

Severe flooding along the eastern Adriatic coast: the case of 1 December 2008

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Abstract This paper addresses an extraordinary storm surge in the Northern Adriatic that was more pronounced on the eastern than on the western shore. On 1 December 2008, Adriatic monitoring stations detected exceptionally high sea levels; the oldest Croatian tide gauge station recorded the highest water level in its operating history at the time. Apart from the Northern Adriatic, large portion of the Dalmatian Coast was also exposed to high water levels, while Venice experienced a less-dramatic event. This marine storm was different from the capital storm of 4 November 1966 during which the surge had the highest impact ahead of Venice and along the north-western coastline. The 2008 event is studied here in detail, and the mechanisms that resulted in the different flooding of the two shores are identified. The study is based on hourly sea level, air pressure and wind data measured along both basin sides together with ECMWF reanalysis fields. Four components of sea-level evolution are identified: the storm surge, tide, Adriatic seiche and, low-frequency variability. The 2008 event was the outcome of a fine interplay between the first three components, which were all superimposed on the raised sea level due to low-frequency variability. The marine storm differed from the 1966 storm in the atmospheric forcing and relative timing of all contributing processes. The 2008 flooding of the eastern coast was mainly due to the Sirocco-wind shear, whereas the 1966 flooding of the western coast was due to the combined effect of almost uniform Sirocco and bottom slope.

Keywords Northern Adriatic · Exceptional sea level · *Acqua alta* · Storm surge

1 Introduction

The Adriatic Sea is a semi-enclosed basin that is surrounded on three sides by high mountain chains: the Apennines to the west, the Dinarides to the east and the Alps to the north. Along the western coast, the gently sloping bottom forms a broad shelf, whereas along the eastern coast, the bottom drops abruptly to an average depth of approximately 80 m. The northernmost part of the basin is a flat plane with a maximum depth of 50 m (Fig. 1). Several times a year, usually during late autumn and winter (Lionello et al. 2012), high water levels occur in the Northern Adriatic. The area most frequently and severely affected by these events is the northernmost shallow coastal area around Venice; the historic city is particularly vulnerable to flooding. On some occasions, the northernmost cities on the eastern coast, such as Umag, Pula and Rijeka, also undergo infrastructure damage. In exceptional cases, even areas in the middle Adriatic are exposed to flooding.

On 4 November 1966, a severe storm led to a disastrous flood in Venice. The sea rose to 155 cm above the mean,¹ which is the highest hourly value ever recorded at the tide gauge station Punta Salute in the Venice city centre (Bonato et al. 2001; Venice Municipality 2014). Damage caused to the city and the surrounding area was estimated at approximately 400 million Euro (De Zolt et al. 2006). An exceptionally high sea level was registered throughout the Adriatic, but the event was less dramatic on the eastern coast. However, this was not the case on 1 December 2008 when the eastern side was hit by

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¹ All sea-level values reported in this paper are relative to the average values of the studied periods (see Section 2)

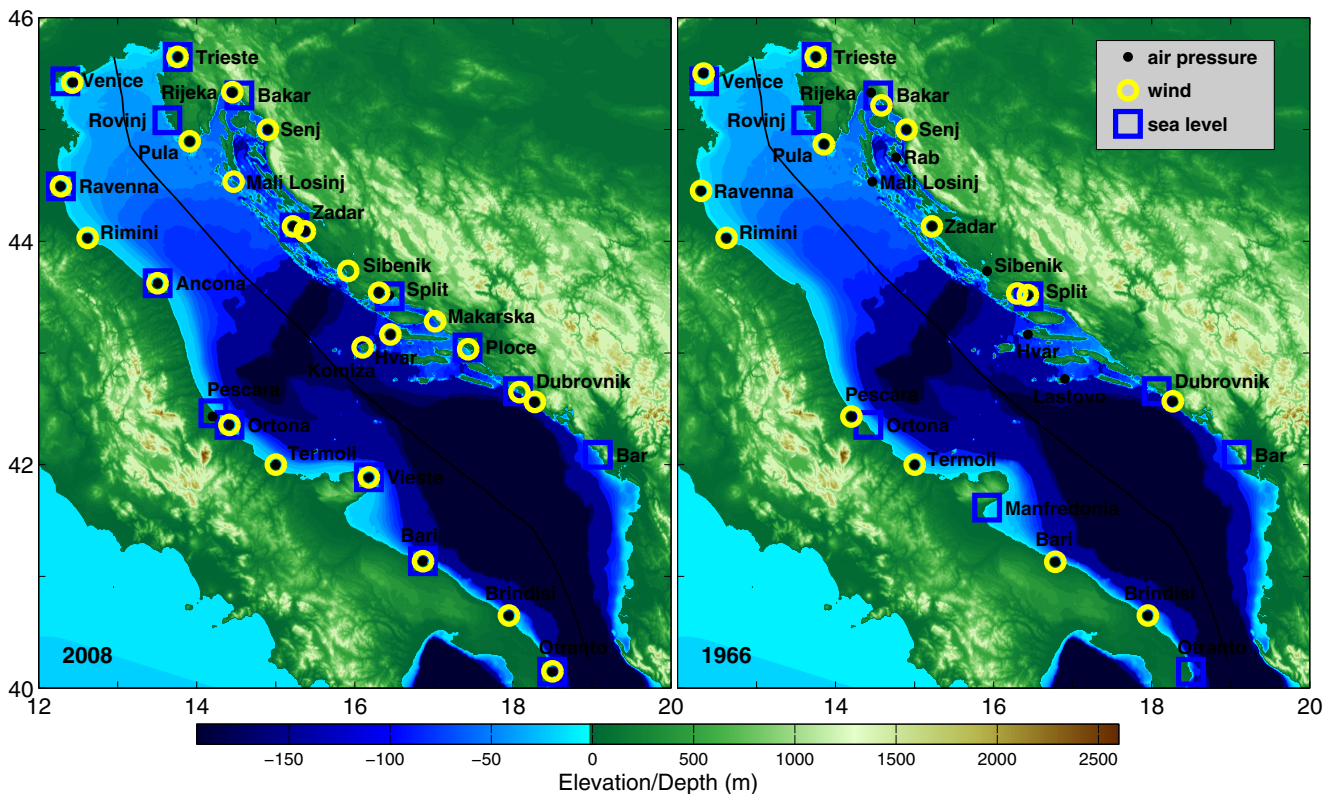


Fig. 1 Bathymetry of the Adriatic and position of the stations from which the data were acquired for the 2008 (*left*) and 1966 (*right*) floods. Same colour is used for all depths greater than 250 m. Also indicated is the along-basin section utilised in Fig. 7

severe flooding. At Bakar, the sea level reached 98 cm above the mean, which was, at the time,² the highest level recorded since the start of its operation. Bakar is the longest operating Croatian tide gauge station established in 1929, and after a 10-year break around the World War II, it has been uninterruptedly measuring since 1949. At Trieste, where the oldest tide gauge in the Adriatic is located, the second highest value was registered, and at Venice, the fourth highest value was registered. Apparently, the meteorological storm that caused the flooding was not particularly pronounced (Bertotti et al. 2011). However, on this occasion, the sea levels at Bakar and Trieste surpassed the value reached during the 1966 flood by 15 and 6 cm, respectively; at Venice, the level was 37 cm lower than the 1966 maximum. Moreover, in addition to the flooded Northern Adriatic, the entire eastern coast north of Split was also flooded.

In this paper, we closely examine the flood on 1 December 2008 and contrast it to the capital storm on 4 November 1966 to determine the specific conditions that lead to intense flooding along the eastern coast of the Adriatic. The 1966 event has been amply investigated in numerous studies that address various oceanographic (e.g. Finizio et al. 1972; Accerboni and Manca 1973; Stravisi and Marussi 1973) and

meteorological (Mosetti 1985; De Zolt et al. 2006; Malguzzi et al. 2006; Cavaleri et al. 2010; Bertotti et al. 2011) aspects and cover the entire basin or focus on Venice. However, details on the event's effects along the eastern coast are lacking. Hence, we reexamine the flood in 1966 by investigating the differences between the 2008 and 1966 events and by focusing on the processes that influence the formation of high sea level at the eastern and western coasts. The study is based on an extensive set of observations of sea level and atmospheric forcing along both sides of the basin, supplemented with ECMWF Reanalysis fields. Long data series related to the two floods enable us to distinguish between various processes that contribute to the formation of high sea level.

Flooding events, also known as *aqua alta*, generally occur as a result of the constructive superposition of several phenomena: storm surge, tide, seiche and low-frequency variability. Storm surge has the dominant impact, but other components can also be important for the formation of high sea level. Atmospheric conditions leading to the formation of Adriatic storm surges are well known and have been examined in many studies, e.g., Robinson et al. (1973), Trigo and Davies (2002) and Lionello et al. (2012). Storm surges in the Northern Adriatic are generally induced by mid-latitude cyclones that approach the basin from the western Mediterranean. These synoptic situations are accompanied by low air pressure in the north and a south-easterly wind (Sirocco) that blows over

² It should be mentioned that on 1 November 2012 sea level at Bakar surpassed the extreme on 1 December 2008 by 8 cm

the greater part of the basin. Both air pressure and wind act in the same direction, which piles up water at the closed end of the Adriatic. The regional orography works in favour of storm surge formation by channelling and intensifying the Sirocco along the main axis of the basin.

