The impact of meteorological data variability on modelling storm surges in the Adriatic Sea

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ABSTRACT

Four different sources of meteorological data are used to model the response of the Adriatic Sea to a storm event on 20th December 1997. The meteorological data are from the operational analysis model of the European Centre for Medium-Range Weather Forecasts; the Local Area Model (LAMBO) of the Agenzia Regionale Prevenzione e Ambiente dell'Emilia-Romagna, Italy; the Mesoscale Analysis and Prediction System (MAPS) of the US Naval Research Laboratory and a set of observations obtained from the UK Meteorological Office. The event modelled gave a recorded surge in sea level of 73cm above the predicted tidal level at Venice on the northern Adriatic coast. A high-resolution two-dimensional model of tides and storm surges for the Mediterranean Sea is used. The model is forced by the direct action of the equilibrium tide, by the incoming tide through the Straits of Gibraltar and by atmospheric forces. The accuracy of the tide-surge model results varied for the different meteorological forcing data but, in general, the results tended to underestimate the height of the observed surge while accurately modelling the timing of the surge.

1 INTRODUCTION

Tidal predictions of sea level differ from those observed because of the effects of the weather. Severe meteorological storms, known as cyclones, which in winter frequently pass across the Adriatic Sea from west to east, can contribute to give higher than expected sea levels along the coast of the northern Adriatic. The combined effects of strong winds and the fall in surface pressure that accompany a cyclone, mean that the water is moved by the force of the wind and the sea level rises in response to the changing pressure. When the water, under the influence of the wind, reaches the coast a surge in the sea level occurs. The total water level can give rise to severe flooding, especially if a positive storm surge coincides with the time of high water on a spring tide.

The Adriatic Sea is an elongated basin, approximately 800km long by 200km wide, which communicates with the Mediterranean Sea through the Otranto Strait. The northern part of the Adriatic is a concave shelf sloping down regularly to the south east with maximum depth less than 300m while, in the south, the basin is much deeper with maximum depth approximately 1200m.

The increasing frequency of storm surges in the Adriatic Sea and the corresponding increasing risk of serious flooding has attracted much attention and a hierarchy of storm surge models for the Adriatic Sea exists (Orlić et al., 1994). The accuracy of any model of storm surges depends crucially on the quality of the meteorological data used as forcing. There are two issues: the accuracy of the data and its resolution. The spatial resolution has an effect on the accuracy, which is reduced on interpolating data from a coarse meteorological model grid to a higher resolution surge model grid. The temporal resolution is also important, particularly for wind data, since a wind event contributing to a surge may be of only short duration, or may peak in magnitude for just a short time.

The results of a high-resolution two-dimensional tide and surge model for the Mediterranean Sea are analysed for a storm surge event in the Adriatic Sea. A comparison is made of the results obtained by using four different meteorological data sets of differing temporal and spatial resolutions. The meteorological data used are from the operational analysis model of the European Centre for Medium-Range Weather Forecasts; the Local Area Model (LAMBO) of the Agenzia Regionale Prevenzione e Ambiente dell'Emilia-Romagna, Italy; the Mesoscale Analysis and Prediction System (MAPS) of the US Naval Research Laboratory and a set of observations obtained from the UK Meteorological Office.

2 THE MODEL

The basic depth-averaged equations governing tide-surge motion in two dimensions may be written in geographical coordinates as

$$\frac{\partial \xi}{\partial t} + \frac{1}{R \cos \phi}\left(\frac{\partial (Du)}{\partial \chi} + \frac{\partial (Dv \cos \phi)}{\partial \phi}\right) = 0, \qquad (1)$$

$$\frac{\partial u}{\partial t} + \frac{u}{R\cos\phi}\frac{\partial u}{\partial \chi} + \frac{v}{R}\frac{\partial u}{\partial \phi} - \frac{uv \tan\phi}{R} - 2\omega \sin\phi\, v = $$
$$- \frac{g}{R\cos\phi}\frac{\partial(\xi + \xi_b - \bar{\xi})}{\partial \chi} - \frac{1}{\rho R \cos\phi}\frac{\partial p_a}{\partial \chi} + \frac{1}{\rho D}(F_s - F_b) + A_h \nabla^2 u, \qquad (2)$$

