CHAPTER 16

EXTREME STORMS IN THE ADRIATIC SEA

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Abstract

We discuss the application of the third generation WAM wave model to the Adriatic Sea. We focus in particular on one of the extreme storms that produced also heavy flooding in Venice. We discuss the problem of a correct description of the wind fields as a crucial input information to the wave model. After hindcasting the wave conditions during the storm, we use them as input for an estimate of the wave set-up towards the shore. We show that its consideration is essential for a proper evaluation of the flood level in the town.

Introduction

We discuss the application of the third generation WAM wave model to the Adriatic Sea. The recent tendency in wave modelling (see WAM-DI Group 1988, Tolman 1989) of neglecting, as far as possible, any empirical parametrization, and to numerically describe the field evolution only in terms of the physics of the phenomena involved, has allowed to properly model also storms with a complicated structure. The Adriatic Sea, enclosed between Italy and Yugoslavia, with a pronounced bordering orography, is characterized by strong gradients, both in space and time, of wind and wave fields. Provided the basin is represented with a sufficiently fine grid, a third generation wave model is likely to provide a very good overall description of the storm.

Three of us (see Cavaleri et al. 1989) have done extensive application of WAM to the Adriatic Sea, considering the various kind of storms acting in the basin, particularly in its northern part. We focus here on one of the heaviest storms, occurred in December 1979. The storm produced also a strong flood of the Venice Lagoon. The main task of this paper is to show how the evaluation of the wave set-up at the coast, obtained from the hindcasted wave conditions offshore, is an essential step for a correct estimate of the flood level in the town of Venice.

Wind and Wave Modelling

The WAM wave model is based on the numerical integration of the wave energy balance equation. This describes, point by point, time step by time step, the energy budget connected to advection, production and dissipation, and to the exchange among the various wave components. The model has been extensively described in the literature (e.g. WAM-DI Group 1988, Cavaleri et al. 1989) and we will limit here to the essential information. In the version used for this study the model runs with twenty-five frequencies in geometric progression ($f_1 = 0.0418$ hz, $f_{n+1} = 1.1\ f_n$) and twelve directions at 12 degree intervals. The Adriatic Sea (Fig. 1) is represented on a 20 km step grid. The main axis of the basin, whose dimensions are approximately 750 x 200 km, is aligned from north-west to south-east; Venice is located at the upper left end. The last 200 km to the north are shallow, the depth of the continental platform decreasing with a more or less constant 1/1000 slope toward the northern end.

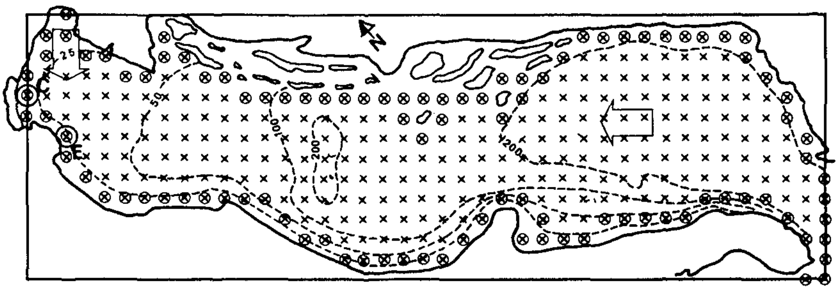

Fig. 1. Grid representation of the Adriatic Sea. The grid step is 20 km. C marks the position of the oceanographic platform off the Venetian coast. The wind model uses the same grid, but with one point out of two in each direction. Depths are in metres.

In general the most crucial aspect in the evaluation of a wave field is the accuracy of the wind field. It is obvious that, if a sophisticated wave model is to be used, the input wind field must have at least a comparable accuracy. This can be a problem when we are dealing with a relatively small basin with a complicated surrounding orography. In this case the large scale atmospheric models fail to correctly reproduce the relatively small details of the field that are nevertheless essential at the scale of the basin. The Adriatic Sea (Cavaleri et al., 1989) is almost completely bordered by high mountain ridges (Apennines to the west, Dinaric Alps to the east), and there is experimental evidence of wind space gradients up to 10 s in modulus and 10 deg m in direction. In these conditions the required grid resolution is of the order of 30-50 km, compared to the 100-150 km resolution of the present models, and to the 70 km one of the high resolution local models. Better examples do exist for specific areas, but they cannot be considered for generalized applications. Note anyhow that these figures should be halved with the next generation models, expected to come into operation in 1990-1991.