Tides can also contribute considerably to coastal floods (Pasarić and Orlić 2001). The Adriatic tide is of a mixed type in which the M2 and K1 constituents have the largest amplitudes of comparable size. K1 has the form of a topographic wave that propagates from the north-eastern to the south-western shores (Malačič et al. 2000), while M2 propagates counter-clockwise around an amphidromic point as a Kelvin wave (Hendershot and Speranza 1971). The amplitudes of both constituents rise towards the shallow northern part of the basin and reach values up to 20 cm (K1) and 26 cm (M2).

Another non-negligible contribution to coastal floods is a pre-existing Adriatic seiche (Robinson et al. 1973; Tomasin and Frassetto 1979; Mosetti 1985). A seiche is usually triggered by a sudden weakening of the Sirocco or its change to Bora wind, which is related to the passage of a cyclone over the Adriatic. A seiche can exist for several days and take part in possible upcoming floods. Estimated period of the first mode is ranging from 21 to 22 h (e.g. Raicich et al. 1999; Lionello et al. 2005), whereas decay is mainly due to energy loss through the Otranto Strait; the decay time was estimated to be 3.2 ± 0.5 days (Cerovečki et al. 1997).

Godin and Trotti (1975) have observed that at Trieste the great surge on 4 November 1966 coincided with a prolonged interval of a higher-than-normal sea level at the station. They noticed that these low-frequency deviations from mean level can last even longer than a month, especially during winter. Low-frequency variability is an essential component of Northern Adriatic floods, which is underestimated in many studies. It is not dominant but is an ever-present component of coastal floods and can cause sea-level changes of up to 70 cm (Pasarić and Orlić 2001). Low-frequency variability is related to planetary atmospheric waves (Pasarić and Orlić 1992), which are prominent in the middle troposphere and slowly travel to the east; the waves are observed at the sea surface as slowly changing (temporal scales of weeks to several months) air pressure and wind (Pasarić et al. 2000).

The four processes are taken into account in the present analysis of the 1 December 2008 event and its comparison to the 4 November 1966 event.

2 Dataset and analysis

The floods are analysed based on two 4-month intervals (1 September 1966–31 December 1966 and 1 October 2008–31 January 2009), generally using hourly sea level, air pressure and wind values measured along both sides of the Adriatic (Fig. 1); some meteorological data were only available at

larger sampling intervals. All of the time series were tested with a Turkey 53H filter to detect possible outliers (Otnes and Enochson 1978) and then linearly interpolated using neighbouring points. Possible outliers that may have occurred on the days of the two floods were not corrected. Gaps shorter than 2 h were filled in by linear interpolation, and those up to 25 h were filled in by multiple regression using the closest stations. The times for all of the sea-level and meteorological data are expressed in Central European Time (CET).

The sea-level time series are uninterrupted, except in 1966 at Venice. The series were reduced to anomalies by subtracting the respective 4-month means from the observed values. During the flood on 4 November 1966, the elevations at stations in Bakar and Venice were obtained by visual observations because the sea level rose above the upper threshold values of the recording instruments. Cavaleri et al. (2010) reported that maximum water level reached during this storm in Venice was estimated from oil marks that remained on walls after the oil had leaked from flooded tanks and floated on the top of the water. As for Bakar, the sea levels above instrument's upper threshold were obtained by measuring the level against a tide pole in front of the tide gauge station.

Four different phenomena were identified in the sea-level series: the low-frequency variability, the astronomical tide, the pre-existing Adriatic-wide seiche and the storm surge.

First, the low-frequency variability was extracted by applying a low-pass digital filter with the half-power point at 10 days. At Venice, the series in 1966 was too short to extract this component, and it was therefore taken from Trieste. This choice seems reasonable due to the vicinity of the two stations and the small spatial variability of processes at these time scales (Pasarić and Orlić 2001).

The tidal signal was synthesised using the T_{tide} tool (Pawłowicz et al. 2002) by taking into account seven harmonic constituents (K1, O1, P1, K2, S2, M2 and N2) that are traditionally used in the Adriatic. The harmonic constants were obtained from the literature (Godin and Trotti 1975; Mosetti 1987; State Hydrographic Institute 1991, 2012). The constants for Bari and Pescara were obtained by harmonic analysis of sea level data over the study period.

The first mode of the Adriatic-wide seiche can be extracted by applying an appropriate band-pass filter to the residual (i.e. de-tided) sea level. However, filtering smears the abrupt start of the oscillation and therefore makes it impossible to distinguish the pre-existing seiche from the newly induced one if the former was generated shortly before the event. Another possibility is to use wavelets. It turns out that seiche onset is more accurately reproduced by wavelets. However, a much broader band of time scales (from 14 to 24 h), which are partly governed by storm surge activity, is required. Hence, to estimate the contribution of a pre-existing seiche to the sea-level maximum, a different approach is used. The residual sea-level

data were inspected for abrupt jumps several days before each event to identify a possible episode of previous seiche generation. The time evolution of the seiche was approximated by an exponentially damped cosine of the 21.5 h period and the decay time of 3.2 days (Cerovečki et al. 1997). The period was chosen as the mean value of the range of estimated values (21–22 h) obtained by different authors (e.g. Lionello et al. 2005). The initial amplitude at each station was set proportionally to the magnitude of the abrupt sea-level change at Trieste (Kasumović 1959). It should be noted that periods of the normal modes of the Adriatic lie in the vicinity of those of tidal motion. Consequently, some leakage of energy between the two processes cannot be avoided.

Finally, once the low-frequency variability, the tide and the basin-wide seiche have been determined, the storm surge activity is defined as the part of the sea-level variability that remained after the three previous components had been removed.

The air-pressure measurements were reduced to the mean sea level. For the 1966 event, only 3-hourly (Brindisi, Bari and Rimini) and 6-hourly (Venice, Trieste, Ravenna, Pescara and Termoli) values were available at the west coast of the Adriatic. The wind was generally measured at approximately 10 m above the ground. For the 1966 storm, only 3-hourly wind data were available at the western coast. Unlike the air-pressure data, the wind data had a number of disruptions due to various factors (e.g. stations were not working, instruments were disabled by strong wind or data transmission failed). The part of the atmospheric forcing related to planetary-scale activity was determined by applying the 10-day low-pass filter to the air-pressure and wind data. Due to uneven wind observations, this component could not be calculated at several stations. In accordance with the dominant direction of the Adriatic basin and the surrounding orography, the wind was decomposed into the along-basin component directed towards the north-west and the across-basin component directed towards the north-east. Also, the geopotential height of the 500-hPa surface over the Adriatic was inspected. The data, taken from ERA Interim of ECMWF (European Centre for Medium-Range Weather Forecasts) Reanalysis (Dee et al. 2011) along the 13 and 18°E meridians, were averaged between 40 and 46°N and smoothed with the 10-day low-pass filter to document the large-scale forcing.

In addition, the meteorological data, which are restricted to the coastal region, were supplemented with results of meteorological modelling to obtain information on the forcing over the open sea and over a larger area. For shorter intervals close to the two peak events, we analysed ECMWF Reanalysis (ERA Interim for 2008 and ERA40 for 1966, Uppala et al. 2005) fields, which are provided on a $0.25 \times 0.25^\circ$ grid with a 6 h time step. For the Adriatic Sea, the ECMWF wind fields exhibit correct overall structure, but the modelled values should be multiplied, depending on the original model

resolution, by an enhancement coefficients ranging from 1.2 to 1.5 (Cavaleri and Bertotti 1997, 2006), to achieve better agreement with observations. Here, we use the coefficients 1.47 for ERA Interim (~78 km resolution) and 1.56 for ERA 40 (~125 km resolution) that were obtained by interpolation or extrapolation of the values available in the literature. It should be mentioned that in our study this choice of calibration is not crucial considering that we use the ECMWF wind fields for qualitative analysis of the storm surge field, and not for numerical calculations sensitive to the overall wind intensity.

Note that all the analyses are based on hourly (or sub-sampled) time series, which do not permit us to very accurately determine the timing of the events. Moreover, actual extremes of the sea-level values may have been significantly different from the values reported here, especially at sites of strong local seiche activity.