$$\frac{\partial v}{\partial t} + \frac{u}{R\cos\phi}\frac{\partial v}{\partial \chi} + \frac{v}{R}\frac{\partial v}{\partial \phi} + \frac{u^2 \tan\phi}{R} + 2\omega \sin\phi\, u = $$
$$- \frac{g}{R}\frac{\partial(\xi + \xi_b - \bar{\xi})}{\partial \phi} - \frac{1}{\rho R}\frac{\partial p_a}{\partial \phi} + \frac{1}{\rho D}(G_s - G_b) + A_h \nabla^2 v, \qquad (3)$$

where

t	denotes the time
Π, ϕ	longitude and latitude
ξ	elevation of the sea surface relative to the earth
u,v	eastward and northward components of the depth-mean current $\boldsymbol{q}$
R	the radius of the earth
T	the angular speed of rotation of the Earth
g	the acceleration due to gravity
ρ	the sea water density, assumed to be constant
ξ_b	the elevation of the seabed above its undisturbed level
$\bar{\xi}$	the equilibrium tide
F_b,G_b	components of $\boldsymbol{\vartheta}_b$, the bottom stress
F_s,G_s	components of $\boldsymbol{\vartheta}_s$, the wind stress on the sea surface
p_a	atmospheric pressure on the sea surface
D	the total water depth (= $h+\xi$, where h is the undisturbed depth)
A_h	the depth-dependent horizontal eddy viscosity parameter, taken to be $5D$ m^2/s.

Equation (1) is the conservation of mass equation and eqns. (2) – (3) represent conservation of momentum in the two coordinate directions.

The bottom stress was expressed in terms of the depth-mean current by the equation $\boldsymbol{\vartheta}_b = k_b \rho \boldsymbol{q}|\boldsymbol{q}|$, where the friction parameter $k_b = 0.003$. The wind stress was calculated from the 10m wind $\boldsymbol{w}$ by $\boldsymbol{\vartheta}_s = c_d \rho_a \boldsymbol{w}|\boldsymbol{w}|$, where ρ_a is the density of air and c_d is a drag coefficient taken to be $c_d = (0.63+0.066|\boldsymbol{w}|)\times10^{-3}$ (Smith and Banke, 1975), with $|\boldsymbol{w}|$ in m/s.

At the coastal boundaries, the current component normal to the boundary was set to zero while, at the open boundary, a forced gravity-wave radiation condition was used: $q = q^* + c\ (\xi - \xi^*)/h$, with $c = (gh)^{1/2}$. The * denotes specified functions of time at the open boundary which define the tidal propagation into the model domain and also incorporate a contribution from atmospheric forcing. The four largest tidal constituents in the area, namely, M_2, S_2, K_1, and O_1 were used. The tidal forcing parameters were adapted from those of Tsimplis et al. (1995).

In addition to the open boundary forcing, the motion was forced by tide-generating forces acting over the interior and by atmospheric forces. The equilibrium tide, $\bar{\xi}$, was expressed in terms of harmonic constants (Cartwright, 1977). Surface pressure fields and 10m wind fields were used as atmospheric forcing.

The computational grid extended over the whole Mediterranean Sea with a grid size 1/12º by 1/12º, equivalent to ~6.5–8.0km in longitude and ~9.2km in latitude. The grid had one open boundary grid square in the Strait of Gibraltar. For numerical stability the time step Δt of integration was chosen to be 20s, satisfying the Courant-Friedrichs-Lewy condition $\Delta t < \Delta s\ (2gh)^{-1/2}$, where Δs is the minimum grid length.

