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POSEIDON: An integrated system for analysis and forecast of hydrological, meteorological and surface marine fields in the Mediterranean area

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Summary. — The Mediterranean area is characterized by relevant hydrological, meteorological and marine processes developing at horizontal space-scales of the order of 1–100 km. In the recent past, several international programs have been addressed (ALPEX, POEM, MAP, etc.) to "resolving" the dynamics of such motions. Other projects (INTERREG-Flooding, MEDEX, etc.) are at present being developed with special emphasis on catastrophic events with major impact on human society that are, quite often, characterized in their manifestation by processes with the above-mentioned scales of motion. In the dynamical evolution of such events, however, equally important is the dynamics of interaction of the local (and sometimes very damaging) processes with others developing at larger scales of motion. In fact, some of the most catastrophic events in the history of Mediterranean countries are associated with dynamical processes covering all the range of space-time scales from planetary to local. The Prevision Operational System for the mEditerranean basIn and the Defence of the lagOon of veNice (POSEIDON) is an integrated system for the analysis and forecast of hydrological, meteorological, oceanic fields specifically designed and set up in order to bridge the gap between global and local scales of motion, by modeling explicitly the above referred to dynamical processes in the range of scales from Mediterranean to local. The core of POSEIDON consists of a "cascade" of numerical models that, starting from global scale numerical analysis-forecast, goes all the way to very local phenomena, like tidal propagation in Venice Lagoon. The large computational load imposed by such operational design requires necessarily parallel computing technology: the first model in the cascade is a parallelised version of BOlogna Limited Area Model (BOLAM) running on a Quadrics 128 processors computer (also known as QBOLAM).

POSEIDON, developed in the context of a co-operation between the Italian Agency for New technologies, Energy and Environment (Ente per le Nuove tecnologie, l'Energia e l'Ambiente, ENEA) and the Italian Agency for Environmental Protection and Technical Services (Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici, APAT), has become operational in 2000 and we are presently in the condition of drawing some preliminary conclusions about its performance. In the paper we describe the scientific concepts that were at the basis of the original planning, the structure of the system, its operational cycle and some preliminary scientific and technical evaluations after two years of experimentation.

PACS 92.10.Hm – Surface waves, tides, and sea level.
PACS 92.40.Ea – Precipitation.
PACS 92.60.Wc – Weather analysis and prediction.
PACS 93.55.+z – International organizations, national and international programs.

1. – Introduction

Mediterranean weather is, it is well known, characterized by usually *secondary* weather: meteorological perturbations, after forming elsewhere (*primary*, typically Atlantic, weather), reach the Mediterranean basin and are locally (often quite strongly) modified. Mediterranean weather generates a wealth of phenomena of great impact on human society. Consequently, several generations of meteorologists have been formed in the context of national and international projects dealing with the observation, the phenomenology, the dynamics of Mediterranean secondary weather generation (in particular secondary cyclogenesis) and, finally, in the construction of the analysis-forecast devices necessary in the context of service operations in the area. More recently, the hypothesis that even some *pre-conditions* of very severe weather development in the Mediterranean region may be determined by external, planetary scale agents has been put forward (see, for example, [1, 2]).

On the other hand, Mediterranean weather is rich of mesoscale phenomena: from subfrontal structures (like rain bands), to local winds (like Bora and Mistral), to localized jets (like the low-level jets often associated with Libeccio wind). Mediterranean hydrographic basins are generally quite small (in most cases a few hundred square kilometers). Many of the high-impact manifestations of weather are perceived in direct association with processes developing on space scales of the order of 1–100 km and time-scales of the order of hours. As a consequence, it is not difficult to understand the reasons why a strong emphasis has been posed over the last years on the problem of resolving even the smallest scales of geophysical fluid dynamical motion in the Mediterranean area. In fact, after achieving the basic understanding of secondary weather generation, many models started being run operationally with horizontal grid spacing of 20–30 km in relatively small domains, because of computational limitations (*e.g.*, DALAM).

