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# Sensitivity of free and forced oscillations of the Adriatic Sea to sea level rise

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ABSTRACT: The expected global warming will cause a sea level rise (SLR) that, in addition to direct effects on coastal areas, will affect ocean dynamics. In the Adriatic Sea, seiches, tides and storm surges will change in a way that will depend on the possible human interventions to counteract floods. Such actions have 2 extremes: a full compensation strategy (FCST), preserving the present coastline by dams, and a no compensation strategy (NCST) that allows a free expansion of the sea into the low plains. Numerical models were used to describe the different scenarios. FCST would result in increased wave speed and reduced friction, while NCST would give a larger basin extension. In the former case, the resonant period was shortened and moved away from the period of tides: the amplitude of these, and also the surge height, would be reduced (if all other conditions are maintained), while seiches would show an overall larger range. In contrast, the absence of countermeasures would lengthen the resonant period, giving larger tidal range in the northern part and stronger surges. In the case of NCST, assuming an extreme 10 m SLR, dramatic effects would be observed on the semidiurnal tide and the second seiche that would almost double their range at the coast. The results emphasize the strong difference stemming from alternate compensation strategies, but they also show that the changes in the amplitude of the sea surface oscillations are small with respect to the SLR; indeed, not relevant for the variations of level expected for the next 100 yr.

KEY WORDS: Global warming · Sea level rise · Adriatic Sea · Defense strategy



## 1. INTRODUCTION

For most coastal zones, SLR (Sea Level Rise) is the most dangerous aspect of climate change. In the Adriatic Sea it would affect many small islands along the Croatian coast and the whole low coast of the Po and Venetian-Friuli plains, including the unique environment of the Venetian lagoon and the city itself. Besides producing direct effects (loss of economically valuable areas, salt intrusion in aquifers, increased coastal erosion, etc.), SLR might change the characteristics of free (seiches) and forced (tides and storm surges) oscillations of the Adriatic Sea. The implications of SLR should be accounted for in planning coastal protection and future harbor management.

The sea surface oscillations in the Adriatic Sea are determined by the superposition of tides, storm surges and seiches. Tides are caused by the astronomical forcing inside the basin and by the tide level forced at the Otranto Strait by the Mediterranean Sea. Storm surges are produced by the combined action of wind stress and atmospheric pressure which accumulate water at the northern closed end of the Adriatic basin. Seiches are free oscillations of the water level which take place after the storm which caused the surge is over and the action of wind stress and sea level pressure is not able to sustain the difference in level between the northern and southern parts of the Adriatic. The dynamics of all these oscillations depends on the shape of the basin, the propagation speed of water waves (which is proportional to the square root of the water depth), and the friction exerted by the sea bottom. SLR could potentially greatly affect these factors, especially the shallow northern part of the Adriatic and the flat

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coastal zone surrounding it, which could be flooded if a substantial SLR occurs in the future. Such changes in the dynamics would imply an indirect effect of climate change on the oscillations of the sea surface in the Adriatic Sea. The identification of mechanisms responsible for this indirect effect and their evaluation is the goal of this study.

Present estimates of SLR and uncertainties are summarized in the 3rd report of the Intergovernmental Panel on Climate Change (Houghton et al. 2001). During the 20th century SLR was in the range 1.0 to 2.0 mm $yr^{-1}$. Projected SLR, accounting for several possible scenarios, ranges from 0.09 to 0.88 m by 2100. Projections further on in time have, obviously, an even larger uncertainty. However, SLR will continue, even if GHG (Green House Gases) concentrations stabilise. Thermal expansion alone could contribute 1 to 4 m for $CO_2$ levels of twice and 4 times the pre-industrial period, respectively. The speed of such growth would depend on the penetration of the temperature increase into the ocean interior. A reasonable estimate is a SLR between 0.5 and 1 m in 500 yr. The melting of polar ice sheets would potentially add a extremely large contribution to SLR. The Greenland ice-sheet is the most vulnerable, and for a warming between 5.5°C (consistent with mid-range GHG stabilisation scenarios) and 8°C, it could contribute between 3 and 6 m to SLR in 1000 yr.

The sea level of the Mediterranean is not always immediately related to the global one. It increased consistently with the mean global value through the 1960s (Church et al. 2001), but it subsequently dropped by 2 to 3 cm until the beginning of the 1990s (Tsimplis & Baker 2000). During the last decade of the 20th century, Mediterranean sea level increased 10 times faster than the global ocean scale (Fenoglio-Marc 2002). Reasons for this behavior are not well known, but it is not conceivable in the long term that the Mediterranean Sea level can be uncoupled from large changes of the global one.

In brief, although there has been a large SLR during relatively recent history (sea level was 120 m below present level during the last glacial maximum about 20 000 yr ago) the largest SLR expected in one century is below 1 m, and a SLR of several meters is possible only on multi-centennial time scales. All these estimates are subjected to very large uncertainties.

This study does not aim to provide a precise estimate of the response of the Adriatic sea level dynamics to SLR in the next 100 yr. As will appear from the results, this is likely to be a negligible effect (at basin scale) whose precise assessment depends on the coastal defense management as well as on the value of SLR itself. On this relatively short scale, the uncer-

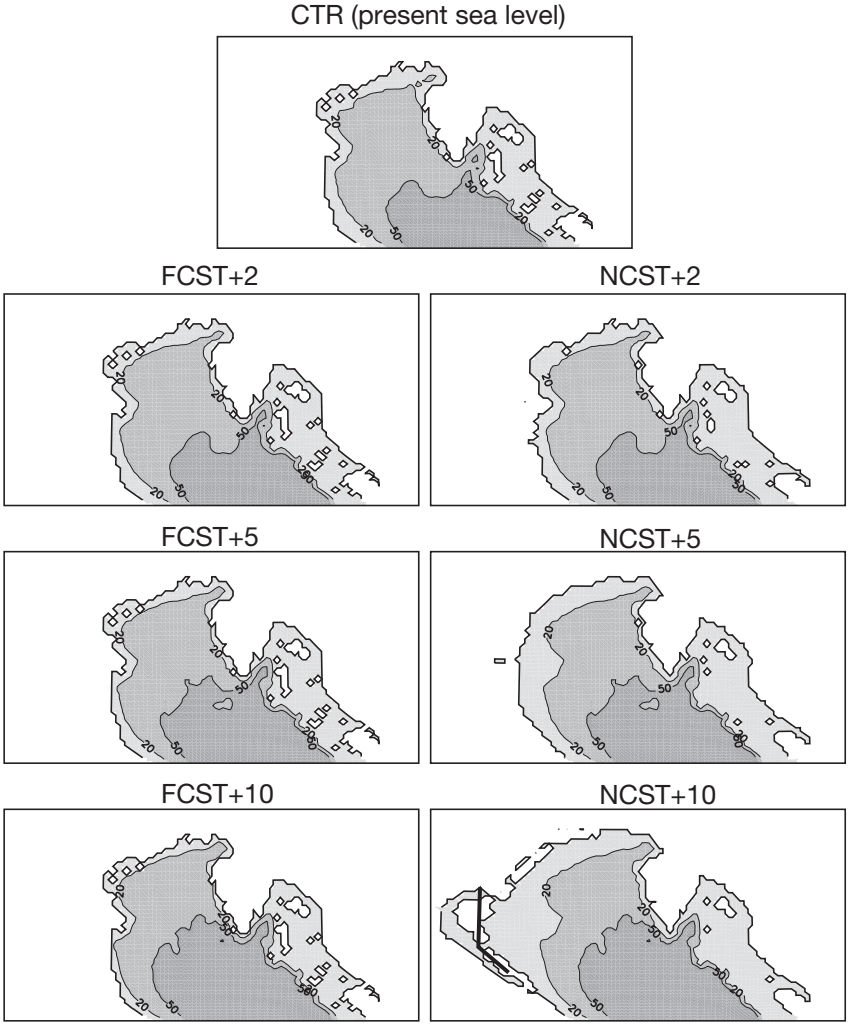


Fig. 1. Top panel: present water depth in the Gulf of Venice, shown as control (CTR). Left hand panels: Full Compensation Strategy (FCST: coastline is maintained) with a 2, 5 and 10 m sea-level rise (SLR). Right hand panels: No Compensation Strategy (NCST), again with 2, 5 and 10 m SLR. The Adriatic Sea covers the whole area below its raised mean level according to the present ground level distribution. Water depth contour lines are shown at 20 and 50 m. The thick black line in the bottom right panel shows a dam blocking a large lagoon present in the NCST for a 10 m SLR, located near the historical town of Ravenna ('Ravenna' lagoon). The area shown is 5° longitude × 2° latitude wide

tainties of the results (due also to the accuracy of the model) would be comparable to the observed signals of climate change. Instead, this study aims to evaluate the sensitivity of seiches, tides and storm surge to SLR, to identify critical issues playing a role in their variations, and establish the order of magnitude of the climate change signal, comparing SLR situations with the present one, referred to as CTR (Control) in this paper.

This study considers 3 SLR values: 2, 5 and 10 m with 2 different responses of human society regarding coastal defense. The FCST (Full Compensation Strategy) assumes that coastal protection and dams are built so that the present coastline is strictly maintained, independently the SLR value. The NCST (No Compensation Strategy) assumes that no action is taken, not even increasing ground level, so that the sea would submerge all areas below the future sea level. The strategies represent 2 unrealistic extremes, but are well defined references for an evaluation. In reality, a compromise between the 2 strategies is expected following cost-benefit logic. The SLR values assumed are conceivable only on multi-centennial time scales, and have been chosen so that imprecision of bathymetry, grid and model are secondary issues for the identification of the climate change signal.

The paper is organized in the following sections. Section 2 describes the model implementation, its accuracy, its computational grid, bathymetry and coastline corresponding to different SLR values and compensation strategies. Section 3 describes the response of the Adriatic seiches to SLR. Section 4 analyzes the behavior of tides and total sea level under strongly adverse meteorological conditions using the meteorological forcing which produced a sequence of floods of Venice in November 1996. The results of the study are summarized in Section 5.