The equations of motion were solved by an explicit finite-difference method (Flather, 1994). The initial conditions were 'cold start' conditions with $\xi=u=v=0$ at time $t=0$ and, for each model run, a 30-day 'warm-up' was performed with tidal forcing alone. A 'warm-up' time of eleven days was used for the meteorological forcing although experiments showed that results differed by less than 2cm by just seven days after the start of forcing.

3 TIDE GAUGE DATA

Hourly tide gauge observations for the year 1997 were obtained for the following three stations in the northern Adriatic Sea: Venice (45º30'N, 12º20'E), Trieste (45º39'N, 13º45'E) and the oceanographic platform (45º18'N, 12º30'E) situated 12km off the Venice Lagoon. The predicted tide was calculated by a harmonic analysis using 63 tidal components (Murray, 1964), and the non-tidal residual was deduced by subtracting the predicted tide from the sea level data. In this way, the effect of the meteorology on the sea level was measured.

The storm surge event we study here occurred on 20th December 1997, when an elevation of 73cm above the predicted level of the tide was recorded at

Venice at 10UTC. The same storm gave a surge of 63cm at 10UTC at the oceanographic platform and a surge of 82cm at 12UTC in Trieste.

4 METEOROLOGICAL DATA

The availability of high quality wind and pressure data is vital for success in modelling storm surges. Storm surges often arise from storms whose centres track across northern Italy from west to east and this sets up a pressure gradient along the length of the Adriatic, with low pressure in the north and high pressure in the south. For the accurate modelling of storm surges the wind field is the most critical forcing factor, but it is also the most difficult to generate. The wind fields over the Adriatic are spatially highly variable and change rapidly with time. They are strongly affected by the mountains that border the sea on three sides: the Alps to the north, the Apennines to the west and the Dinaric Alps to the east (Fig. 1).

Four meteorological data sets with a range of spatial and temporal resolutions were used to model the storm surge event that occurred in the Adriatic Sea on 20th December 1997.

4.1 Observational data

Observational data consisting of pressure, wind speeds and wind directions were obtained from the UK Meteorological Office (UKMO). The data were available every three hours for 21 meteorological stations distributed around the coast of the Mediterranean Sea. The locations of the stations used were chosen to give as even a distribution of data over the region as possible.

At each observing time, a pressure field was constructed by interpolating using neighbourhood averaging onto a regular grid of 0.5º by 0.5º resolution. The geostrophic wind field was calculated from the pressure field using standard formulae and the corresponding surface wind was deduced using an empirical result (Hasse and Wagner, 1971). Wind observations were assimilated to improve the accuracy of the wind field over the northern Adriatic.

The use of coastal wind observations in offshore wind stress calculations is known to be a source of error as the wind speed recorded offshore is generally greater than that recorded at the coast. Accerboni and Manca (1973) quote a figure for offshore winds being up to 80% stronger than coastal ones in the middle and northern Adriatic. A comparison of the wind speeds recorded during storm surge periods from 1993 to 1997 at Venice with those recorded at the oceanographic platform outside the Venice Lagoon showed that, during storms, the magnitude of the wind recorded offshore may be two to three times that at the coast. To take account of this, a scaling factor of 2.0 was introduced for assimilating the wind observations.