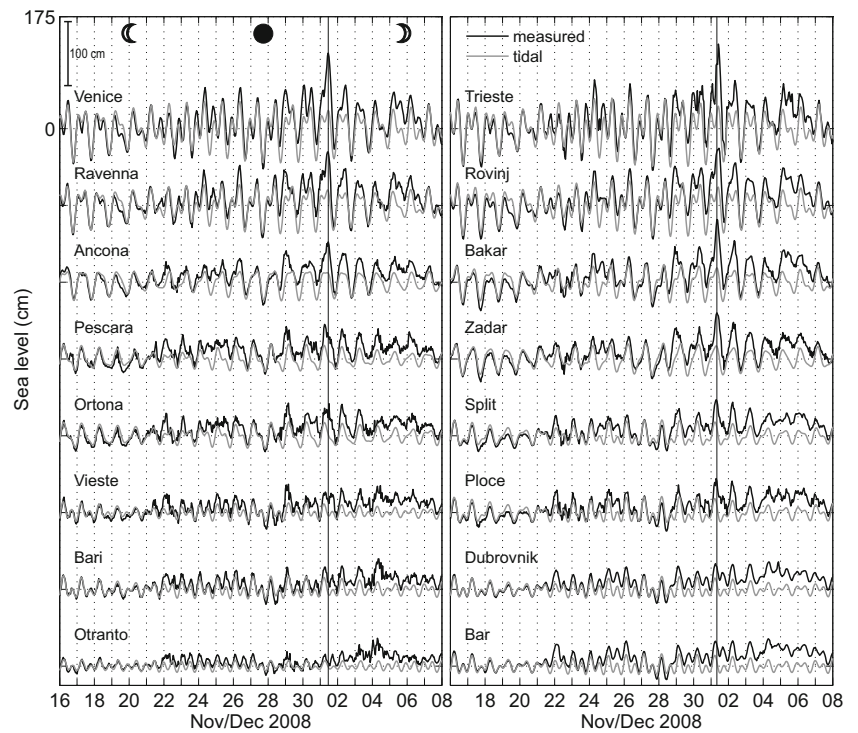
3 Results

3.1 The flood on 1 December 2008

On 1 December 2008, the coastal region throughout the Northern Adriatic was exposed to extremely high sea levels (Fig. 2). The event was stronger along the eastern side, where the greater part of the coast north of Split was flooded. In Bakar, the sea level rose at 08 CET to its highest point since the start of measurements in 1929. The peak was reached at 10 CET in Trieste and at 11 CET in Venice. The maximum at Rovinj, registered at 11 CET, was not remarkable.

During the week prior to the occurrence of *acqua alta*, a series of low air-pressure systems passed over the basin with the last one being decisive for the flooding. The synoptic situation related to the main cyclone, analysed by Bertotti et al. (2011), can be summarised as follows. Two days before the flood, an intense cyclone that was linked to an upper-air trough (Fig. 3a) centred over south-western Europe supported strong westerly flow over the entire Mediterranean (Fig. 3b). By 1 December at 01 CET, a secondary cyclone developed over the Gulf of Genoa (Fig. 3c), which changed the wind over the Adriatic to a more southerly direction. The wind in the Adriatic reached its maximum in the early hours on 1 December as the small-scale atmospheric system propagated towards the Po Valley (Fig. 3d) and across the Northern Adriatic where it diminished in the afternoon. Our data show that while it was active, the cyclone supported a strong air-pressure gradient along the Adriatic (Fig. 4a). During the 24 h before the peak event, coastal stations recorded a Sirocco of non-uniform intensity over the basin (Fig. 4b) that was much stronger on the eastern coast than on the western coast and generally stronger in the south than in the north. However, Venice experienced a change from strong northerly wind to strong Sirocco. The air-pressure and wind fields over the

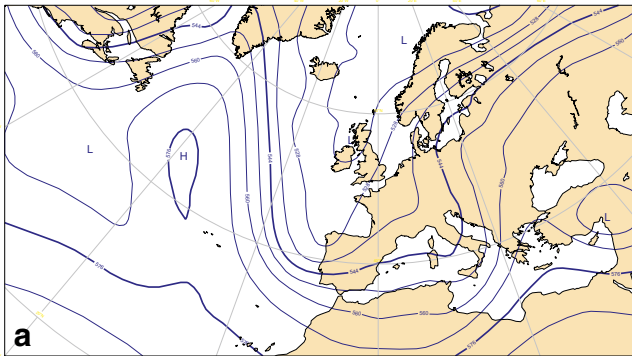
Fig. 2 Observed 1-hourly sea level series, referred to the respective 4-month means, and the corresponding tidal predictions along the west (*left*) and east (*right*) coasts of the Adriatic for the 2008 flood. The vertical line (here and in subsequent figures) indicates the onset of the sea-level maximum at Venice (*left*) and Bakar (*right*). The moon phases are also indicated in the figure



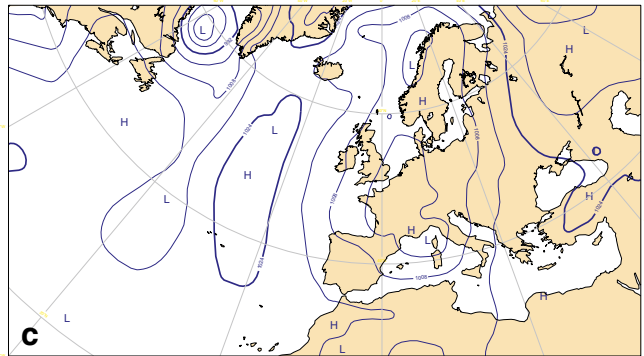
Adriatic, as obtained by ERA Interim reanalysis, are shown in Fig. 5 (left). On 1 December 2008, the synoptic situation supported a strong air-pressure gradient along the basin and a

spatially variable southerly wind blowing from the Italian coast; the maximum wind speed was closer to the eastern coast. In the northern area, the wind was directed from

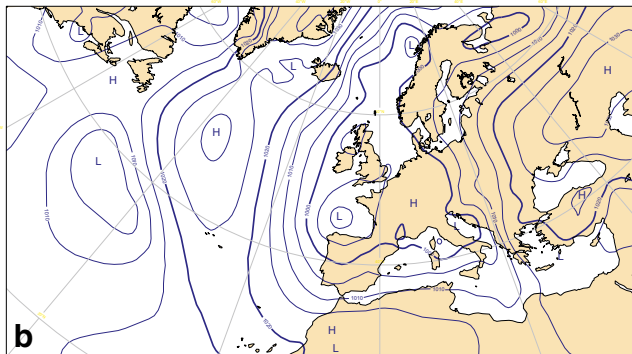
29 Nov 2008 00UTC 500hPa Geopotential (dam)



1 Dec 2008 00UTC Surface: Mean sea level pressure (hpa)



29 Nov 2008 00UTC Surface: Mean sea level pressure (hpa)



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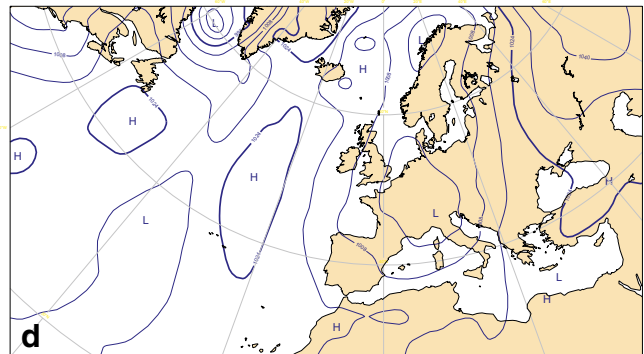
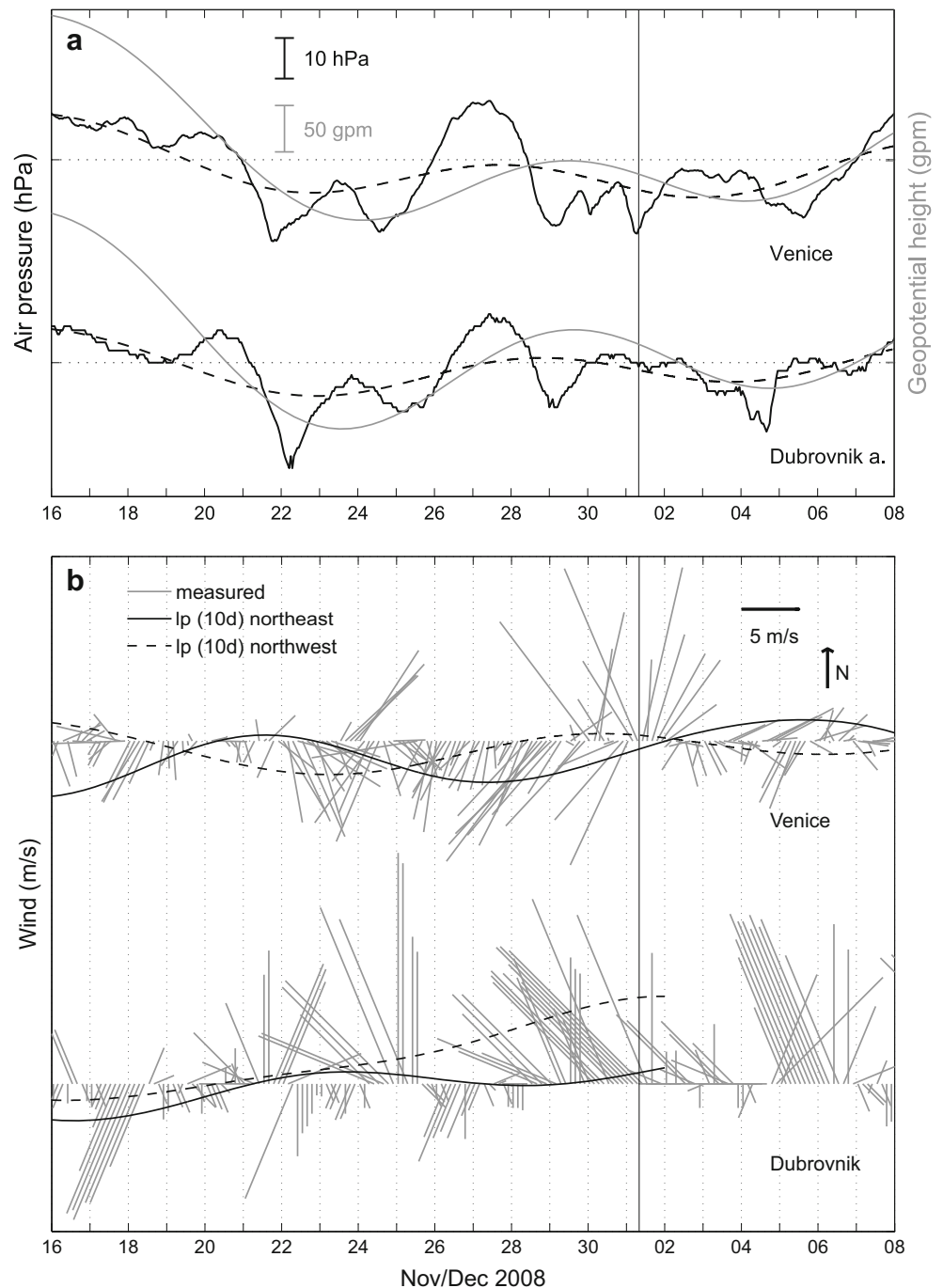