## 2. MODEL IMPLEMENTATION

The change of the basin extension and depth associated with 2, 5 and 10 m SLR is shown in Fig. 1. The map is restricted to the northern part of the basin where the relative change of depth and effect on coastline are larger. Figures are based on bathymetric data, which have been extracted from a global dataset at $1/30$ degrees resolution (Smith & Sandwell 1996) and on land elevations extracted from the dataset of the GTOPO30 model (GTOPO30 is a global Digital Elevation Model [DEM] resulting from a collaborative effort led by the staff at the U.S. Geological Survey's EROS Data Center in Sioux Falls, South Dakota).

No compensation for local adjustment of the slope was included, though for increasing SLR values the FCST bathymetry presents a progressively larger step at the coast, which would be unrealistic on a sandy sea floor. If NCST is followed, the large lowland areas presently existing along the northern Adriatic coast, determine a large increase of the sea surface extension which would partially invade the present Italian coastal plain. The construction of a coastal dam (denoted by a black line in the bottom right panel of Fig. 1) to close off the inlets of a large lagoon (called 'Ravenna' lagoon in this paper, because of its location) created by a 10 m SLR, has been included in the PCST (Partial Compensation Strategy) only for this extreme SLR.

The model, called HYPSE (Hydrostatic Padua Sea Elevation model) is a standard 1 layer shallow water model, whose equations are derived from the vertical average of the momentum equation assuming a constant velocity profile. It adopts an orthogonal (possibly curvilinear) C-grid (Kantha & Clayson 2000). It uses the leap-frog time integration scheme with Asselin filter to prevent time splitting. It includes astronomical tide, meteorological forcing (sea level pressure and wind stress), a bottom stress vector

$$\vec{\tau}_b = -b_f \vec{u}|u| \tag{1}$$

where $b_f$ is the bottom friction coefficient, $\vec{u}$ is the current velocity vector and $|u|$ is its modulus, and a Smagorinsky horizontal diffusivity $A$ with coefficient $c_s$, whose expression in cartesian coordinates is:

$$A = c_s \Delta x \Delta y \left[ \left(\frac{\delta u}{\delta x}\right)^2 + \left(\frac{\delta v}{\delta y}\right)^2 + \frac{1}{2}\left(\frac{\delta v}{\delta x} + \frac{\delta u}{\delta y}\right)^2 \right] \tag{2}$$

where $u$ and $v$ are the current $x$ and $y$ components, respectively. Metric factors enter the expression actually used in the model, considering the earth's curvature.

The model's reliability depends on resolution and on the grid used for its implementation. Three different grids were tested. All of them had a varying resolution, higher in the northern shallow part of the basin where the sea surface oscillations have the highest amplitude. Two were orthogonal grids, with variable mesh. These 2 grids differed in the minimum step, which was 0.03° for the HRG (High Resolution Grid) and 0.05° for the LRG (Low Resolution Grid). For both grids, the highest resolution was reached in the northern part of the basin at 14° E, 44° N. Starting from that point, the grid step increased with a logarithmic increment (which uses a 1.01 factor) in both latitude and longitude. Fig. 2 shows the area covered by HRG and LRG, and how the density of grid points varied (right hand panel). Individual points cannot be distinguished, because of the high resolution . The HRG covered the whole Adriatic with $N_x = 133$ and $N_y = 146$ points in longitude and latitude. In practice, its resolution varied from 3.3 to 7 km.

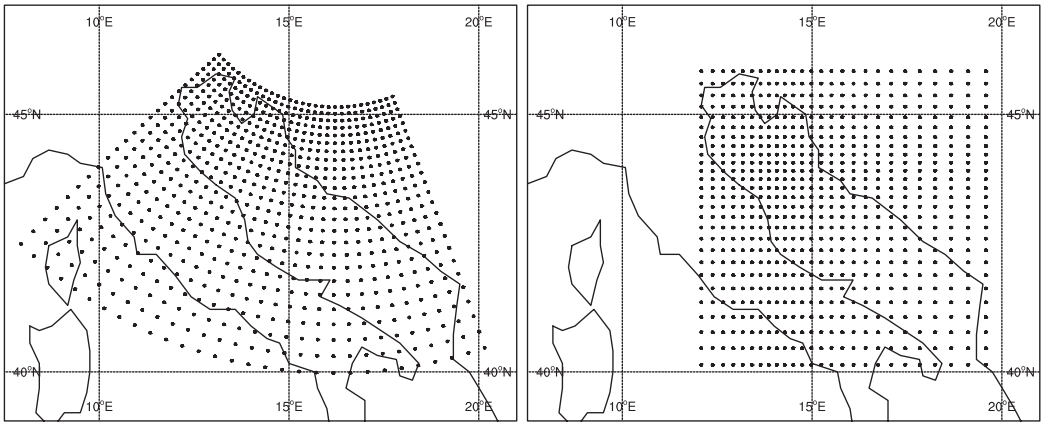


Fig. 2. Areas covered by the curvilinear grid (CG, left hand panel) and high resolution grid (HRG, right hand panel). Dots represent the grid point location (only 1 point out of 5 is plotted). The low resolution grid (LRG) covers the same area as the HRG

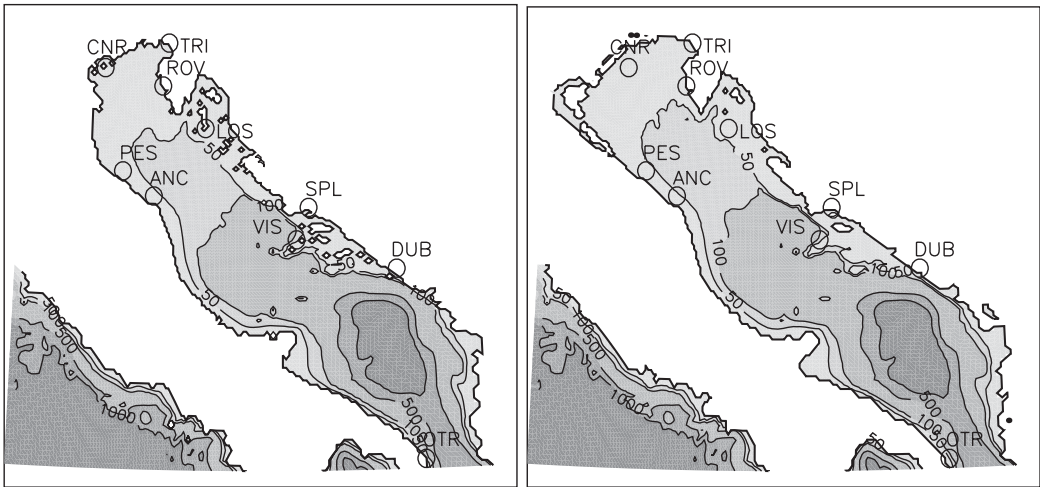


Fig. 3. Bathymetry of the Adriatic Sea and location of the stations used for the model validation. TRI: Trieste; CNR: Venice (CNR platform); PES: Pesaro; ANC: Ancona; SPL: Split; DUB: Dubrovnik; LOS: Losinj; ROV: Rovinj; VIS: Vis; OTR: Otranto. Left hand panel: present sea level; right hand panel: a 10 m SLR in the No Compensation Strategy (NCST). Contour lines at 50, 100, 500 and 1000 m are shown

The LRG covered the Adriatic with $N_x = 91$, $N_y = 86$, and its resolution varied from 5 to 11 km. A CG (Curvilinear Grid) was also tested. The CG covered an area corresponding to a circular sector on the global surface (Fig. 2, left hand panel). The sector originated from a centre located north of the basin, was 74° wide, and had 148 × 122 nodes (in the angular and radial direction), extending for 670 km to a distance of 890 km from the centre. The grid resolution progressively decreased from 2.7 to 7.7 km (at the northern and at the southern limit of the grid, respectively).

The accuracy of the model was tested by comparing the computed tidal levels with those observed at 9 stations along the Adriatic coast (Fig. 3). The hourly levels during a 1 mo period were used for computing the RMS (Root Mean Squared) error using all 9 stations as a function of $b_f$, bottom friction coefficient, and $c_s$, Smagorinsky diffusivity coefficient. The range explored was different for each grid and corresponds to that shown in Fig. 4. More than 100 simulations, each of them with a different value of the pair ($b_f$,$c_s$) were carried out in order to provide information for the contour plot algorithm used to produce Fig. 4, which describes the behavior of the model error as a function of the grid and of the values of these 2 parameters. Results (Fig. 4 and Table 1) show that the HRG grid was the most accurate, with a minimum RMS error of 1.4 cm for $b_f = 5 \times 10^{-4}$ and $c_s = 0.4$. The HRG and these values of the aforementioned parameters have been used in this study. The $b_f$ value shows that bottom fric-

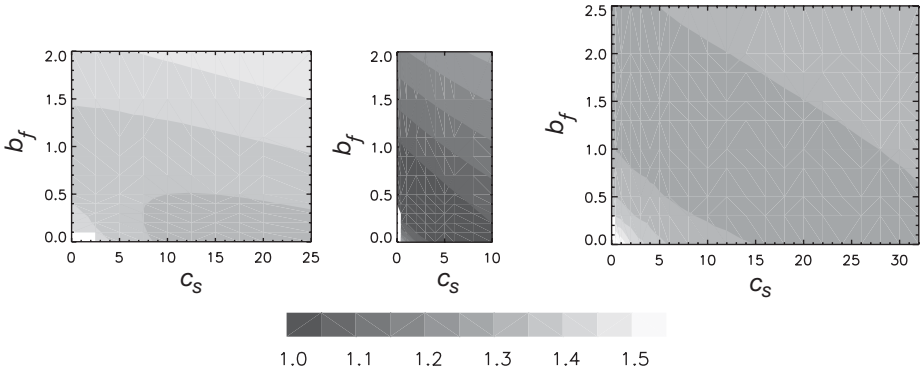


Fig. 4. Accuracy of the model for tidal simulation. The plots show the root-mean-squared (RMS) values for 9 stations along the coast of the Adriatic Sea. The panels refer to the low resolution grid (LRG, left), high resolution (HRG, center) and curvilinear (CG, right). Values are normalized with the minimum value (1.40 cm) which was attained using the HRG (see Table 1). The normalized RMS error was calculated as a function of the Smagorinsky constant ($x$-axis, $c_s$) and the bottom friction coefficient ($y$-axis, $b_f \times 10^3$). The axes have the same scale in all panels, and their different size corresponds to the different range explored using the various grids. Darker tones represent lower values (from 1.0 to 1.5, contour interval 0.05, according to the gray-scale bar below the panels). The small white areas near the origin of the axes denote parameter values where the model is unstable

tion was low and compatible with the smooth sandy bottom of the shallow part of the basin. The low value of $c_s$ is reasonable considering the high resolution of the model grid. Note, in fact, that the 2 coarser grids required higher values in order to simulate larger subgrid dissipation. Obviously, even in the HRG, $c_s$ and $b_f$ cannot be arbitrarily reduced, otherwise no mechanism could prevent the growth of dynamical instabilities, as shown by the white areas at the bottom left corners in all panels of Fig. 4, which denote parameter values that make the simulations unstable. Fig. 5 and Table 2 show the RMS error values at the single stations for the HRG. Local conditions, related to the complicated shape of the coastline and the position of the station were probably responsible for the higher model error in Split. The model parameters were optimized to reduce the error at the CNR station (a scientific platform of the Italian Consiglio Nazionale delle Ricerche) so that model accuracy is higher at the northern Adriatic coast, which is the most vulnerable area in the basin.

