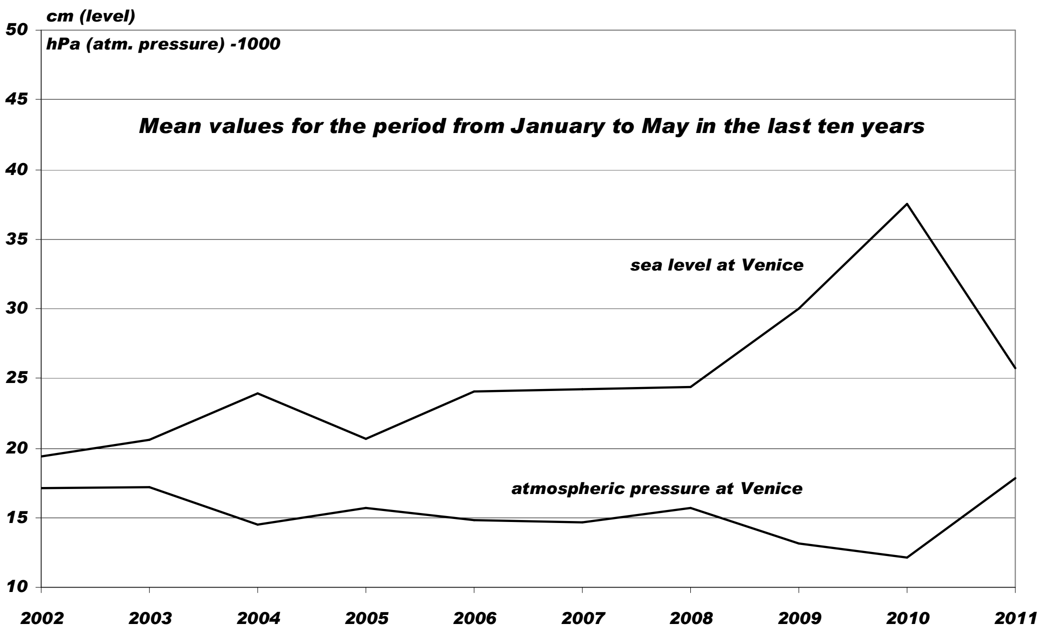


Figure 8 – The reverse trend at Venice from January to May, 2011: comparison with the same months in the last ten years. As usual, changes of atmospheric pressure correspond to larger changes of level. Data from ICPSM of Venice.

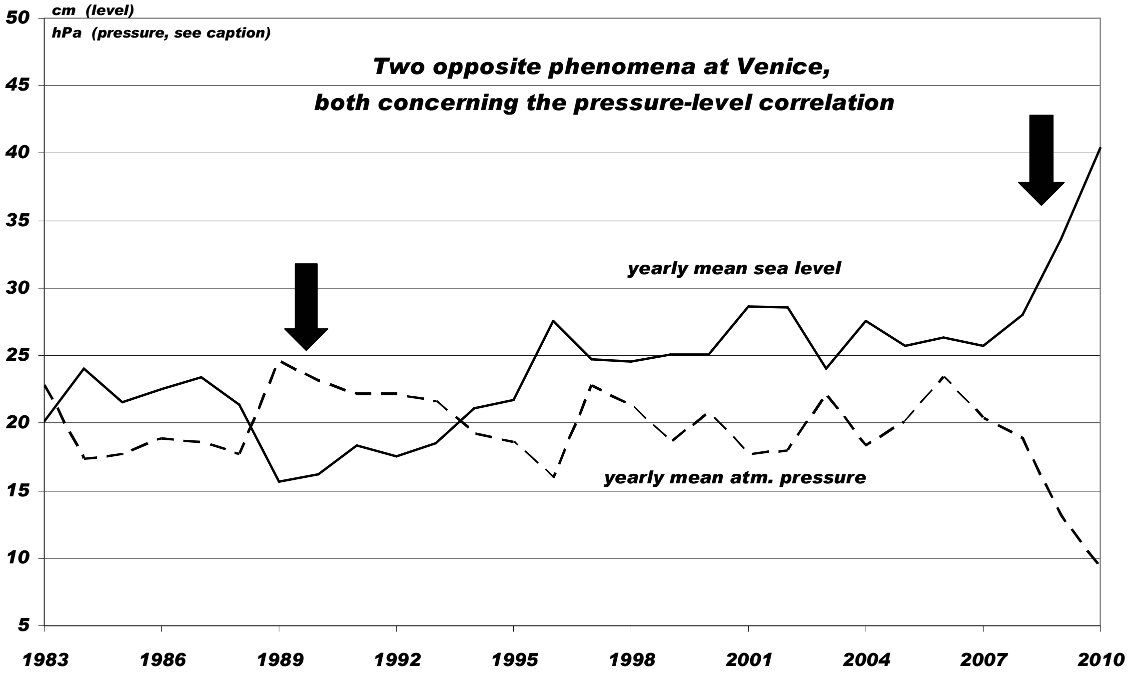


Figure 9 – Two opposite phenomena in recent years at Venice. Here pressure values are magnified, in order to be compared with the effect discussed in the text (three times larger, then subtracted). Data from ICPSM.

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