To satisfy the accuracy requirements we resorted therefore to a much simpler model (Cavaleri et al., 1990), where the accuracy is obtained by tuning the model to the local conditions. The model makes use of the one-layer balance equation whose solution provides the gradient wind. This is then transferred to the surface on the base of wind speed and air-sea stability conditions. The field modification, in modulus and direction, due to the constrainment of the bordering ridges is evaluated on the base of long-term experimental evidence. The input information is given by the atmospheric pressure recorded at the bordering meteorological stations. These are interpolated in space at the knots of a 40 km grid (Fig. 1) fitted to the wave model grid. A higher resolution would be only apparent because of the distance among the various stations. The above procedure provides one wind field for each synoptic time at the 3-hour interval.

The Storm of 21-23 December 1979

In these days strong wind over 20 ms , aligned all the way along the axis of the basin, produced very high waves in its central and northern part. Fig. 2 shows the wind and wave fields at 06 UT of 22 December. Note how the wave field is aligned along the axis of the basin till the northern coast (the left in the figure). No detailed comparison between model results and recorded data is possible as the oceanographic tower located offshore the Venetian coast (point C in Fig. 1) suffered heavy damage during the storm. Our estimate of wave height at the tower is anyhow consistent with the damage reported on board.

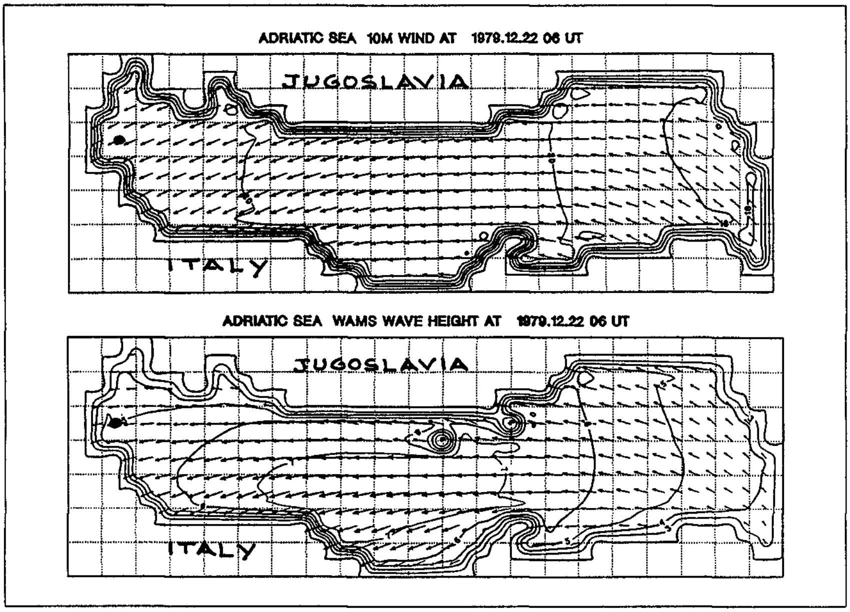

Fig. 2. Wind and wave fields at 06 UT of 22 December 1979. The wind has been interpolated from its 40 km resolution on the original grid. The dot to the left marks the position of the oceanographic platform.

The storm produced also one of the most severe floods ever recorded in Venice. The local geometry is shown in Fig. 3. At the town the peak sea level was measured at +1.66 metres above m.s.l., +1.85 metres at the Lido harbour entrance. Subtracting the expected +30 cm due to astronomical tide (Fig. 4a,b), we are left with +1.36 and +1.55 cm surge respectively. Fig. 4b shows also the predicted storm surge level, obtained by a statistical model fitted to data of the last decade (Canestrelli et al., 1986). There is an evident strong underestimate of the flood, particularly at and after the peak. This was not surprising. On the average the model works rather well (r.m.s. error at the peak of the order of 10 cm), but it seems to fail, with a permanent underprediction, for the largest storms.

The only oceanographic instrument on the platform to survive the storm was the tide gauge, and we could therefore compare its record with the one at the Lido entrance (point B in Fig. 3). The two records showed up to 40 cm difference (Fig. 4c), the higher values being recorded at the coast. Notwithstanding our immediate doubts, a careful check confirmed the correct functioning of the gauge on board and the correctness of the data.