The model implementation included the boundary condition at the southern open boundary (the Otranto Strait) along which the sea level, varying in time, has to be imposed as an external condition. Therefore, the

Table 1. Minimum and maximum values of the root-mean-squared (RMS) error in the range explored and shown in Fig. 4 (values in cm). LRG: Low resolution grid; HRG: high resolution grid; CG: curvilinear grid

| Grid | Min. RMS error | Max. RMS error |
|---|---|---|
| LRG | 1.85 | 2.09 |
| HRG | 1.40 | 1.79 |
| CG | 1.79 | 2.24 |

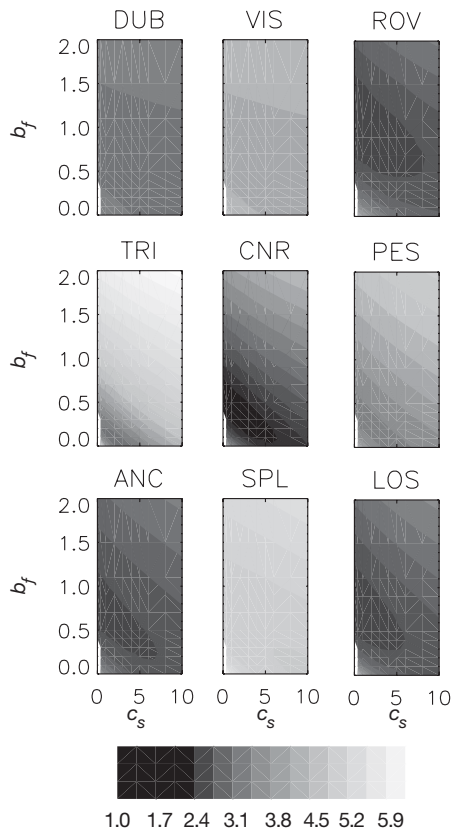


Fig. 5. Accuracy of the model for tidal simulation. The plots show the root-mean-squared (RMS) value for the 9 stations (see Fig. 3) for the high resolution grid (HRG) simulation. Values are normalized with the minimum value (0.64 cm) which is attained at the Venice CNR station (see Table 2). The normalized RMS error was calculated as a function of the Smagorinsky constant ($x$-axis, $c_s \times 10$) and of the bottom friction coefficient ($y$-axis, $b_f \times 10^3$). Darker tones represent lower values (from 1.0 to 6.25, contour interval 0.35 in all panels, according to the gray-scale bar below the panels). The small white areas denote parameter values where the model is not stable

Table 2. Minimum and maximum values of the root-mean-squared (RMS) error in the range explored for each station in Fig. 5 for the high resolution grid. Values in cm. See Fig. 3 legend for full station names

| Station | Min. RMS error | Max. RMS error |
|---|---|---|
| DUB | 1.90 | 2.24 |
| VIS | 2.72 | 3.19 |
| ROV | 1.12 | 2.95 |
| TRI | 1.79 | 5.66 |
| CNR | 0.64 | 3.12 |
| PES | 2.12 | 3.60 |
| ANC | 1.23 | 2.45 |
| SPL | 3.52 | 5.59 |
| LOS | 1.14 | 3.10 |

simulation of the tide also involves, besides $b_f$ and $c_s$, the specification of the amplitude forcing at the southern open boundary, along which the tide level was never recorded, and whose value was chosen to match that observed at the Otranto station, a few kilometers north of the boundary. Besides this, the diurnal tide requires the specification of the phase along the whole boundary. After several attempts, a phase lag of 30° between the western and eastern coast was imposed. With respect to tide and surges, a slightly different grid was used for the simulation of seiches, as a preliminary investigation showed that the optimal length of the basin in order to reproduce their observed periods is obtained by extending the grid about 50 km south of Otranto. The boundary conditions at the Otranto strait were identically maintained in all simulations, independently from the SLR values. This configuration implicitly neglects the changes in the dynamics of tides and, in general, of the sea surface oscillations, that are due to SLR at large scale in the Mediterranean basin. However, this limitation is not expected to be important for the results of this study, because the Ionian Sea and almost the entire Mediterranean Sea, apart from small coastal areas, are deep, so that even a 10 m sea level rise would make a negligible relative change of water depth.

## 3. THE EFFECT OF SLR ON SEICHES

Seiches are free oscillations of a basin (like the Adriatic) which appears as semi-enclosed. Perfectly free oscillations never occur in practice, since some external forcing is active at all times. However, the main reason to study seiches, in the present study, is the search for resonant frequencies of the system, so that the similar condition of forced oscillations (instead of free) is considered. They were identified by a sequence of simulations forced by an oscillation imposed at the southern boundary of the model. The model was spun-up starting with a state of rest until a steady oscillation was established and the amplitude of the oscillation inside the basin remained constant. In all simulations, the amplitude of the forcing oscillation at the boundary had the same value, but the period was different. Seiche periods are those characterized by maximum amplitude of the oscillation inside the basin. Fig. 6 shows the response of the whole basin for periods in the range from 10 to 24 h with a representation similar to tidal charts. Gray tones show the amplitude of the oscillation (co-range lines) and black lines connect points of constant phase (co-phase lines). The amplitude of the oscillations reached a maximum when a node was at the southern border of the basin. The longest period at which this happens is between 21 and 22 h (first seiche). As the period diminished, the wavelength also decreased and the node initially located at the southern border of the Adriatic moved northward. While moving north, it also shifted away from the western coast. This was due to the dynamics of the oscillations in the Adriatic Sea. The presence of the amphidromic point resulted from the superposition of the Kelvin wave traveling north-westward along the Croatian coast, which reflected at the end of the basin, and then travelled south-eastward along the Italian coast (Hendershott & Speranza 1971). The input energy was dissipated as the wave travelled up the basin and back, so the ratio of incoming to reflected energy on the section through the amphidrome diminished as it moved north causing it to shift simultaneously away from the western coast. The new node appeared at the southern border for a period between 10 and 11 h (second seiche). Therefore this analysis shows that, with the present sea level, the first 2 seiches have a period between 21 and 22 h (the first seiche with a structure similar to the diurnal tide) and between 10 and 11 h (the second seiche with a structure similar to the semidiurnal tide).

These 2 ranges were explored in detail by varying the period of the forcing with a 10 min step. Fig. 7 shows the amplification at Venice, that is the ratio between the amplitude of the seiche at the Venetian coast (CNR station) and at Otranto (southern open boundary of the Adriatic) as a function of the forcing period for the different strategies and various SLR values. The seiche is identified as the frequency at which amplification reaches a maximum. There is large uncertainty in the literature on the period of the Adriatic seiches. Though a peak in the spectrum of observed records of tide gauges clearly shows their presence, their frequency is case dependent, and a type of noise-seiche is observed almost at all times. This seems to limit the identification of a precise frequency for the seiches and explains the variety of esti-