However, resolution is only one aspect of the problem and appropriately modeling the interactions among all the scales, from planetary to local, characterizing the key dynamical processes remains crucial in producing good forecasts. For this reason we felt the need of trying to achieve an acceptable compromise between the two opposite needs of high resolution and great coverage by setting up a numerical model able to cover at good resolution an adequately extended area. This could be done only disposing of appropriate computation facilities.

At the beginning of nineties, when the project was first envisaged, Mediterranean Meteorology was in the process of transforming into practical applications the knowledge accumulated in the course of several national and international projects. These projects, culminated in the ALPine EXperiment (ALPEX) sponsored by the National Science Foundation (NFS) and other international agencies, had as major target the development of weather and weather-induced phenomena in the Mediterranean area. At the same time, the resulting models showed all the requisites for becoming the core of a system of analysis-forecast capable of exploiting all the modern technologies in observation (in particular from space) of geophysical fields and data transfer-storing. An early example of such experience is given by the (still) operational DALAM model, which actually can be considered a previous version of the BOlogna Limited Area Model (BOLAM, see [3]). Moreover, as will be seen later, Italian computer-science was at a stage of rapid development in the direction of setting up high-speed computing devices.

In the following we propose a synthesis of the various concepts that were at the basis of the original planning of the Prevision Operational System for the mEditerranean basIn and the Defence of the lagOon of veNice (POSEIDON).

The POSEIDON project was, and still is the first fully Italian effort aimed to produce integrated weather and sea-state forecasts over the entire Mediterranean area, abridging from planetary to local scales. Such ambitious project is the result of a joint effort among different Italian scientific and service institutions, and precisely between the Italian Agency for New technologies, Energy and Environment (Ente per le Nuove tecnologie, l'Energia e l'Ambiente, ENEA) and the Italian Agency for Environmental Protection and Technical Services (Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici, APAT), in collaboration with the Italian National Research Council (CNR).

The paper is organized as follows. In the following sect. **2** we analyze in more detail the concepts, already outlined above, which were at the basis of the original formulation of the project. Section **3** describes the system in its overall structure and single components. In sect. **4** we outline the post-processing procedures that are being developed for relevant specific applications of the numerical outputs. Section **5** provides some preliminary results of statistical evaluation of the model performance. In sect. **6** we, finally, draw our conclusions.

2. – Mediterranean weather and its impact: global and local modeling

Mediterranean major impact weather is typically characterized by the simultaneous presence of physical processes operating at different space-time scales: from the planetary scales of *primary* disturbances (usually middle-latitude, Atlantic cyclones), generating *secondary* weather in the Mediterranean area, to the modulation of precipitation and run-off at the (usually quite small) scale of river basins. The central problem of Mediterranean weather forecast lies, it was then recognized, in modeling the dynamics of atmospheric evolution simultaneously at all the above space scales and, in particular, the nonlinear interaction among the different physical processes. Intense precipitation with flooding and/or landslides like the ones recently occurred in north-western and southern Italy (*e.g.*, Piedmont 1994 and 2000, Basin of Sarno 1998), Mistral sea storms, sea surge (Acqua Alta) along the northern Adriatic coast, are all examples of recurrent phenomena that express their catastrophic potential locally, but are embedded in an evolution dynamics characterized by physical processes of much larger (sometimes, in fact, even planetary) scale. An outstanding, recent example is provided by the event that hit Piedmont and

Aosta Valley in October 2000 during the entire occurrence of which a planetary scale split-flow (with an anticyclone going all the way to the North Pole) was present, while the entire Northern Hemisphere middle-latitude planetary circulation appeared characterized by little (if any) propagation of its disturbances.

At the time of initial planning of POSEIDON, NWP (Numerical Weather Prediction) was unable to deal with the above complexity. In fact, between the scale of ECMWF (European Centre for Medium-range Weather Forecasts) global model, usually providing the analysis and boundary conditions for regional Limited Area Models (LAMs) and LAMs themselves there was a gap both in space-time resolution (about 10 km) and in domain-size (all the Mediterranean area).