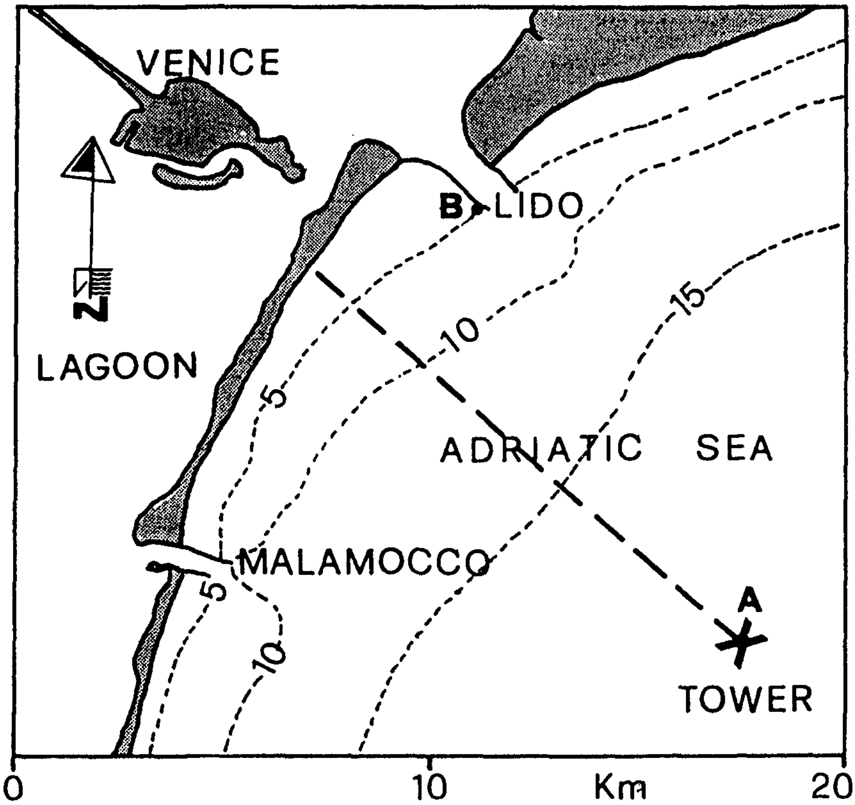

Fig. 3. Geometry of the Venetian coast. Lido and Malamocco are two of the three inlets connecting the lagoon to the sea. A and B show the position of the tide gauges. Depths are in metres.