Fig. 3 ERA-Interim **a** geopotential heights at 500-hPa surface and **b** sea-level pressure, both on 29 November 2008 at 00:00 UTC, 2 days before the flood. Sea-level pressure on 1 December 2008 **c** at 00:00 UTC and **d** at 06:00 UTC

Fig. 4 **a** Observed air-pressure time series reduced to mean sea level (*solid line*) and the low-pass filtered data at 10 days (*dashed line*) at Venice and Dubrovnik airport stations for the 2008 flood; the data are given around the reference value of 1013 hPa and plotted with an arbitrary offset. Also shown are the geopotential heights of the 500-hPa surface (*grey line*) along the 13°E (for Venice) and 18°E (for Dubrovnik) meridians low-pass filtered at 10 days; the data are presented around the reference value of 5500 gpm. **b** Wind data for the 2008 flood: measured hourly vectors at Venice and Dubrovnik stations and corresponding wind components low-pass filtered at 10 days. For clarity, every third measured vector is plotted. Some parts of the planetary components are missing due to the absence of observed data. The *vertical line* indicates the onset of the sea-level maximum at Bakar

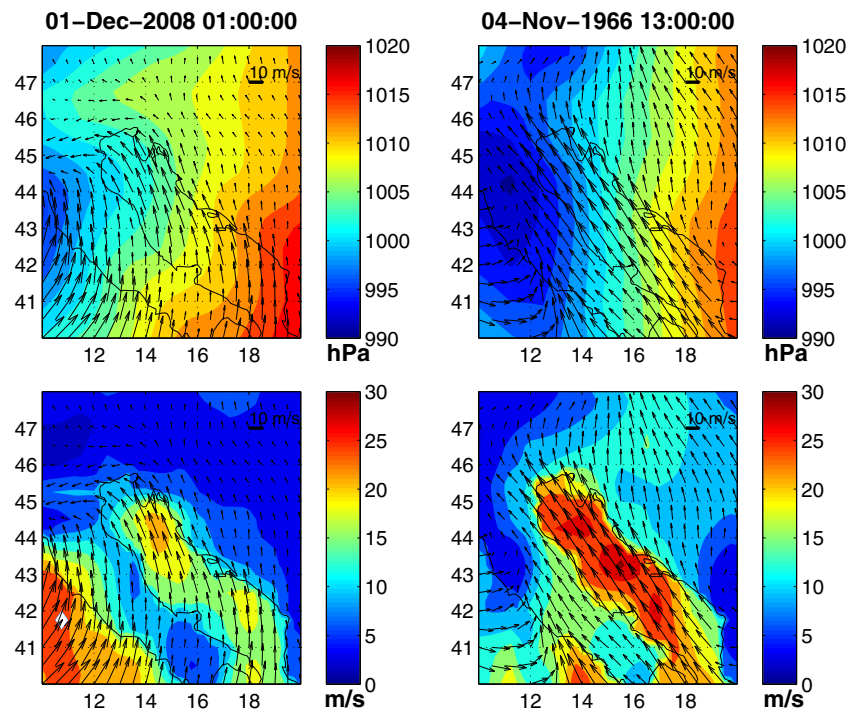


south-east, while in the Southern Adriatic, a more uniform south wind was prevalent. The reanalysis field exhibits larger wind speeds over the north part of the basin, whereas the coastal stations registered stronger wind in the south. The reanalysis data agree with the observations in that the 2008 wind field was spatially variable with higher speeds along the eastern shore.

Preconditions for the flooding started to develop more than a week prior to the event when the sea level began to slowly rise (Fig. 6b) due to a large-scale atmospheric disturbance

(Fig. 4, dashed lines). The disturbance was closely related to passage of planetary waves in the middle atmosphere as indicated by the geopotential height of the 500-hPa surface (Fig. 4a). The series of the synoptic disturbances that passed over the area prior to the event led to seiche activity. The seiche that was excited on the night of 28/29 November (Fig. 3b) was still active (Fig. 6c) when the decisive weather front passed over the Adriatic on the morning of 1 December. The air pressure at Rijeka dropped to its minimum between 07 and 08 h shortly before the tide reached its daily maximum at

Fig. 5 Contours of air pressure (top) and calibrated wind speed (bottom) with wind vectors from ECMWF Reanalysis. The figure shows atmospheric conditions one interval before peak events, i.e. 7 h before the maximum on 1 December 2008 in Bakar (left) and 5 h before the maximum on 4 November 1966 in Venice (right)



Bakar, and the pre-existing Adriatic seiche was slightly positive and rising. The onset of the sea-level maximum in the northernmost part of the basin coincided with the tidal maximum (Fig. 2). At the time, the moon phase was between new moon and the first quarter; hence, the cyclonic propagation of the M2 tide may explain the lag of the sea-level maximum

along the coast. However, the lapse of the peak event at Rovinj was affected by the onset of the positive contribution of high tide and seiche. By focusing on storm-surge activity (Fig. 7), we notice that the surge was rather high. However, surprisingly, it was only slightly higher in Venice, which is situated at the very shallow head of the basin, than in Bakar, where the

Fig. 6 Sea-level series for the 2008 flood in Venice (left) and Bakar (right): **a** observed 1-hourly sea levels and corresponding tidal predictions, **b** residual series and low-frequency variability (data low-pass filtered at 10 days), **c** first mode of the pre-existing Adriatic seiche