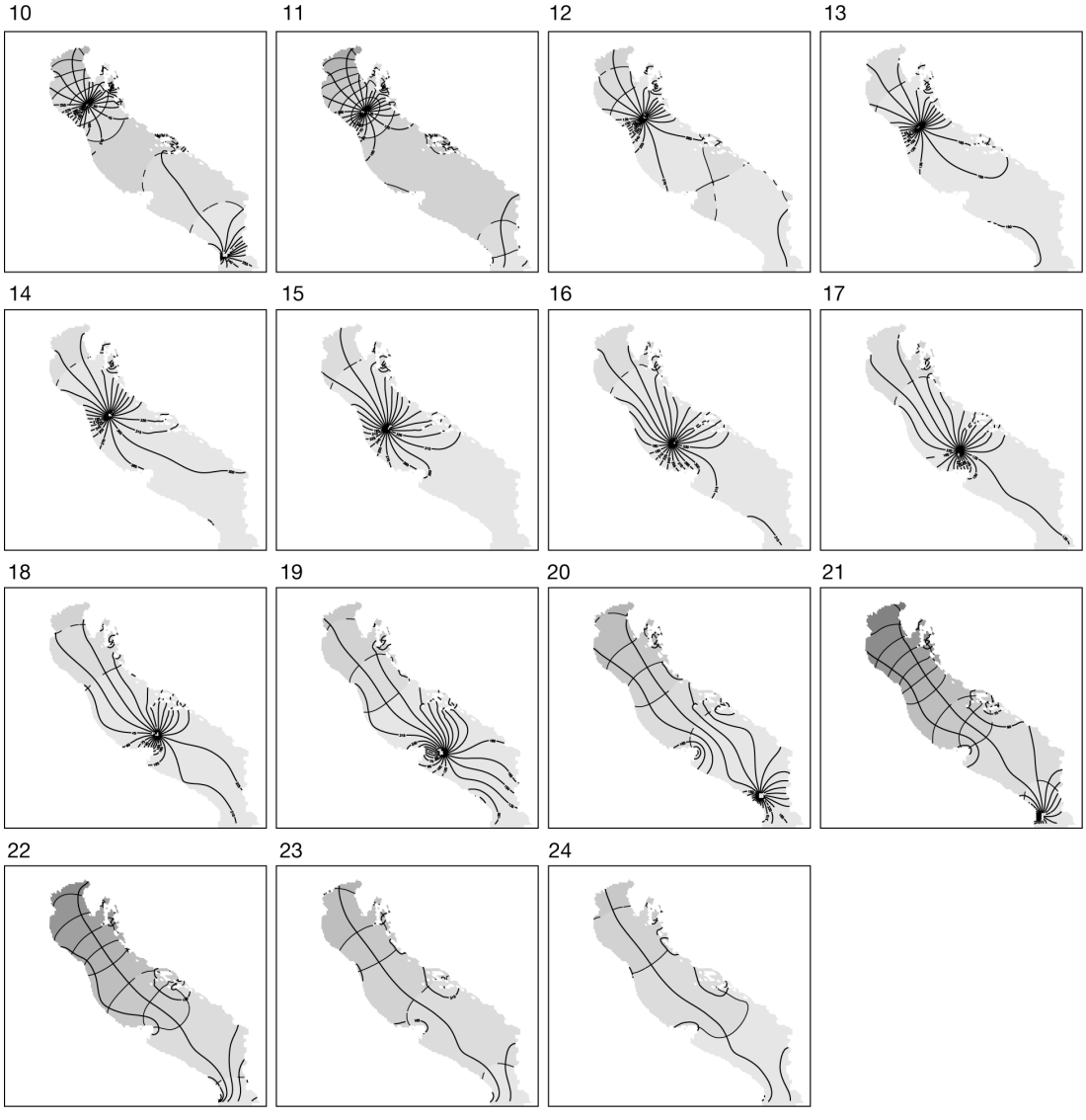


Fig. 6. Dependence of the response of the Adriatic Sea to the frequency of the external forcing in the present sea level situation. Numbers at top left hand corner of panels denote the forcing period (h). Gray shading denotes amplitude (contour step 4 cm) and black lines denote the phase (interval between lines is 15°). The amplitude of the forcing oscillation at the Otranto boundary is 2 cm

mates of their period by authors using different recorded cases. Lower and upper limit (based on estimates by Mosetti & Purga 1983, Vilibic & Orlic 1998, and not forgetting the above distinction between free and forced oscillations) are denoted by the vertical dashed lines in Fig. 7. The agreement between model simulation and observations was very good for the first seiche, but poorer for the second one. As sea level increased in the FCST (grey curves labeled F+2, F+5, F+10) the period of both seiches decreased, while in the NCST (black curves labeled N+2, N+5, N+10) the period increased. The presence of the 'Ravenna' lagoon affected the amplitude of the 'exceptional' seiche, but not its period, and the construction of a dam (PCST, dashed black curve labeled P+10) would increase the amplitude of the seiche, probably because it eliminates the drag exerted by the 'Ravenna' lagoon.

Fig. 8 shows the behavior of amplitude and period of the first seiche for the CNR station and Ancona. Lines represent the ratio between values in the SLR conditions and in the CTR one (for example, a value of 1.5 represents 50% increase).

Simulations were carried out allowing for the oscillation at the open boundary to have a 2 and 5 cm amplitude representing 'medium size' and 'exceptional' amplitude for seiches. Little relative increase/

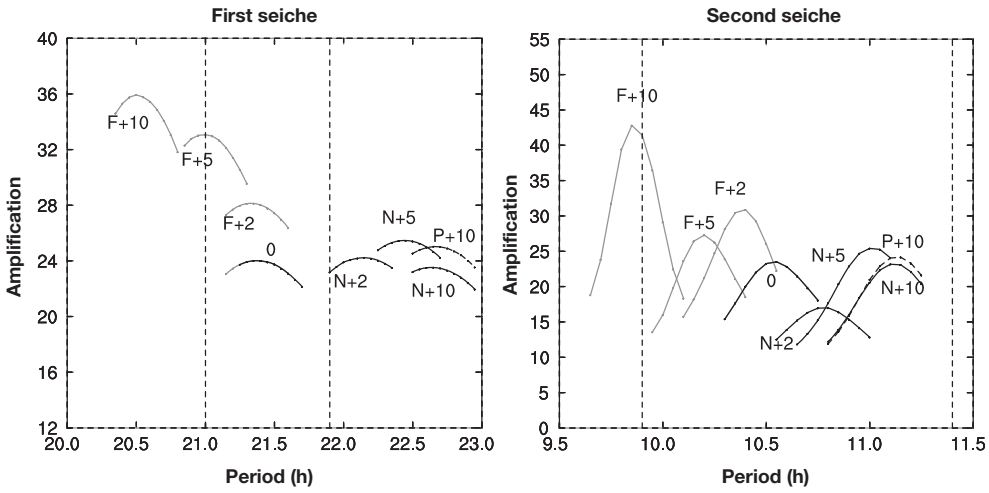


Fig. 7. Amplification (ratio between the amplitude at Venice and at Otranto) as a function of the forcing period. Each curve refers to a different SLR. Gray curves (F+2, F+5, F+10) show the response in case of full compensation strategy (i.e. conservation of the shoreline), for 2, 5, 10 m SLR, respectively. Black curves (N+2, N+5, N+10) show the response in case of no compensation. The dashed curve labelled P+10 shows the response in the special case in which a coastal dam prevent the flooding of the 'Ravenna' lagoon present in the N+10 simulation. The curve labelled 0 shows the model response in the present situation. Vertical dashed lines mark the range found in the literature for the seiche period

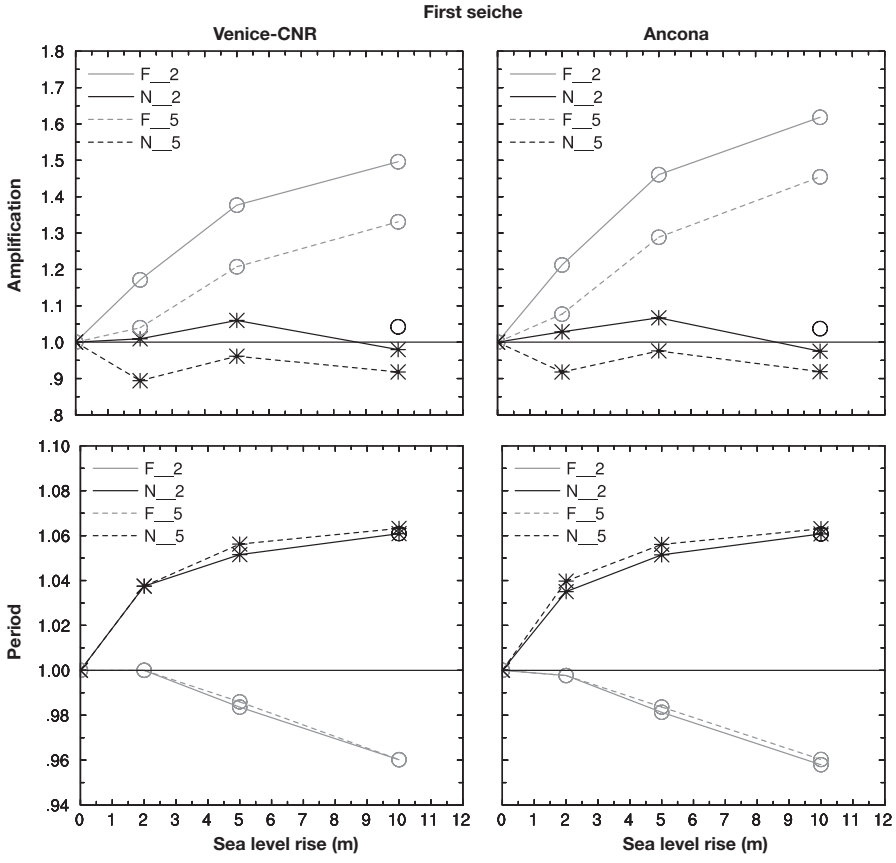


Fig. 8. Amplification at Venice (top left panel) and Ancona (top right panel) for the first seiche as function of SLR. Period at which the maximum amplification occurs at Venice (bottom left panel) and Ancona (bottom right panel). All values are normalized with those corresponding to the present condition (CTR, horizontal black line). Black lines describe the response if no defense is built (NCST), grey lines for full compensation (FCST). Continuous lines refer to a 'medium size' seiche (2 cm amplitude at Otranto, denoted as F_2), dashed lines to an 'exceptional' seiche (5 cm amplitude at Otranto, denoted as F_5). The isolated circle shows the special case in which a dam closes the 'Ravenna' lagoon for an exceptional seiche

reduction of period was associated with SLR (reaching a maximum of 6 and 4 % for a 10 m SLR) in the NCST and FCST, respectively. The NCST would produce limited changes of amplitude both at Ancona and at the CNR station (which would not be representative of coastal conditions for large SLR if NCST is followed). Results showed that large seiches would actually be slightly reduced. The FCST would increase the amplitude of the first seiche, with a behavior strongly dependant on its amplitude. The increase would be larger for smaller seiches, since on the big ones the bottom friction acts more severely, being quadratic in the current speed. Note that the increase of the seiche would be larger than 50 % for a 10 m SLR, and about 20 % for 2 m SLR in case of a medium size seiche. This suggests that some limited effect would be present also on a decadal to century time scale when expected SLR is about 1 m. Note the effect of closing the large 'Ravenna' lagoon with a dam has on the amplitude of the 'exceptional' seiche (isolated circle in Fig. 8). This appears to follow a PCST (partial compensation stragety) +10 instead of a NCST+10, and it modifies the amplitude of the seiche to a 5 % increase instead of a 10 % reduction with respect to CTR. Fig. 9 shows the various SLR values and compensation strategies for the first seiche in the Adriatic Sea.

The period length of the second seiche varied similarly to that of the first seiche, but the situation is more complicated with regards to amplitude (Fig. 10). When FCST was adopted, the main effect of the SLR was a reduced amount of friction and consequently, increased amplitude. When NCST was followed, small shifts of the amphidromic point in the northern Adriatic, which moved closer or further away from the CNR station and Ancona (Fig. 11), had a large effect on the local amplitude. For instance, the northward motion of the amphidromic point implied an increased amplitude at Ancona for cases NCST+5 and +10 (Fig. 11), while no change took place at the CNR station. Moreover, in the NCST+10 and PCST+10 strategies, the northwest of the basin included relatively large shallow water areas, which produced a local convergence of the wave energy flux and increased the amplitude of the second seiche. The first seiche had a simpler structure, with no amphidromic point inside the basin, and it did not present similarly critical behavior (Fig. 9).