Together with the above-underlined inadequacies in the overall representation of Mediterranean weather evolution, somewhat opposite requirements of "local" definition for specific applications had to be considered. Significant wave height, for example, was known to be extremely sensitive to the resolution of marine surface wind. A practical forecast rule([1]) warns that the wave forecast cannot be better than that of marine surface wind. This dictated, in practical terms, horizontal grid spacing of the order of a few kilometers. Successive experience has confirmed this ancient wisdom (see subsect. **5**˙1).

Another, even more complex problem is that of modeling the forcing and propagation of tidal waves. In fact, Laplace tidal equations can show sensitivity to boundary conditions at the scale of entire sea basins (see subsect. **5**˙2), while practical applications require very detailed modeling of their propagation in channels and lagoons (we, obviously, refer here to the case of Venice).

2˙1. *Computing: requirements and background.* – In view of the accumulated scientific knowledge, the practical needs, the technological potential, it appeared a feasible useful and challenging enterprise that of setting up a system of numerical models aimed at bridging the gap between global and local dynamics and integrating the meteorological, oceanographic, hydrological (including hydrogeology) aspects of forecasting. The project requirements were:

- an operational setting, with at least daily capability in producing a high-resolution meteorological and sea-state forecast for the Mediterranean area, in particular the water level in the Adriatic sea and in the Venice Lagoon;
- real-time availability of the products;
- build-up of a historical database.

Such requirements imposed a forecasting lead-time of 48 hours, and automatic post-processing procedures, together with a robust hardware and software design.

The NWP system requirements were that all the useful geophysical quantities needed to be computed over the entire Mediterranean area with a horizontal grid spacing of about 10 km in latitude and longitude. As will be seen more in detail later, to fulfil these requirements the meteorological model inner domain had to have 386×210 grid points, with 40 vertical levels in sigma coordinates. So, in order to produce a useful meteorological forecast (*i.e.*, approximately one day forecast in one hour), supercomputing capabilities were needed. At that time the system was devised. The Array Processor Experiment (APE) project [4] was proposing a parallel supercomputer, named Quadrics

([1]) Almost as old as the one stating that: *it is difficult to beat persistence!*

in its commercial version, which promised to provide the basic capabilities for facing the formidable task of modeling, simultaneously and explicitly, many decades of scales of motion involved in the complex Mediterranean phenomenology. For the POSEIDON system an APE100 machine with 128 processors was selected. This is a general purpose Single Instruction Multiple Data (SIMD) computer, based on a 3-dimensional cubic mesh of nodes with periodic boundary conditions, each node being connected to its 6 neighbors. The machine has a modular architecture, the building block being a $2 \times 2 \times 2$ cube, with 6 GFlops performance peak speed. This architecture was well suited for NWP with a LAM [5].

3. – Description of the integrated system for analysis and forecast

The operative integrated system consists of a Limited Area Model (BOLAM), coupled with a WAve Model (WAM) [6] and a high-resolution shallow-water model (Princeton Ocean Model, POM-2D) [7, 8] of the Adriatic and Ionian Sea. The atmospheric and the wave model are run over the whole Mediterranean basin at a resolution of 0.1 degrees. An intermediate-resolution run of the atmospheric model is performed with a grid spacing of 0.3 degrees, using ECMWF forecast as input. Water levels computed by POM-2D at the entrances of the lagoon are given as input to a finite element model of water level in the lagoon itself, to predict surface levels in Venice. An Optimal Interpolation code has been implemented in order to allow assimilation of *synop* and *temp* observations in the initial condition provided by the ECMWF analysis.

In order to satisfy the operational requirements (*i.e.* approximately one day forecast in one hour), the meteorological model, which is by far the most demanding in terms of the computational effort required, was implemented on APE100/Quadrics, a massively parallel computer with a peak power of 6 billion floating point operations per second in the maximal 128 processors configuration.