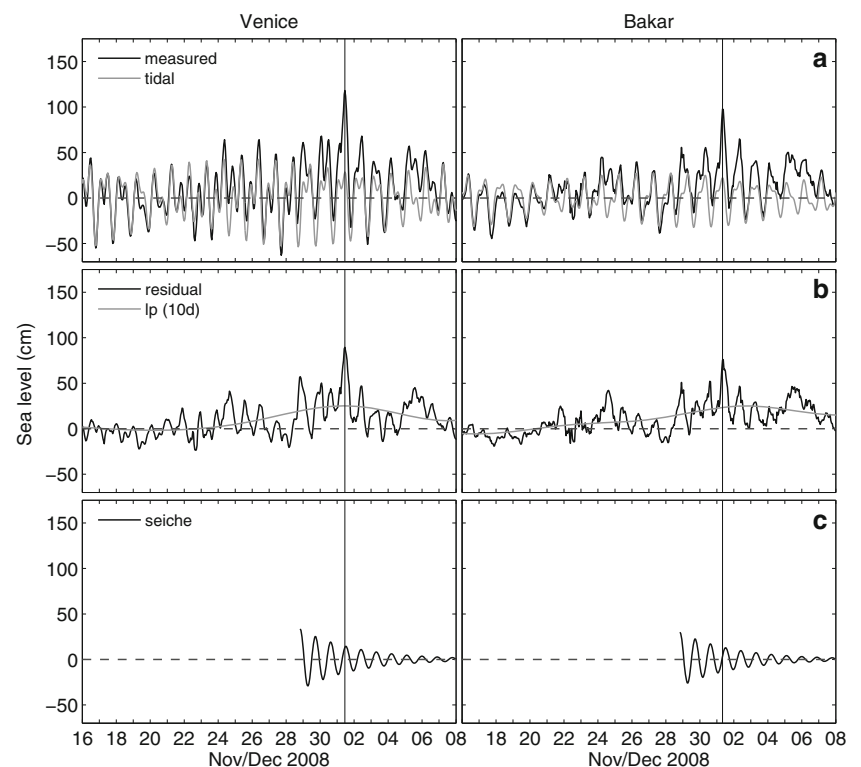
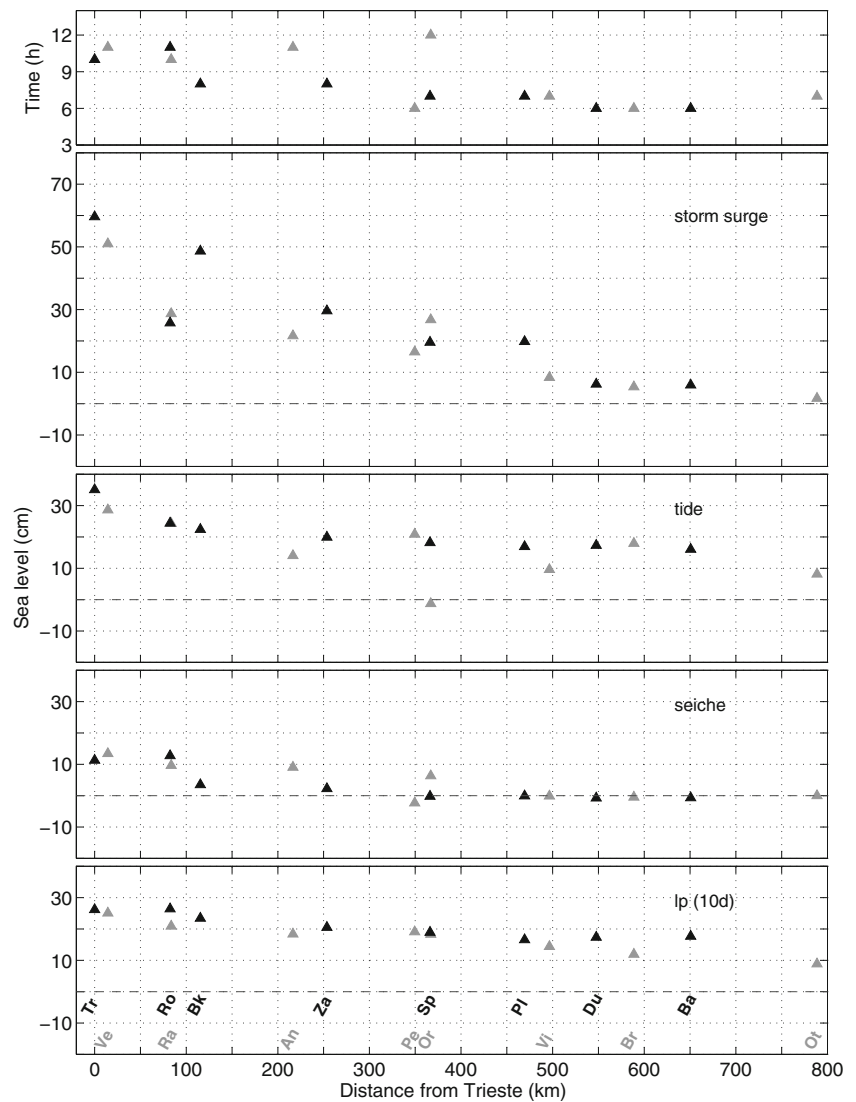


Fig. 7 Contribution of the four components at the onset of the local sea-level maximum for the 2008 flood. The east Adriatic stations are denoted with *black triangles*, and the west Adriatic stations are denoted with *grey triangles*: Trieste (Tr), Rovinj (Ro), Bakar (Bk), Zadar (Za), Split (Sp), Ploče (Pl), Dubrovnik (Du), Bar (Ba), Venice (Ve), Ravenna (Ra), Ancona (An), Pescara (Pe), Ortona (Or), Vieste (Vi), Bari (Br), and Otranto (Ot). The abscissa denotes the station distance from Trieste when the stations are projected onto the along-basin section indicated in Fig. 1. The exact times of the peak onset are indicated on the top panel; the ordinate axis refers to the 03–14 h interval on 1 December 2008



depths are significantly larger. The wind caused a considerable sea-level slope along the basin and a weaker across-basin slope with somewhat higher levels on the eastern coast of the Northern Adriatic than at corresponding locations on the western coast. This is evident from Fig. 7, in which we analyse the contribution of each of the above-mentioned processes to the formation of the local maximum. Interestingly, the wind and air pressure mostly accumulated water in Trieste Bay, but surprisingly less in the vicinity of Rovinj.

The storm surge was, as expected, decisive for flooding while the other components intensified its strength. In many locations, the storm surge contributed an amount twice as high as the tide; the low-frequency variability was of comparable height with the tide. The excited Adriatic-wide seiche was not very intense, and it played a rather small part in the high sea-level formation in the Northern Adriatic: it was slightly positive at Bakar, and it was in the positive phase with a contribution of approximately 13 cm at Venice and Rovinj (Fig. 7). Hence, the flood on 1 December 2008 occurred due to a

delicate interplay between the high storm surge, the tide and the basin-wide seiche, which were all superimposed on a 20 cm sea-level maximum due to low-frequency atmospheric forcing. However, the spatial structure of the storm surge (an up-sloping sea level to the east) resulted in the rarely experienced flooding along the eastern Adriatic coast. To identify the underlying conditions, we compare this event with the well-studied flood on 4 November 1966 and focus on the spatial structure of the two storm surges and on the differences in the associated meteorological forcing.

3.2 The flood on 4 November 1966

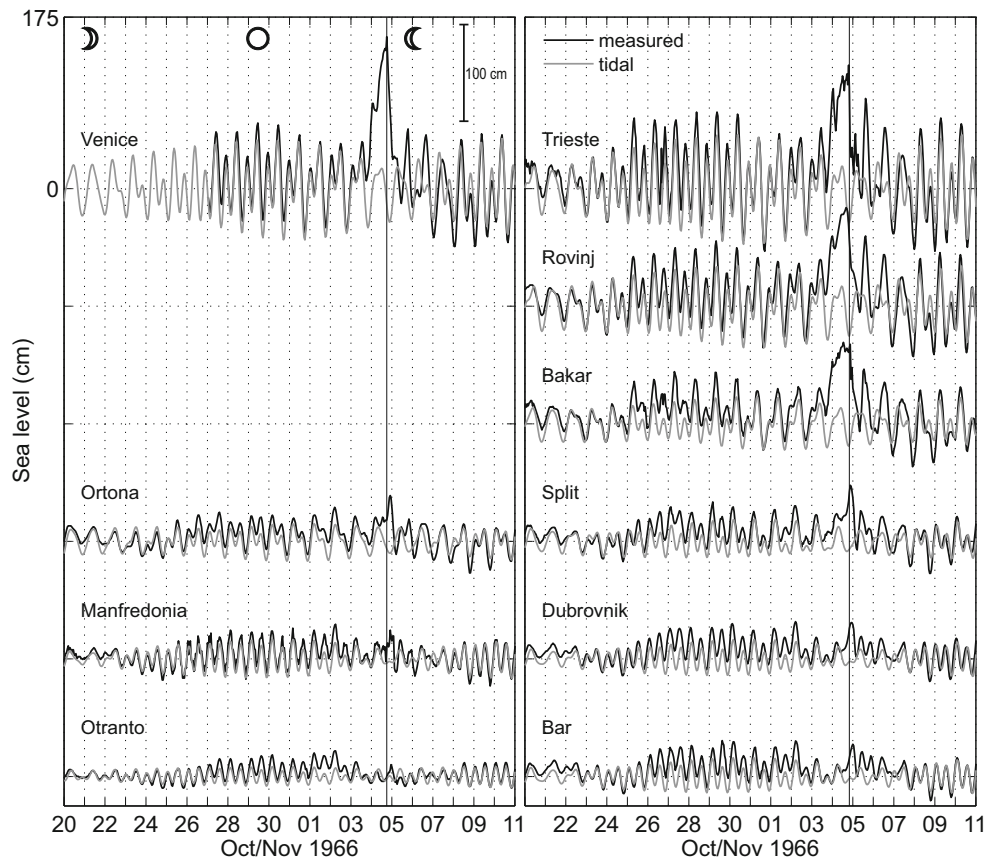
The flood on 4 November 1966 is often perceived as the flood of the century because the sea level at Venice reached its highest point ever recorded and was 30 cm above the second highest value. However, the maximum level recorded is only the seventh highest at Trieste, the fourth highest at Rovinj and the ninth highest at Bakar. The synoptic situation related to the

event has been extensively studied (De Zolt et al. 2006; Malguzzi et al. 2006; Cavaleri et al. 2010; Bertotti et al. 2011). The flood was induced by a cyclone that formed 2 days earlier over Spain, and while moving eastward, the cyclone reached the Gulf of Genoa in the morning on 3 November. At the same time, an anticyclone positioned over the Balkans intensified, which led to a strong zonal air-pressure gradient and a persistent southerly air flow. Channelled by the surrounding mountains, the wind in the Adriatic further strengthened and aligned along the basin. On 4 November, the cyclone rapidly deepened and moved northward over north-eastern Italy (documented on synoptic charts in, e.g. Malguzzi et al. 2006, their Fig. 1). The low was not very deep, but the advection of large amounts of warm and moist air from the south dramatically intensified the air-pressure gradient across the Adriatic. Our data show that at 13 CET the air-pressure difference between Rimini and Dubrovnik was 18 hPa. The Sirocco still intensified and coastal stations in the Northern Adriatic registered a maximum wind speed of 19 m/s at 16 CET, while closely offshore the wind was estimated up to 28 m/s (Bertotti et al. 2011). Farther south, the wind measured along the coast of the Middle Adriatic was of comparable strength and slightly stronger at the eastern side (not shown), which indicates that several hours before the peak surge, the wind field was rather uniform over the basin. According to the