The PCST has been considered for the 10 m SLR and for the 5 cm forcing only. It shows that building a dam to close the 'Ravenna' lagoon has a large effect (increase) on the amplitude of seiches and suggests that coastal defenses of very large scale might have a detectable effect on the oscillations of the whole basin.

Seiche period changes with SLR were very regular (Figs. 8 & 10, right hand panels), because kinetic effects associated with the time required by waves to travel across the basin dominate. In general, increased water depth of the FCST implied higher wave speed and shorter periods, large basin extension in the NCST implied longer resonant wavelength and longer resonant period. In the FCST, generally,

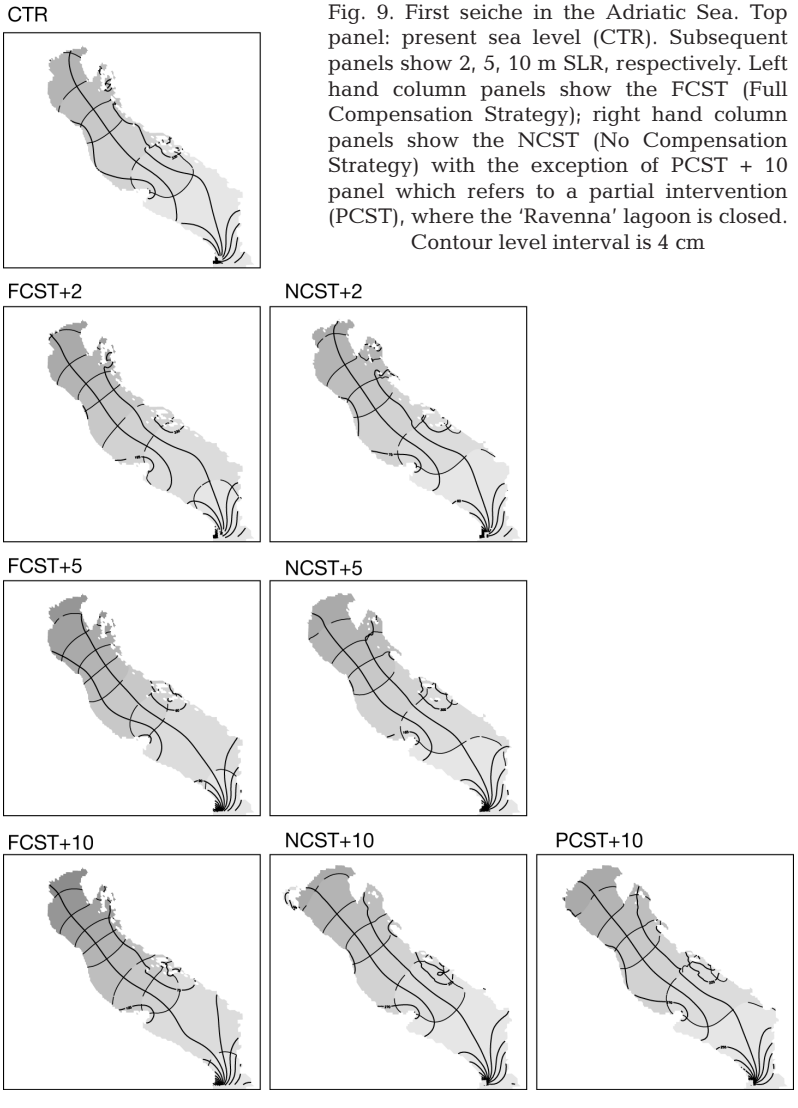


Fig. 9. First seiche in the Adriatic Sea. Top panel: present sea level (CTR). Subsequent panels show 2, 5, 10 m SLR, respectively. Left hand column panels show the FCST (Full Compensation Strategy); right hand column panels show the NCST (No Compensation Strategy) with the exception of PCST + 10 panel which refers to a partial intervention (PCST), where the 'Ravenna' lagoon is closed. Contour level interval is 4 cm

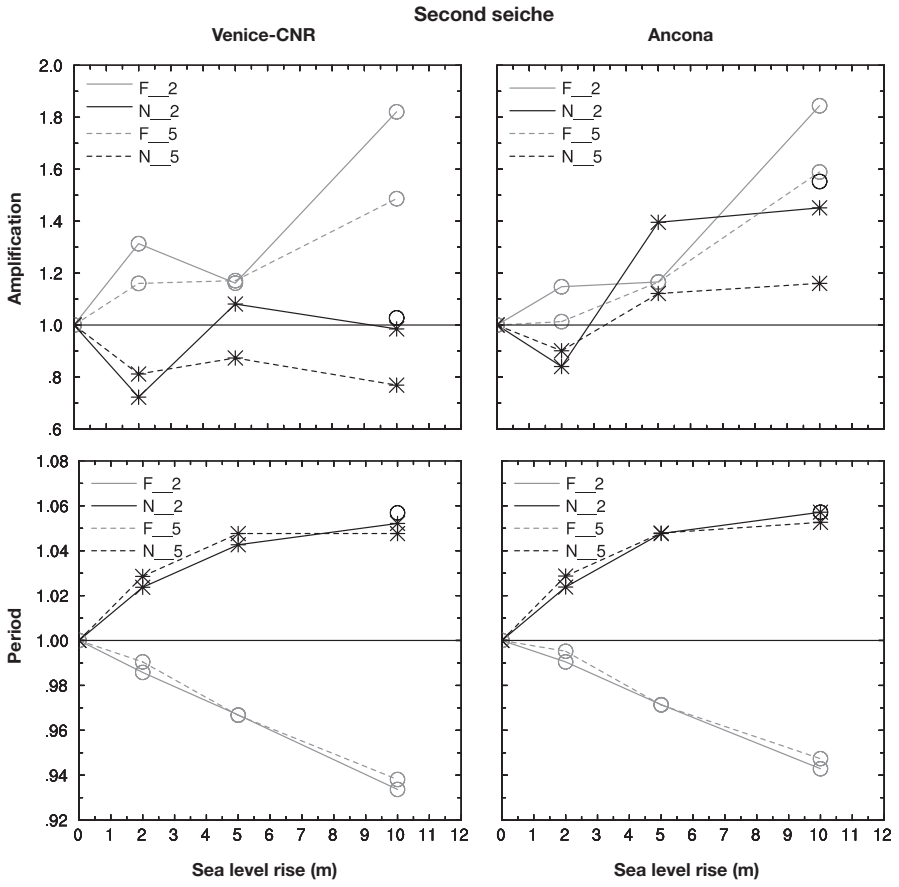


Fig. 10. Amplification at Venice (top left panel) and Ancona (top right panel) for the second seiche as function of SLR. Period at which the maximum amplification occurs at Venice (bottom left panel) and Ancona (bottom right panel). See Fig. 8 for further details

diminished friction would increase the amplitude of seiches. In the NCST, amplitude was conditioned by the change in the coastline and also the friction, and oscillation pattern changes were important particularly for the second seiche. However, changes inside the present area of the basin are likely to be small, except for locations relatively close to the amphidromic point, which are affected considerably by shifts of its location.

Note that the effect at the coast in the NCST was actually larger than that suggested by the previously discussed results, because the CNR station was not representative of coastal conditions for large SLR values (see Fig. 3, right hand panel) and seiches at the coast can be much larger than at the CNR location. Fig. 12 shows the amplification of the seiche along the northern part of the Italian coast as SLR increases, between 43.5 to 45.5° latitude north. The ratio with respect to the present value as a function of latitude is plotted. The break in the 10 m SLR curve represents the 'Ravenna' lagoon, inside which the amplitude of the seiches is very small. The part most affected was located north of 44.5° where SLR determined the replacement of the present low and flat land areas with a shallow coastal sea. Along this part of the coast, the amplitude of the first seiche increased appreciably and regularly with SLR to a maximum 20% for a 10 m SLR. The amplitude of the second seiche had a more complicated behavior. For a modest SLR, the amplitude was reduced because of the northern shift of the amphidromic point. For a large SLR, seiches are expected to more than double their amplitude for a long part of the coastline.

## 4. TOTAL LEVEL: EFFECTS ON TIDES AND STORM SURGE

The tide in the Adriatic Sea is mainly forced at the southern open boundary. In fact, since the periods of first and second seiche are relatively close to those of the diurnal and semidiurnal tide, respectively, the relatively small tidal amplitude at the open boundary forces a comparatively large oscillation at the northern

closed end. Consequently, the northern Adriatic Sea experiences among the highest tidal amplitudes in the Mediterranean. When a SLR was simulated, the behavior of tides was mostly influenced by the change of the resonant frequency of the sea (which is shown by seiches), but it also depended on the space shift of the amphidromic point, which is important for the semidiurnal constituents. This analysis considered the largest semidiurnal (M2) and diurnal constituent (K1). Their amplitude at the southern open boundary has been assumed not to depend on SLR and this was established by the model validation described in Section 2. This is not strictly true, and, eventually a tidal model of the whole Mediterranean Sea would be required to establish the correct value, but the assumption is sensible as the prevalently deep water condition in the basin would imply minor relative changes of depth for the SLR values considered in this study.