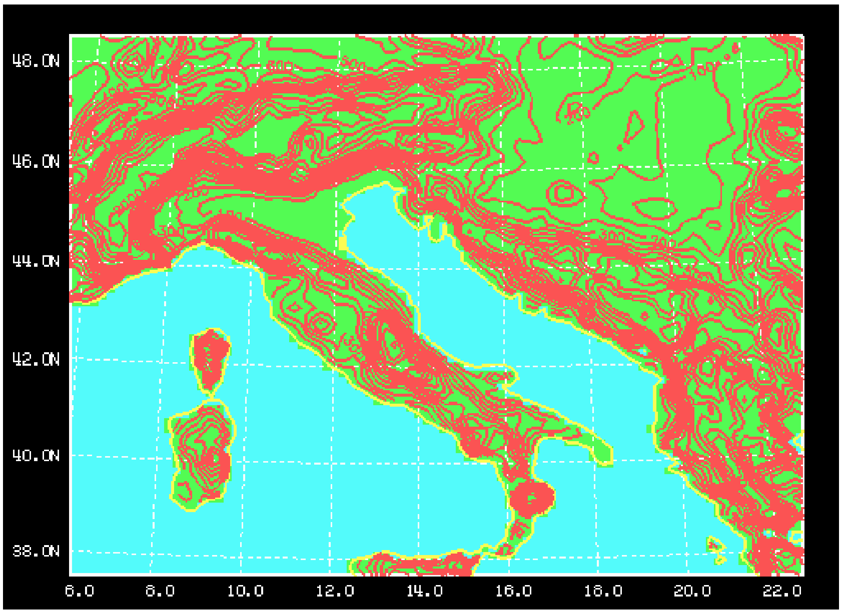

Figure 1: Topography of the Adriatic region. Contour interval 100m. Data resolution 16.2km.

4.2 European Centre for Medium-Range Weather Forecasts data

Mean-sea-level pressure and 10m wind fields were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis model (ECMWF, 1995). The data were available every six hours and extended over the globe on an N80 gaussian grid, corresponding to a resolution of approximately 1.125º by 1.125º in the Mediterranean area.

4.3 Local Area Model (LAMBO) data

Agenzia Regionale Prevenzione e Ambiente dell'Emilia-Romagna, Italy provided data from a high-resolution Local Area Model. These consisted of pressure and wind data on a rotated-pole grid with resolution 0.125º (approximately 0.2º by 0.2º in latitude-longitude coordinates). The data were available every six hours and covered the Adriatic region. Each model run was for 72 hours with the initial conditions being taken from the 00UTC ECMWF operational analysis model and boundary conditions from a 0.25º resolution local area model.

4.4 Mesoscale Analysis and Prediction System (MAPS)

The US wind data is derived from a mesoscale hydrodynamic primitive equation atmospheric model using sigma coordinates in the vertical (17 sigma levels) that is based on the model of Leslie et al. (1985). The model is part of a globally relocatable tide/surge forecast system developed for use by the US Navy. Initial conditions and boundary conditions for the model were provided by the analysis and forecasts of the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan and Rosmond, 1991) on a 1º by 1º grid. The boundary conditions from NOGAPS are provided to the mesoscale model every six hours during the forecast. The global land topography has a horizontal resolution of three minutes and is a subset of a 30 second resolution USGS data base. For this study, a 16km resolution grid was set up over the Adriatic. The mesoscale atmospheric model was run for the period December 8-26, 1997 and provided a 48-hour forecast of surface winds at three-hourly intervals for each day.

4.5 The tide-surge model forcing

Meteorological data were required for each model time step (every 20s) and for each grid box in the tide-surge model domain. The data for each time were obtained by linear interpolation between two times when data were available. The data for each grid box were calculated by a bilinear interpolation from the meteorological data grid to the tide-surge model grid. Pressure and wind data for the whole domain were needed so that the data sets that covered only the Adriatic region, that is, the LAMBO and MAPS data, were inserted as patches into the appropriate fields generated from the UKMO observations. The pressure field obtained from UKMO observations was combined with the MAPS wind data to give a complete forcing field.

Figures 2–5 show data from the four data sets at 6UTC on 20th December 1997, shortly before the storm surge was recorded. The meteorological situation was of a weather system tracking across the northern Mediterranean from west to east during 19th to 20th, which, by 12UTC on 20th, had a low pressure value of 1000mb positioned over Austria. The large-scale features of the pressure and wind fields are similar for all of the data sets. The data do not extend far enough north to pin-point accurately the location of the low-pressure centre but all of the fields have isobars with roughly north-south orientations over the Adriatic, consistent with the presence of a low-pressure centre to the north and east of Italy at that time. The wind fields of the ECMWF, LAMBO and MAPS data all have southerly winds at the entrance to the Adriatic, swinging south-easterly in the north. The UKMO wind field is southerly over much of the Adriatic and turns south-easterly only to the west of 14ºE.