ERA 40 atmospheric fields (Fig. 5, right), the synoptic situation on 4 November 1966 was characterised by a sharp west-to-east air-pressure gradient and a very strong, fairly homogeneous south-easterly Sirocco wind blowing along the entire Adriatic. It should be noted that the reanalysis wind field achieved a good agreement with the observed wind data, particularly with regard to the wind direction.

The main *acqua alta* occurred early in the evening (Fig. 8) when the air pressure over the Northern Adriatic reached its minimum and the weather front crossed the area. The flood would have been significantly higher if, at the moment of the highest level, the tide had not been approaching its minimum. Apparently, the tide mitigated the flood in Venice by 16 cm and in Trieste by more than 30 cm. However, at Bakar, the maximum occurred twice during the day: first at 13 CET while the storm surge was still building up and when, with the onset of the high tide, the flood occurred, and again in the evening during the passage of the weather front. Furthermore, the surge on 4 November 1966 was an isolated event and was not supported by a previously generated seiche (De Zolt et al. 2006); our sea-level and meteorological data provided no evidence to conclude otherwise. Hence, the flood on 4 November 1966 was a result of the storm-surge activity. A strong, spatially homogeneous Sirocco blew uninterruptedly along the Adriatic for more than a day and, by driving water

Fig. 8 The same as in Fig. 2, but for the 1966 flood



into the closed end of the basin, produced the great surge on the northern Adriatic shelf. Meanwhile, low air pressure, especially at the western coast, also increased the height of the surge. It is interesting to notice that the residual sea level at Venice was 36 cm higher than at Trieste, which indicates that the water surface sloped upwards from the eastern towards the western shore.

4 Discussion

The intriguing question is why the surge on 1 December 2008 had such an outstanding effect on the eastern coast and not on Venice, while the storm surge on 4 November 1966 was so severe at Venice and of a milder intensity at the opposite shore. The data collected along both sides of the Adriatic show that in 1966 the surge formed a sharp across-basin gradient, with sea level in the northern Adriatic tilted upward towards the western coast. On the other hand, during the 2008 event the storm surge formed a weaker across-basin gradient with levels being somewhat higher at the eastern coast.

The two episodes were governed by distinct meteorological forcing. With the aim of illustrating the difference, we shall represent the forcing by the equilibrium elevation ζ_e . Its meaning becomes obvious if the standard storm-surge equations (e.g. Murty 1984) are written in a somewhat different way:

$$\begin{aligned} \frac{d\vec{c}}{dt} - f\vec{c} \times \vec{k} &= -g\nabla(\zeta - \zeta_e) - \frac{\vec{\tau}_b}{D\rho} + \vec{\lambda} \\ \frac{\partial\zeta}{\partial t} + \nabla(D\vec{c}) &= 0 \end{aligned} \quad (1)$$

where ζ is the elevation of sea level, \vec{c} is the vertically averaged current, \vec{k} is the unit vector pointing vertically upwards, f is the Coriolis parameter, g is the acceleration due to gravity, D is the water depth, ρ is the density, $\vec{\tau}_b$ is the bottom stress and $\vec{\lambda}$ is the lateral friction. The equilibrium elevation is defined by:

$$\nabla\zeta_e = -\frac{\nabla p_a}{g\rho} + \frac{\vec{\tau}_s}{gD\rho} \quad (2)$$

with p_a denoting the air pressure and $\vec{\tau}_s$ being the wind stress. With the wind stress decomposed into the along-basin and across-basin components, there are three contributions to the equilibrium elevation.

In order to depict the air-pressure-related equilibrium elevation, the balance between the left side and the first term on the right side of Eq. (2) is considered. The equation is integrated using $g=9.81 \text{ m/s}^2$ and $\rho=1029 \text{ kg/m}^3$ and assuming that over the integration area the positive and negative equilibrium elevations balance each other while the mean air pressure is close to the global mean value (1013 hPa). The result is

shown in Fig. 9 (top). Obviously, air pressure supported a different spatial distribution of equilibrium elevation in the years 1996 and 2008, with a range that was significantly larger in the former than in the latter year. In both years, equilibrium sea levels were higher along the western than along the eastern coast. However, in neither case did the air-pressure-controlled equilibrium elevation surpass some 10–20 cm.

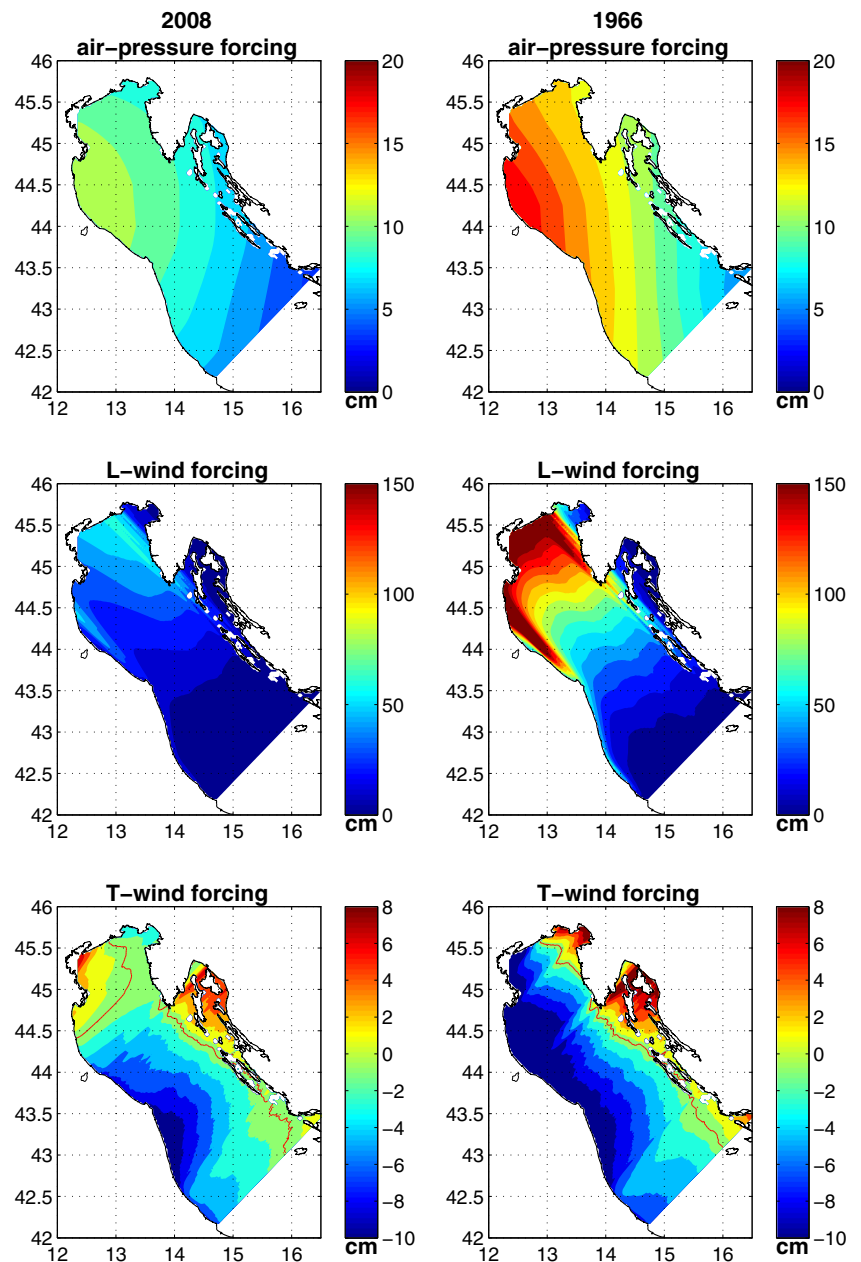
With the aim of mapping the wind-related equilibrium elevation, the balance between the left side and the second term on the right side of Eq. (2) is utilized. The wind stress is computed following:

$$\vec{\tau}_s = C_D \rho_a |\vec{W}| \vec{W} \quad (3)$$

with \vec{W} being the wind velocity, ρ_a the air density ($\approx 1 \text{ kg/m}^3$) and C_D the wind-dependent drag coefficient computed as proposed by Lionello et al. (2006). The equilibrium elevation is then determined by taking into account the Adriatic bathymetry and by integrating along and across the basin. The integration in the along-basin direction is done from an across-basin section in the Middle Adriatic, with the arbitrary integration constant set to zero there. The across-basin integration is done from the western to the eastern shore, requiring that the integral of equilibrium elevation along each transverse section be equal to zero. The results, illustrating the combined effect of wind stress and variable bathymetry on the equilibrium elevation, are also shown in Fig. 9. They reveal that the along-basin wind supported the equilibrium-elevation distribution characterized by amplitude and shape noticeably differing between the two floods (Fig. 9, middle). The wind set-up imposed along the basin in 1966 was much steeper than in 2008, due to the overall higher wind speeds (Fig. 5, bottom). However, the interesting feature is the across-basin slope related to the along-basin wind forcing. In 1966, the spatially uniform long-shore wind, due to bottom-slope effect, tilted equilibrium level across the basin, resulting in a raise at the shallower western coast. In 2008, the wind shear related to stronger winds blowing along the eastern coast surpassed the competing bottom-slope effect and therefore supported an oppositely directed equilibrium slope—that is, a raise close to (but not at) the eastern coast. The across-basin slope related to across-basin wind (Fig. 9, bottom) was rather small due to a relatively low wind speed and short wind fetch. Moreover, it was of comparable size in 2008 and in 1966, except in the northernmost part of the Adriatic. Hence, the across-basin wind was of secondary importance for the flooding of the eastern coast in 2008 and for the differences between the two episodes.

It may be expected that real sea levels during the 1966 and 2008 episodes differed from the equilibrium values, and the question is, to what extent? In the case of air-pressure forcing, the response of sea level to the forcing probably did not depart

Fig. 9 Meteorological forcings related to the ECMWF fields on 1 December 2008 (*left*) and 4 November 1966 (*right*) that are shown in Fig. 5 and expressed as equilibrium elevation (cm): air-pressure forcing (*top*), along-basin wind forcing (*middle*) and across-basin wind forcing (*bottom*)



much from the inverted-barometer response, because the forcing field was characterized by large scales (Fig. 9, top) and it changed rather slowly. Thus, for example, the speed of air-pressure perturbations U during the two episodes ranged between 13 and 15 m/s, implying—with a mean depth of the Adriatic shelf of about 100 m—that $U^2/(gD) \ll 1$ and that therefore the inertial effect was relatively small (e.g. Lamb 1932). The near-equilibrium response of the Adriatic sea level to the air-pressure forcing at synoptic scales was previously detected by Karabeg and Orlić (1982), on the basis of cross-spectral analysis of meteorological and oceanographic time series.

The case of wind forcing is a more complex one. As is visible from Fig. 9 (middle and bottom), spatial variability

of the forcing field was much larger than in the case of air-pressure forcing, and it may therefore be assumed that inertial-cum-frictional adjustment resulted in real sea levels considerably departing from the equilibrium values. Most likely, the adjustment was further complicated by a complex morphology of the Croatian coast. A proper reproduction of these processes obviously requires a high-resolution numerical modelling, which, however, is beyond the scope of the present paper. Still, it seems reasonable to conclude that the wind-driven equilibrium maxima contributed to the nearby sea levels, and that therefore the bottom-slope effect was important for the cross-basin difference in 1966 whereas the shear of along-basin wind contributed to the difference in 2008.

The effect of wind stress over the variable bathymetry and the relative importance of the along-basin and the across-basin wind forcing is examined more closely by mapping wind-stress-to-depth ratio (Fig. 10). Evidently, in 1966, the effect of along-basin wind was significantly stronger along the western coast of Northern Adriatic, while in 2008, it was maximum at the eastern coast. As already observed, the effect of the across-basin wind was only minor, in 2008 being slightly larger at the eastern coast than in 1966.

5 Conclusions

The flood in 2008 was induced by a depression centred above the Ligurian Sea and by a spatially variable wind field with maximum wind speeds along the much deeper eastern coast and wind directions varying from south in the southern Adriatic to south-east over the northern part of the basin. The surge in 1966 was generated by a depression above the northern Italy and by an exceptionally strong, rather homogeneous wind blowing along the main axis of the basin, with comparable strengths over the deep eastern side and the shallow western side. It is evident that the difference between the two sides of the Adriatic in the two events depended more upon the air pressure and the longitudinal wind than upon the transversal wind. Dynamics related to the longitudinal wind was the essential factor which determined whether the western or the eastern coast would be exposed to stronger flooding.

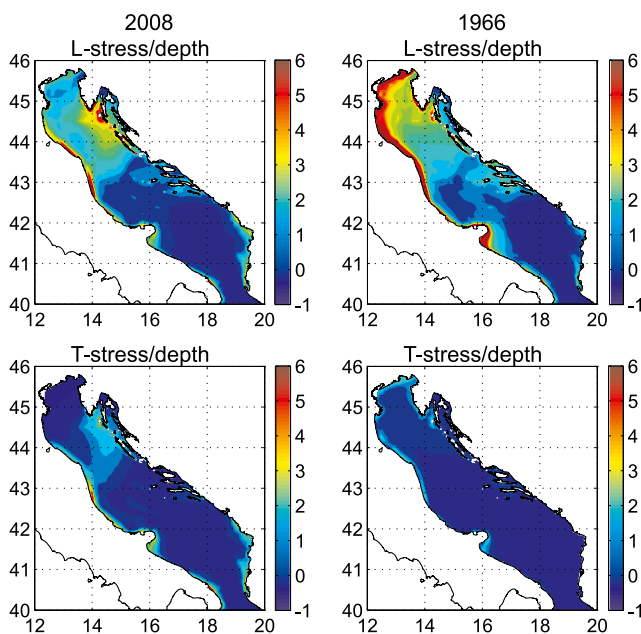


Fig. 10 The along-basin (*top*) and the across-basin (*bottom*) wind stress divided by depth and normalized by the respective average values of wind stresses over the basin for the two events (in units 10^{-2} m^{-1}), related to the ECMWF wind fields on 1 December 2008 (*left*) and 4 November 1966 (*right*) shown in Fig. 5

Climatology of extreme events in the Northern Adriatic and the trends in marine storminess have recently been studied in several papers, but there is no consensus on this issue. Lionello et al. (2012) have shown that there is no net increase of the large and the extreme events. Still, Masina and Lamberti (2013) have detected a slight increase in the magnitude of extremely high sea levels along the north-western side of the Adriatic, namely, at Venice and Porto Corsini (Ravenna), and this has mainly been attributed to the intensification of the north-easterly Bora wind. Bora induces a positive storm surge that is generally smaller than that due to Sirocco along the western Adriatic, but it induces a negative surge in the Gulf of Trieste (Raicich 2003). However, this study shows that Sirocco produces under certain conditions a higher storm surge at the western coast and under different conditions at the eastern coast, the interaction between variable topography and the Sirocco-wind shear being the controlling mechanism. More specifically, a spatially homogeneous Sirocco, as in 1966, due to the effect of the sea-bottom slope leads to a higher response along the western shore. On the other hand, on those occasions when the Sirocco velocity increases towards the east, as in 2008, the shear of along-basin wind may cancel out or even surpass the influence of the bottom topography, which results in higher water levels along the eastern shore. Wind-induced currents during strong Sirocco modify the generally cyclonic circulation in the Adriatic and can temporarily even reverse the outgoing flow along the Italian coast (Orlić et al. 1994). Such a behaviour is expected in situations such as was the storm on 4 November 1966. However, on the occasion of 1 December 2008 storm, it may be expected that the currents related to the across-basin slope would reinforce the Adriatic cyclonic circulation. Hence, it could prove rewarding to examine this in some long-term current measurements performed close to the Italian coast.

Wind waves can substantially affect the water level along a coastline, the more so if the area is shallow and breaking starts farther from the coast (e.g. Bowen et al. 1968). In the Adriatic, the wave set-up should have a stronger effect on the exposed, gently-sloping western coast than on the eastern coast which is steep and protected by the chain of islands. On 4 November 1966, the maximum wave-induced set-up close to Venice was estimated to 30 cm (De Zolt et al. 2006) when closely offshore wave heights were above 8 m (Cavaleri et al. 2010). On 1 December 2008, north/north-westward propagating waves were generated, with greatest wave heights of some 5 m at the eastern coast of the Northern Adriatic (Bertotti et al. 2011). However, these could not produce any significant wave set-up at the Punta Salute tide gauge inside the Venetian Lagoon, and even less at the steep Croatian coast, especially in a sheltered position of the Bakar tide gauge. If not so, the wave set-up would have been larger at the western coast and would have diminished the across-basin sea-level difference; hence in 2008, the storm-surge slope imposed by the along-basin wind shear would have been even greater.