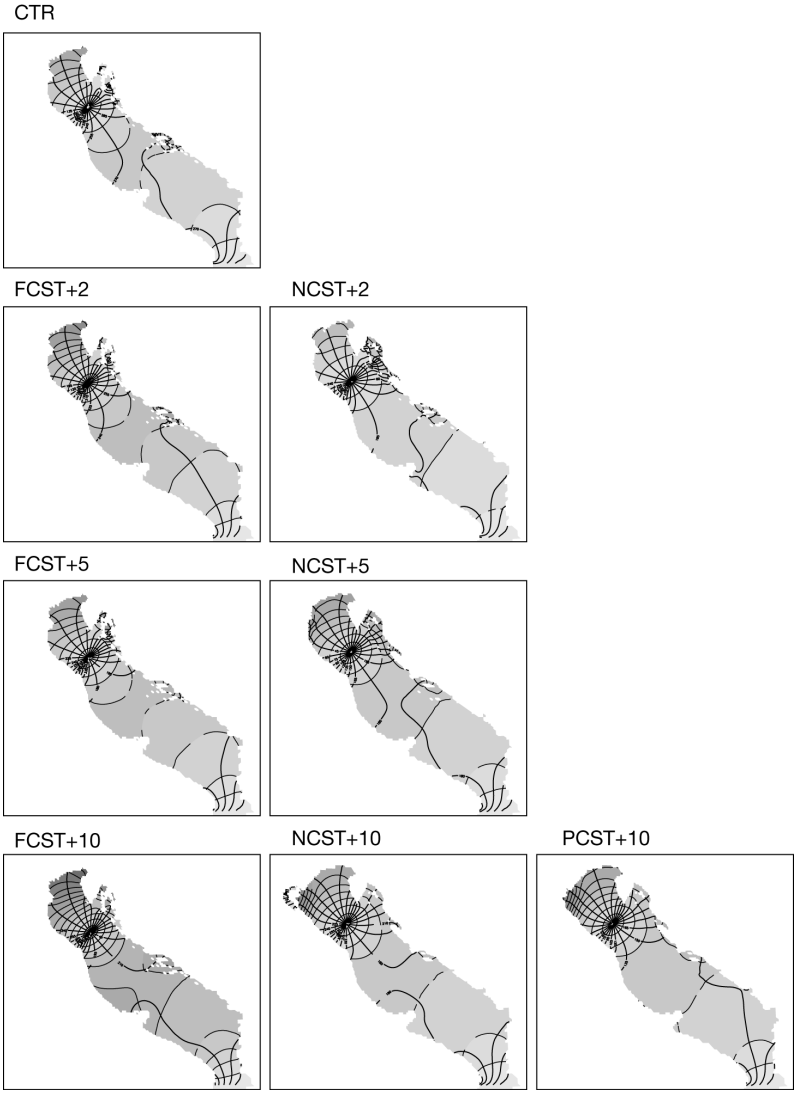


Fig. 11. Second seiche in the Adriatic Sea. See legend to Fig. 9 for further details

In the Adriatic, the periods of the first and second seiche are shorter than those of the diurnal and semidiurnal tide. As SLR increased, the FCST implied a progressively smaller period for both the first and second seiche, and a progressively larger separation in frequency between seiches and tides. Consequently the amplitude of tides was reduced (Figs. 13 to 15). The amplitude of M2 at Ancona does not follow this general trend. In fact, the location of the amphidromic point near Ancona results from the addition of the Kelvin wave traveling north-westward along the Croatian coast to the one traveling south-eastward along the Italian coast (Hendershott & Speranza 1971). As bottom friction was reduced, the second Kelvin wave increased its amplitude and the amphidromic point moved away from Ancona (Fig. 15). The NCST produced the opposite effect because it determined longer periods of the seiches and therefore they became closer to the period of tides. The diurnal K1 constituent experienced a large increase (about 50% increase for a 10 m SLR). However, for the semidiurnal constituent this effect is compensated by the shift of the amphidromic point and changes of the amplitude pattern, which keep amplitude low at both the CNR station and at Ancona.

In the NCST, analogously to what happened for seiches, a large effect was found at the northern coast, where tide increased on the large shallow water extension produced by SLR (Fig. 16). The growth of both M2 and K1 was larger than 50% for a 10 m SLR, though M2 actually decreased for smaller (2 m) SLR. As far as tidal oscillations are concerned, growth due to SLR would take place since a shallow sea would replace the present low lying coastal plain areas.

The analysis of the effect of SLR on surge was investigated by simulating the effect of a real sequence of meteorological events assuming 2, 5 and 10 m SLR in the NCST and FCST case. The events took place during November 1996, when a sequence of storms produced several floods in Venice, and the effect of the single storms was superimposed on the seiches triggered by the previous ones. The SLP and wind fields used as forcing were produced by the MIAO model (Lionello et al. 2003). The results of the surge simulation during this 'November' period

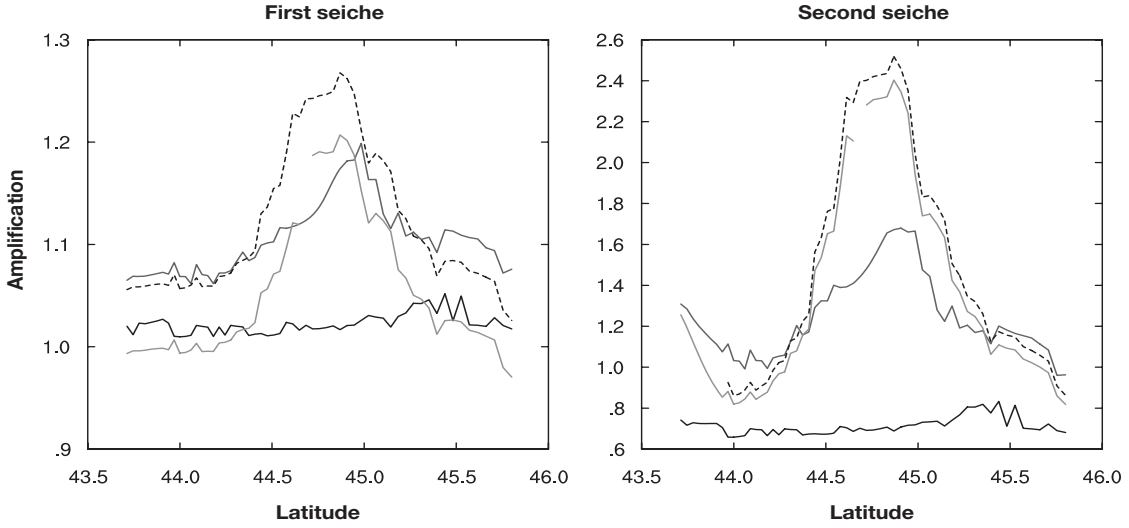


Fig. 12. Amplification of the first (left hand panel) and second (right hand panel) seiche along the northern coast of the Adriatic. Black, grey and light grey lines shows results for 2, 5, and 10 m SLR respectively, in NCST. The uppermost dashed curve shows results for a 10 m SLR, with a dam closing the 'Ravenna' lagoon. The lines represent the ratios with respect to present values

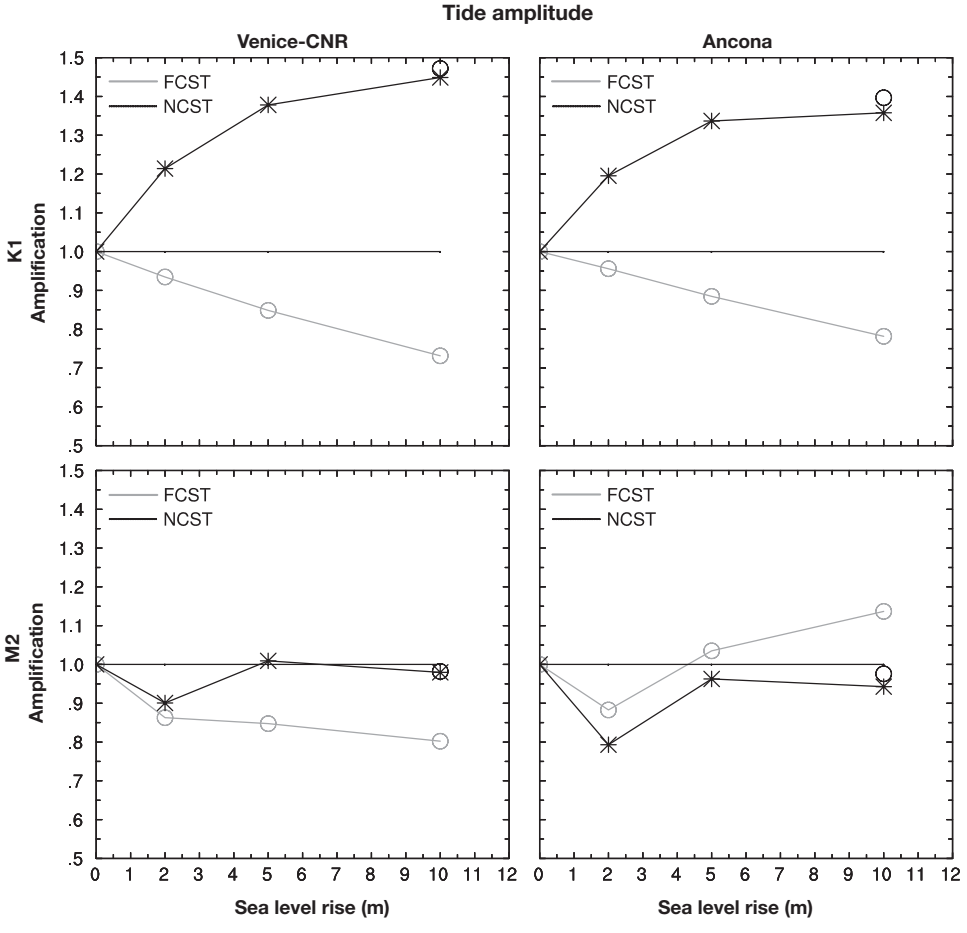


Fig. 13. Amplitude of the K1 (top row) and M2 (bottom row) tidal constituents at Venice (left hand panels) and Ancona (right hand panels). Values are relative to present state (CTR, horizontal black line). The isolated circle shows the special case in which a dam closes the 'Ravenna' lagoon for an 'exceptional' seiche

at the CNR station is shown in Fig. 17 (top panel), in which a tendency for FCST to reduce the amplitude of the sea level oscillations (both of the surge and the seiches) and for NCST to increase them is noted. However, the values of individual maxima and minima of sea level depended on the superposition of the surge event with previously triggered seiches (and tidal maxima if the total elevation is considered, Fig. 17, bottom panel). Small changes of timing of maxima and minima can be more important that those of their values. The randomness of this superposition implies a very irregular behavior, meaning that a given peak may not necessarily be higher in the NCST simulation. If FCST is adopted, the increased water depth near the coast reduces the surge, consistently with the inclination of the sea surface being inversely proportional to water depth, during a storm surge, in steady conditions. On the contrary large divergence of the transport above large shallow water areas increases the surge if NCST is followed. In order to quantify these effects, the variance of the sea level for the whole simulated period was calculated, both with and without including the astronomical tide. Fig. 18 (left hand panel) shows that the variance decreases/increases with SLR if FCST/NCST is followed (and, consequently, oscillations are smaller/larger). In the FCST case note that though seiches should increase with SLR, the decrease of the surge dominates the time series and the variance of the oscillation resulting from their superposition diminishes with