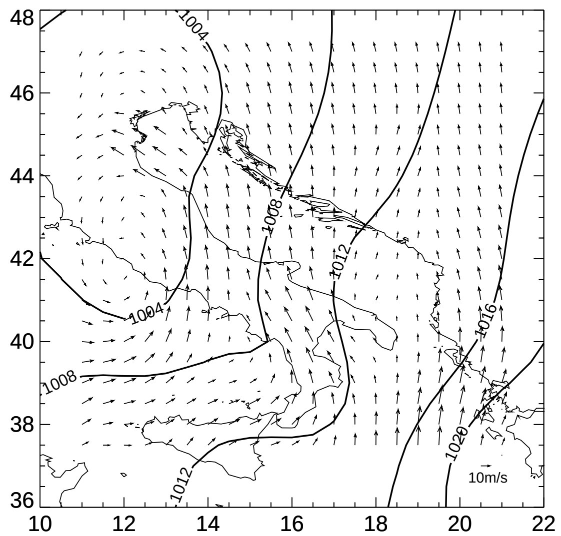

Figure 2: Pressure and wind fields from UKMO data interpolated onto a 0.5º by 0.5º grid for 6UTC on 20th December 1997. Wind data are plotted every second point.

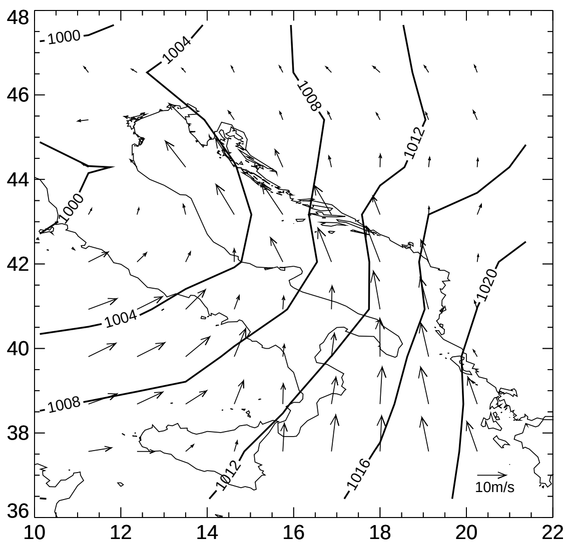

Figure 3: Pressure and wind fields for ECMWF data for 6UTC on 20th December 1997.

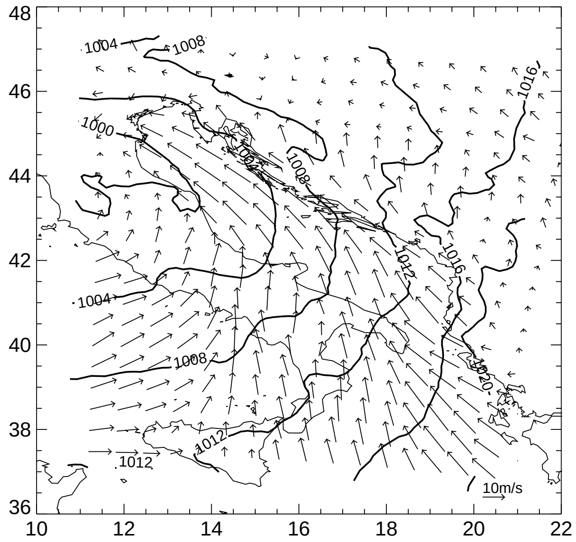

Figure 4: Pressure and wind fields for LAMBO model data for 6UTC on 20th December 1997. Wind data are plotted every fourth point.