In conclusion, the presence of the Sirocco-wind shear over the Adriatic on 1 December 2008, in combination with high tide and the prolonged interval of the raised water level due to planetary atmospheric forcing, caused the flooding of the eastern shore. On the other hand, the spatially uniform Sirocco on 4 November 1966 generated the highest surge along the shallow north-western coastline due to the bottom-slope effect; the sea level would have been even higher if the tidal contribution had been positive during the event. Although this study considers only two floods, these are exceptional events that carry valuable information on decisive factors that control which side of the Adriatic will be exposed to stronger flooding. The results obtained in this study provide an explanation of the underlying physical mechanisms. They will be used as a basis for future work in which a numerical model will be applied with realistic forcing and a basin configuration to evaluate the hypothesis in detail.

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References

- Accerboni E, Manca B (1973) Storm surge forecasting in the Adriatic Sea by means of a 2d hydrodynamical numerical model. *Boll Geofis Teor Appl* 15(57):3–22
- Bertotti L, Bidlot JR, Buizza R, Cavaleri L, Janousek M (2011) Deterministic and ensemble-based prediction of Adriatic Sea sirocco storms leading to ‘acqua alta’ in Venice. *Q J Roy Meteor Soc* 137(659):1446–1466. doi:10.1002/qj.861
- Bonato N, Egiatti G, Ferla M, Filippi M (2001) Tidal observations in the Venetian Lagoon. Update on sea level change from 1872 to 200. Book of Abstracts, Final Workshop of COST Action 40. Hydrographic Institute of the Republic of Croatia, Split, 97–105
- Bowen AJ, Inman DL, Simmons VP (1968) Wave set-down and set-up. *J Geophys Res* 73(8):2569–2577
- Cavaleri L, Bertotti L (1997) In search of the correct wind and wave fields in a minor basin. *Mon Weather Rev* 125:1964–1975. doi:10.1175/1520-0493(1997)125<1964:ISOTCW>2.0.CO;2
- Cavaleri L, Bertotti L (2006) The improvement of modelled wind and wave fields with increasing resolution. *Ocean Eng* 33:553–565. doi:10.1016/j.oceaneng.2005.07.004
- Cavaleri L, Bertotti L, Buizza R, Buzzi A, Masato V, Umgiesser G, Zampieri M (2010) Predictability of extreme meteo-oceanographic events in the Adriatic Sea. *Q J Roy Meteor Soc* 136:400–413. doi:10.1002/qj.567
- Cerovečki I, Orlić M, Hendershott MC (1997) Adriatic seiche decay and energy loss to the Mediterranean. *Deep-Sea Res I* 44(12):2007–2029. doi:10.1016/S0967-0637(97)00056-3
- De Zolt S, Lionello P, Malguzzi P, Nuhu A, Tomasin A (2006) The disastrous storm of 4 November 1966 on Italy. *Nat Hazard Earth Sys* 6:861–879
- Dee DP, Uppala SM, Simmons AJ et al (2011) The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q J Roy Meteor Soc* 137:553–597. doi:10.1002/qj.828
- Finizio C, Palmieri S, Riccucci A (1972) Numerical model of Adriatic for prediction of high tides at Venice. *Q J Roy Meteor Soc* 98(415):86–104. doi:10.1002/qj.49709841508
- Godin G, Trotti L (1975) Trieste-water levels 1952–1971: a study of the tide, mean level, and seiche activity. Miscellaneous special publication 28. Department of the Environment, Fisheries and Marine Service, Ottawa
- Hendershott MC, Speranza A (1971) Co-oscillating tides in long, narrow bays: the Taylor problem revisited. *Deep-Sea Res* 18:959–980. doi:10.1016/0011-7471(71)90002-7
- Karabeg M, Orlić M (1982) The influence of air pressure on sea level in the North Adriatic—a frequency-domain approach. *Acta Adriat* 23(1/2):21–27
- Kasumović M (1959) Dynamical effect of the atmosphere on sea-level oscillations in the Adriatic (in Croatian). *Rasprave odjela za matematičke, fizičke i tehničke nauke JAZU* 2(1):1–48
- Lamb H (1932) *Hydrodynamics*. Cambridge University, Cambridge
- Lionello P, Mufato R, Tomasin A (2005) Sensitivity of free and forced oscillations of the Adriatic Sea to sea level rise. *Clim Res* 29:23–39
- Lionello P, Sanna A, Elvini E, Mufato R (2006) A data assimilation procedure for operational prediction of storm surge in the Northern Adriatic Sea. *Cont Shelf Res* 26:539–553. doi:10.1016/j.csr.2006.01.003
- Lionello P, Cavaleri L, Nissen KM, Pino C, Raicich F, Ulbrich U (2012) Severe marine storms in the Northern Adriatic: characteristics and trends. *Phys Chem Earth* 40–41:93–105. doi:10.1016/j.pce.2010.10.002
- Malačić V, Viezzoli D, Cushman-Roisin B (2000) Tidal dynamics in the northern Adriatic Sea. *J Geophys Res* 105:26.265–26.280
- Malguzzi P, Grossi G, Buzzi A, Ranzi R, Buizza R (2006) The 1966 ‘century’ flood in Italy: a meteorological and hydrological revisit. *J Geophys Res-Atmos* 111:D24106. doi:10.1029/2006JD007111
- Masina M, Lamberti A (2013) A nonstationary analysis for the Northern Adriatic extreme sea levels. *J Geophys Res Oceans* 118:3999–4016. doi:10.1002/jgrc.20313
- Mosetti F (1985) Problems on storm surges forecasting in the Northern Adriatic Sea. *Boll Oceanol Teor Appl* 3(4):263–297
- Mosetti F (1987) Distribuzione delle maree nei mari italiani. *Boll Oceanol Teor Appl* 5(1):65–72
- Murty TS (1984) Storm surges: Meteorological ocean tides. Department of Fisheries and Oceans, Ottawa
- Orlić M, Kuzmić M, Pasarić Z (1994) Response of the Adriatic Sea to the bora and sirocco forcing. *Cont Shelf Res* 14(1):91–116
- Otnes RK, Enochson L (1978) *Applied time series analysis*, vol 1, 2nd edn. Wiley, New York
- Pasarić M, Orlić M (1992) Response of the Adriatic Sea level to the planetary-scale atmospheric forcing. *Geogr Monog Series* 69:29–39
- Pasarić M, Orlić M (2001) Long-term meteorological preconditioning of the North Adriatic coastal floods. *Cont Shelf Res* 21:263–278. doi:10.1016/S0278-4343(00)00078-9
- Pasarić M, Pasarić Z, Orlić M (2000) Response of the Adriatic sea level to the air pressure and wind forcing at low frequencies (0.01–0.1 cpd). *J Geophys Res* 105:11423–11439. doi:10.1029/2000JC900023
- Pawlowicz R, Beardsley B, Lentz S (2002) Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. *Comput Geosci* 28:929–937. doi:10.1016/S0098-3004(02)00013-4
- Raicich F (2003) Recent evolution of sea-level extremes at Trieste (Northern Adriatic). *Cont Shelf Res* 23(3–4):225–235. doi:10.1016/S0278-4343(02)00224-8

- Raicich F, Orlić M, Vilibić I, Malačič V (1999) A case study of the Adriatic seiches (December 1997). *Nuovo Cimento C* 22:715–726
- Robinson AR, Tomasin A, Artegiani A (1973) Flooding of Venice, phenomenology and prediction of the Adriatic storm surge. *Q J Roy Meteor Soc* 99(422):688–692. doi:10.1002/qj.49709942210
- State Hydrographic Institute (1991) Tide tables: Adriatic Sea - east coast, Split
- State Hydrographic Institute (2012) Tide tables: Adriatic Sea - east coast, Split
- Stravisi F, Marussi SA (1973) Analysis of a storm surge in Adriatic Sea by means of a 2-dimensional linear-model. *Atti Accad Naz Lincei Cl Sci Fis Mat Nat* 54(2):243–260
- Tomasin A, Frassetto R (1979) Cyclogenesis and forecast of dramatic water elevations in Venice. In: Nihoul J (ed) *Marine forecasting*. Elsevier, Amsterdam, pp 427–437
- Trigo IF, Davies TD (2002) Meteorological conditions associated with sea surges in Venice: a 40 year climatology. *Int J Climatol* 22:787–803. doi:10.1002/joc.719
- Uppala SM, Kållberg PW, Simmons AJ et al (2005) The ERA-40 re-analysis. *Q J Roy Meteor Soc* 131:2961–3012. doi:10.1256/qj.04.176
- Venice Municipality – Tide Monitoring and Forecast Center (<http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/25419>, reached on 23 March 2014)