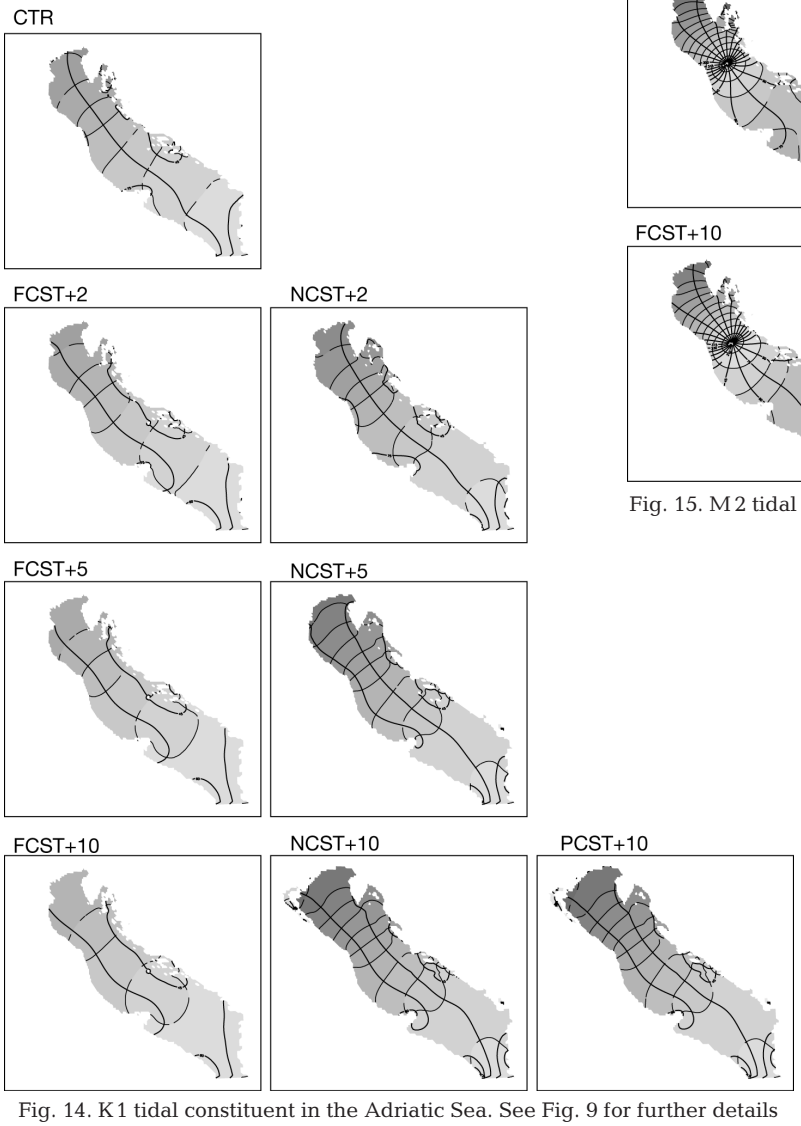

Fig. 14. K1 tidal constituent in the Adriatic Sea. See Fig. 9 for further details

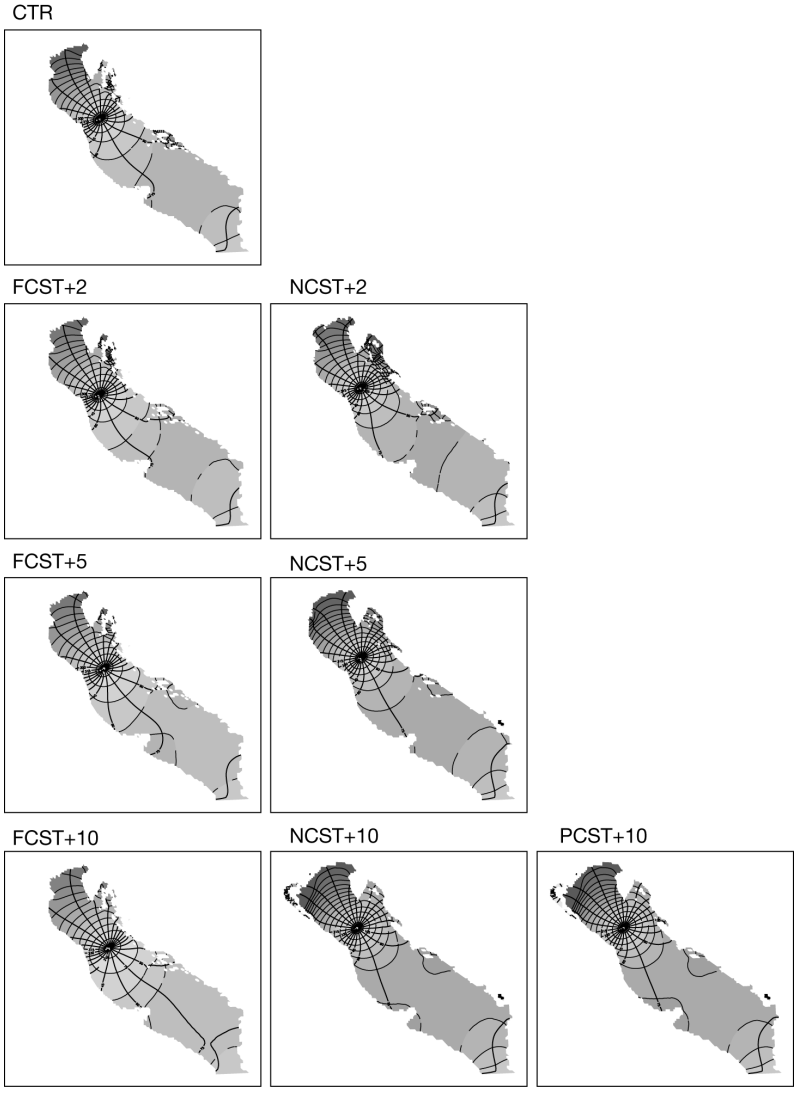

Fig. 15. M2 tidal constituent in the Adriatic Sea. See Fig. 9 for further details

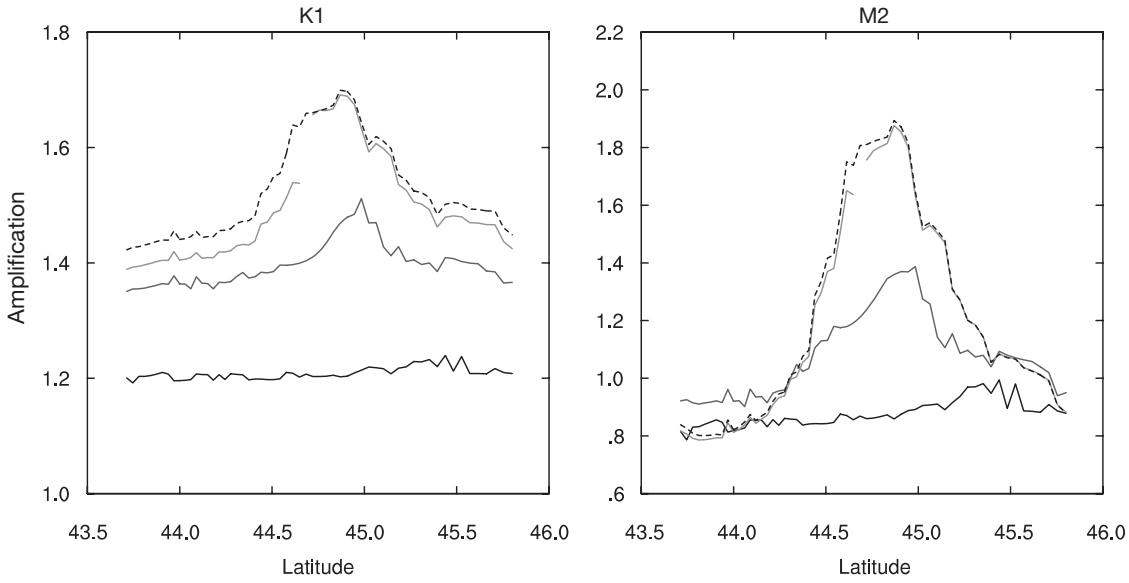


Fig. 16. K1 and M2 tidal constituents. Black, grey and light grey lines show results for 2, 5 and 10 m SLR, respectively, in NCST. The uppermost dashed line shows results for a 10 m SLR, with a dam closing the 'Ravenna' lagoon. The lines represent the ratios with respect to present values

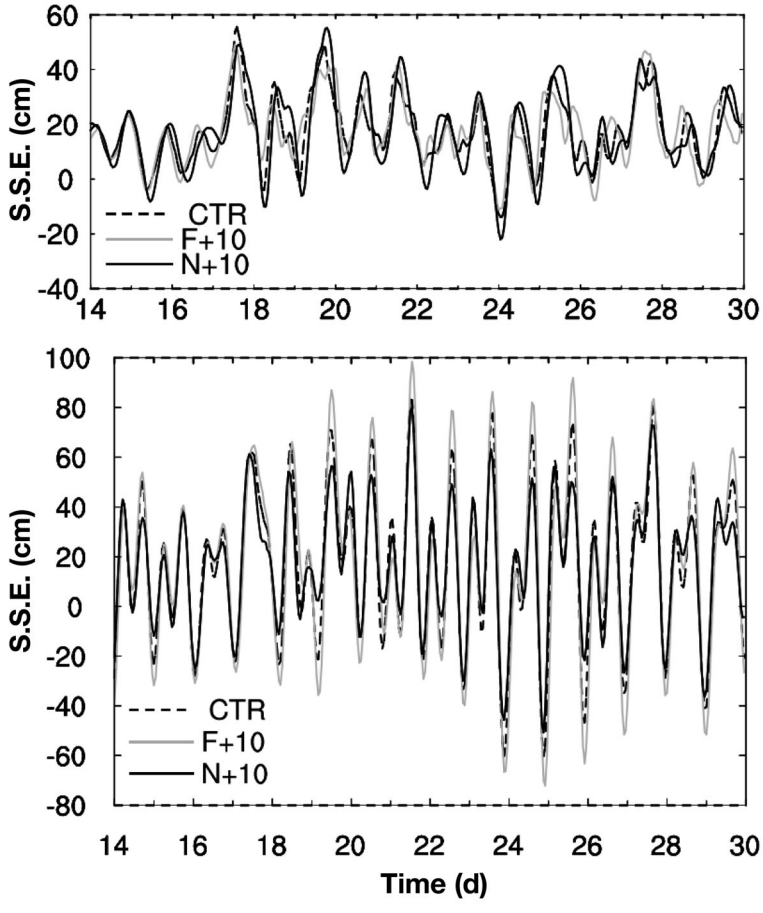


Fig. 17. Time series of the SSE (Simulated Sea Elevation), for surge (top) and total (surge and tide) level (bottom). The black and grey lines represent the results in case of 10 m SLR with no intervention (N+10, NCST) and full compensation (F+10, FCST), respectively. The dashed line shows the results with the present sea level