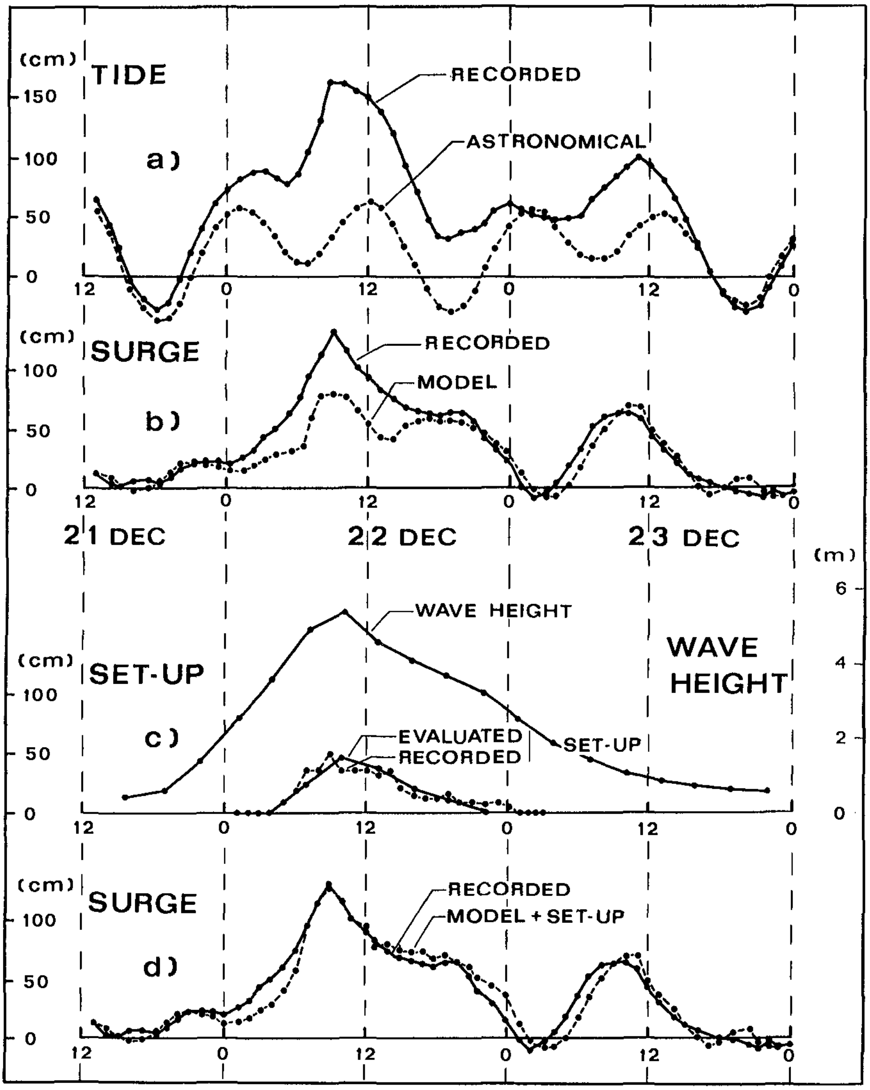

Fig. 4. a) Recorded and astronomical tide at Venice; b) recorded storm surge level (difference of the two graphs in a) and model prediction; c) wave height at the tower, evaluated and recorded set-up at the harbour entrance; d) recorded storm surge level (same as b) and corresponding model result (addition of prediction in b) and recorded set-up in c).

The explanation of this large difference is found in the wave fields. The entrance pier extends 3 km offshore till 6-metre depth. Both the reported damage on the platform and the hindcast (Fig. 4c) indicate that the waves were already breaking well before reaching the pier end. We must therefore expect that wave set-up was present at the pier end (and higher at the beach of course) and contributing to the local sea level. Starting from the hindcasted wave conditions at the platform we have evaluated the set-up at B (Fig. 3) making use of a one-dimensional set-up model (Bertotti and Cavaleri, 1985). The model assumes equilibrium conditions and evaluates the surface profile due to set-up from the platform till the shore. The one-dimensionality is justified by the strong concentration in direction of the wave field perpendicular to the shore, the equilibrium conditions by the limited distance (16 km) between the platform and the coast and the consequent fast response to any change in conditions.

The evaluated set-up, as sea level difference between the pier end and the platform, is shown in Fig. 4c. Its fit with the recorded difference is excellent (average difference at the estimate times + 1 cm), and we confidently conclude that the difference between the two gauges is effectively due to set-up.

We now make the hypothesis (discussed in the next section) that the storm surge model does not take set-up into consideration. Consequently we combine the predicted sea level and the set-up (Figs. 4b and 4c respectively) and compare again with the recorded sea level. The result is in Fig. 4d. The error has been drastically reduced (average error -1 cm, r.m.s. 9 cm), and the model evaluation is now good for all practical purposes.

Discussion

In the previous section we have stated that the statistical model of storm surge is actually evaluating the sea level off the coast, and, for the evaluation of the coastal sea level, we have to take into account the set-up due to waves. To be conclusive this statement must be made consistent with the general behaviour of the storm surge model, i.e. good results in most of the cases, with underestimate in the worst storms.

We first point out the structure of the storm surge model. Its estimate for the immediate future is based on the local sea level data during the last 15 hours and on the pressure values at some chosen station. Whatever the physics at the base of the phenomenon under study, it would be natural to assume that a statistical model should reproduce it, the degree of accuracy depending on the complication of the phenomenon itself and on that of the model.

The second argument points to the structure of the wind fields during the storm surge events. These are basically due to the Sirocco wind, blowing from the southeast along the axis of the Adriatic Sea. Fig. 2 is a good example in this sense. But the Sirocco produces also heavy sea conditions in the northern part of the basin. Hence a surge in the Venice area is usually associated with high waves from the southeast, that produce also a coastal set-up. For our purpose, i.e. for the evaluation of the surge in Venice, we are not interested in the set-up at the shoreline, but at the end of the pier (point B in Fig. 3). A positive set-up at B is present only when breaking begins before B, which is true only for the heaviest sea conditions. Consequently the storm surge model statistically fitted to the data of the last decade, and implicitly to the main body of them, is unavoidably built with no set-up information into it. When this appears also at B, the model produces only the surge part, with a consequent underestimate of the sea level.

Our conclusion is therefore that the set-up plays an important role in determining the flood level in the Venice Lagoon during the worst event. As a correct estimate of the set-up requires the knowledge of the wave conditions off the Venice coast, their estimate becomes mandatory for a correct tidal forecast at the town.

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