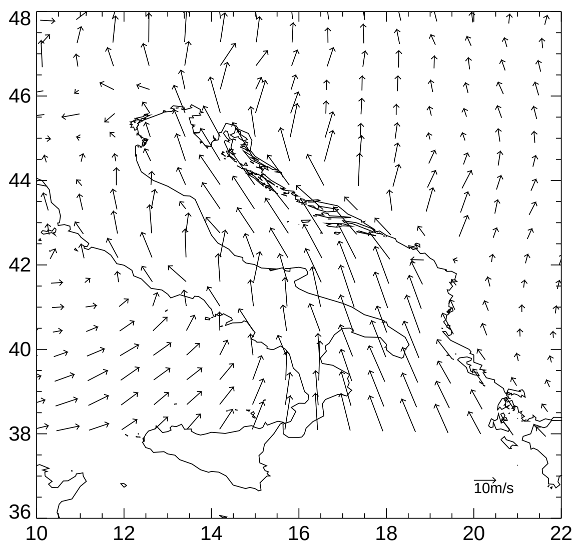

Figure 5: Wind field from MAPS data for 6UTC on 20th December 1997. Wind data are plotted every fourth point.

5 RESULTS

The model was run with tidal forcing alone for an initial warm-up period of 30 days from 0UTC 8th November to 0UTC 8th December 1997. Five model runs for the period 0UTC 8th December to 0UTC 24th December were made, once with tidal forcing and once with tidal and meteorological forcing using each of the data sets UKMO, ECMWF, LAMBO and MAPS in turn. Time series of hourly elevations were output for the five runs. The differences between the elevations using tidal and meteorological forcing and the elevation using tidal forcing alone are the residuals due to meteorological forcing.

A comparison between the model residuals for the different meteorological forcing fields and the residuals obtained from tide gauge records for Venice, the oceanographic platform and Trieste (Fig. 6) shows that there is a wide variation in the height of the modelled surge depending on the meteorological forcing. At Venice, for example, the maximum height of the observed surge is 73cm whereas the maxima for the modelled surges are 68cm for UKMO, 33cm for

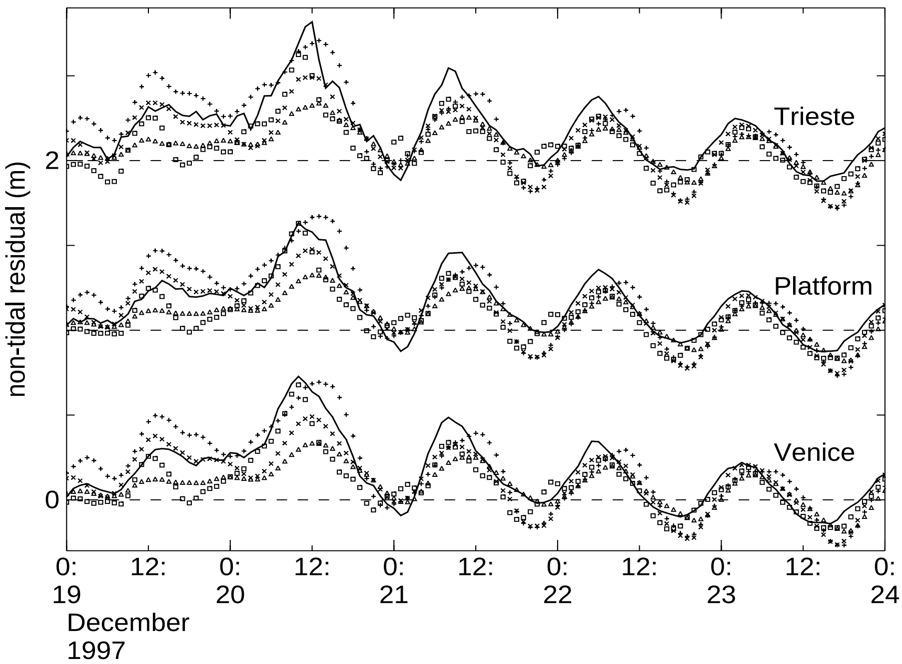

Figure 6: A comparison of the model residuals with UKMO (Θ Θ Θ), ECMWF (∊ ∊ ∊), LAMBO (×××) and MAPS (+ + +) data forcing with tide gauge residuals (——) for Trieste, the oceanographic platform and Venice. The residuals are offset for display with a dashed line (– – –) indicating the zero for each station.