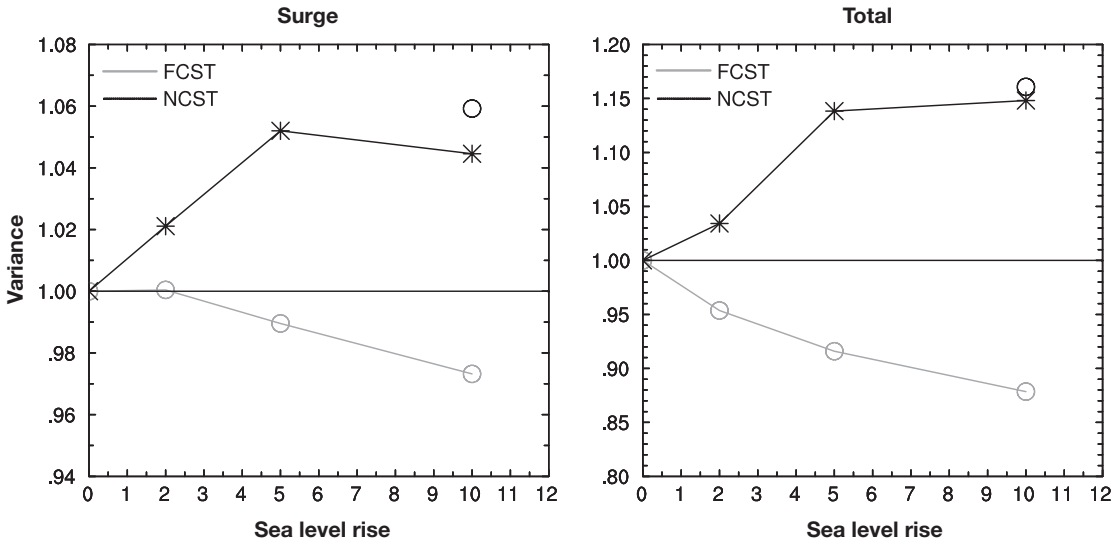


Fig. 18. Variance of the signal at CNR station for the 30 d simulations. The values represent the ratios in respect to present value simulation. Left hand panel: surge only; right panel: total level (surge and tide)

SLR. Including the astronomical tide (the 7 largest constituents were considered) reinforces this trend. In fact, since tidal amplitude is also reduced/increased in the FCST/NCST, the variations of surge and tide with SLR act in the same direction on total sea level, reinforcing each other (Fig. 18). As a consequence, variance would increase/decrease by 15/10% for a 10 m SLR in the NCST/FCST case.

It is important to analyze what would be the effect at the new coastline in the NCST case. Fig. 19 shows the dependence of variance (top row panels) and maximum surge level (bottom row panels) on SLR, including astronomical tide or considering only surge and seiches. Both variance and maximum level would increase (for a 10 m SLR by more than 50% if tide is considered). This indicates that tidal regimes (mainly the semidiurnal constituents) would be the most sensitive element of the Adriatic Sea surface dynamics in the NCST case.

## 5. CONCLUSIONS

This study simulated the changes in tidal regimes, seiches and storm surges associated with SLR in the Adriatic Sea. The response is expected to be similar in other semi-enclosed basins with large shallow water areas. Neither the SLR values nor the assumed strategies are meant to be strictly realistic, but only to provide a basis for discussing sensitivity to SLR and evaluate the effect of large SLR on the sea level dynamics at regional scale.

If FCST is adopted, the SLR results in higher wave speed and lower friction. This reduces the period of seiches and increases their amplitude. The amplitude of tidal constituents decreases because of the increased separation between their periods and those of seiches. The surge is reduced, mainly because water depth is increased. However, in practice, if maintaining the present coastline is possible, the effect of SLR on tides and surges would be small and tend to reduce them.

If NCST is followed, the increased extension of the basin implies longer resonant waves and longer periods of seiches. Tidal amplitude would increase because the separation between their period and seiche periods decreases. The change of the location of the amphidromic point is important for the amplitude of semidiurnal tides and second seiche in the northern part of the basin. Storm surge elevations would also increase, because of large shallow sea coastal areas. The largest effect is actually associated with the presence of new coastal shallow sea in the northern part of the basin. The most dramatic case, a 10 m SLR with no compensation strategy, would imply a 50% increase in oscillation amplitude inside the area presently covered by the basin and a larger than 100% increase at the new coastline. However, a 10 m SLR is an extreme case and may only happen 1000 yr or more in the future. However, the investigation as a whole suggests that appreciable changes (of the order of 10%) can also be expected for smaller values of the SLR, and they cannot be ruled out (and should actually be expected) in centennial time scales.

In brief, FCST tends to reduce amplitude of oscillations, while NCST would result in more dangerous situations at the coast. In other words, it appears that the Adriatic dynamics would strongly depend on the strat-

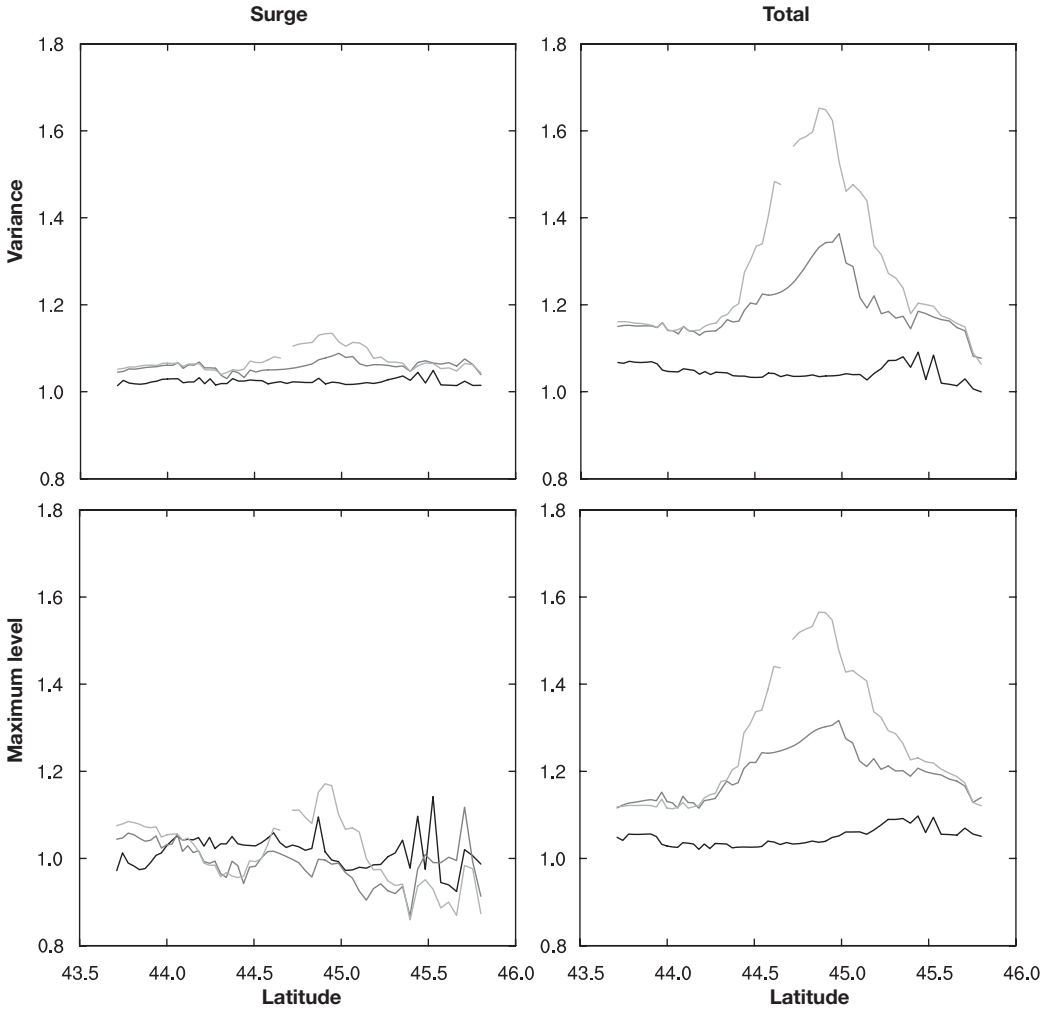


Fig. 19. Surge and total sea level during the 'November' period. Top panels: percent variance of the variance; bottom panels: percent variance of the maximum surge levels. Black, grey and light grey lines refer to 2, 5 and 10 m SLR, respectively, in the NCST case

egy adopted to maintain the coastline. Future studies, attempting to make a more precise evaluation, should include a model of coastal morphology and consider several strategies and differentiated actions for compensation. A more focused investigation, together with a resolution capable of resolving small coastal details, seems necessary for estimating changes caused by smaller (e.g. 20 cm to 1 m) SLR values, which are expected on a decadal time scale, and might have important consequences at local scale, though not changing the overall dynamics of the basin. Moreover, a tidal model of the whole Mediterranean Sea should be used to evaluate tidal amplitude at the southern open boundary of the Adriatic. Note that the new shallow water areas are the most important source of changes in the tidal and surge regimes and this extreme consequence of SLR can be avoided with adequate coastal defenses. Coastal lagoons, e.g. the 'Ravenna' lagoon of this study, can have a detectable effect so that one might speculate that permanent dams and coastal defenses could influence the dynamics of the northern Adriatic Sea.

In spite of these comments, however, the effect of SLR on the dynamics of the oscillations of the Adriatic sea level is small at basin scale with respect to the problems produced by SLR itself and could be compensated by a careful planning of coastal defenses.

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