ECMWF, 49cm for LAMBO and 69cm for MAPS data. The timing of the peak of the surge using the UKMO field is close to that observed while the other three results peak two to three hours later. Following the initial surge on the 20^{th} December is a series of seiches with period approximately 22 hours. These seiches are mainly due to the excitation of the fundamental longitudinal oscillation of the Adriatic Sea (Pugh, 1987). The results for all of the models reproduce these oscillations, although slightly underestimating the sea level.

6 SUMMARY

Significant differences in the modelled storm surge in the northern Adriatic arise from the four different forms of meteorological forcing.

The two data sets that give the most accurate approximations to the observed surge, UKMO observations and US Navy MAPS data, are both available at three-hourly intervals, in contrast to the six-hourly resolutions of the LAMBO and ECMWF data. The time resolution of the meteorological forcing is an important factor contributing to the accuracy of the tide-surge model results.

The coarsest resolution data, from ECMWF, produces the lowest surge. The highest resolution data, from US Navy, produces arguably the best surge, similar in magnitude to the surge produced by the adjusted wind fields derived from UKMO observations and close to that observed. The surge produced by LAMBO data lay between these. These results show the importance of modelled meteorological data with sufficiently high spatial resolution to resolve the effects of local topography. It appears that only the US Navy model (MAPS) has sufficiently high resolution (at 16km) to resolve this topography.

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REFERENCES

Accerboni, E. and Manca, B., 1973: Storm surge forecasting in the Adriatic Sea by means of a two-dimensional hydrodynamic numerical model. Bollettino di Geofisica Teorica ed Applicata, **15**, 3-22.

Cartwright, D.E., 1977: Oceanic tides. Reports on Progress in Physics, **40**, 665-708.

ECMWF, 1995: User guide to ECMWF products 2.1. European Centre for Medium-Range Weather Forecasts Meteorological Bulletin M3.2, 39pp.

Flather, R.A., 1994: A storm prediction model for the Northern Bay of Bengal with application to the cyclone disaster in April 1991. J. Phys. Oceanogr., **24**, 172-190.

Hasse, L. and Wagner, V., 1971: On the relationship between geostrophic and surface wind at sea. Monthly Weather Review, **99**, 255-260.

Hogan, T.F. and Rosmond, T.E., 1991: The description of the Navy Operational Global Atmospheric Predictions System's Spectral Forecast Model, Mon. Wea. Rev., **119**, 1786-1815.

Leslie, L.M., Mills, G.A., Logan, L.W., Gauntlett, D.J., Kelley, G.A., Manton, M.J., McGregor, J.L. and Sardoe, J.M., 1985: A high resolution primitive equation NWP model for operation and research. Aust. Meteorol. Mag., **33**, 11-35.

Murray, M.T., 1964: A general method for the analysis of hourly heights of the tide. International Hydrographic Review, **41**(2), 91-101.

Orli◖, M., Kuzmi◖, M. and Pasari◖, Z., 1994: Response of the Adriatic Sea to the bora and sirocco forcing. Continental Shelf Research, **14**, 91-116.

Pugh, D.T., 1987: Tides, Surges and Mean Sea-Level. John Wiley, New York, 472 pp.

Smith, S.D. and Banke, E.G., 1975: Variation of the sea surface drag coefficient with wind speed. Quart. J. Roy. Meteor. Soc., **101**, 665-673.

Tsimplis M.N., Proctor, R. and Flather, R.A., 1995: A two-dimensional tidal model for the Mediterranean Sea. J. Geophys. Res., **100** C8, 16223-16239.