Here in the following we give some basic information concerning the system, its single segments and the operational chain.

3˙1. *The modeling chain.* – The quality of the prediction of sea surge depends on the quality of the atmospheric forcing (mean sea level surface wind) which, in turn, is essentially determined by the representation of the complex orography present in the area. International scientific programs such as ALPEX [9], the Pyrénées Experiment (PYREX) [10] and the Mesoscale Alpine Programme [11], have been internationally organized in the last twenty years with the aim of improving the understanding and the modeling of the impact of mountainous massifs surrounding the Mediterranean on the local atmospheric behavior.

In order to achieve a satisfactory representation of the atmospheric conditions induced by the orography around the Adriatic and the central Mediterranean Sea, the limited area model BOLAM has been used, as it has proved to have an excellent behavior with respect to other state-of-the-art LAMs in the context of the PYREX experiment [12, 13]. Nesting in two steps has been set, which allows a smooth transition from the coarser resolution of the boundary data (ECMWF analysis with a spectral truncation of T319) to a very high-resolution (VHR) grid in the region of interest. Therefore the VHR BOLAM (10 km resolution) is driven by a high-resolution (HR) BOLAM (30 km resolution), which is in turn driven by the ECMWF analysis. Boundary data for the HR model are given every 6 hours, and every 3 hours for the VHR model. Both the HR and VHR models run with 40 sigma levels.

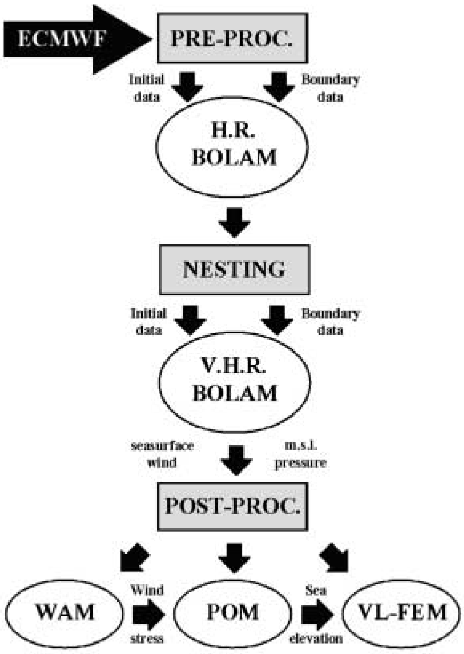

Fig. 1. – Description of the POSEIDON operational chain. ECMWF previous day analysis at 1200 UTC and boundary conditions are provided to HR BOLAM, for a 60 h forecast. VHR BOLAM is forced with HR boundary data, neglecting the first 12 h, hence producing a daily 48 h forecast starting at 0000 UTC. The 0.1° grid size 10 m wind field and mean sea level pressure are used to force firstly WAM, then POM-2D and finally the VL-FEM model.

WAM is forced by the surface wind, while POM-2D is driven by the surface wind stress field computed by WAM and by the sea level pressure field computed by BOLAM.

Finally, a finite element, very high-resolution model of the interior of the Lagoon is used to predict the water level in Venice. The whole operational chain is shown in fig. 1.

3˙1.1. The Atmospheric Limited Area Model: BOLAM. The atmospheric model used in the system was developed at the Institute of Atmospheric Sciences and Climate (ISAC-CNR), formerly FISBAT-CNR, Bologna [3]. BOLAM is an explicit, primitive equations, hydrostatic, three-dimensional grid point model which uses pressure-like vertical coordinates (sigma coordinates). Horizontal discretisation is performed on the Arakawa C-grid, with rotated latitude and longitude as independent variables. The model integrates the equations of momentum, mass continuity and energy conservation on a regular latitude/longitude grid. The prognostic variables are longitudinal and latitudinal wind components, potential temperature, specific humidity and surface pressure. The time integration of the prognostic advection equations is performed using the Forward-Backward Advection Scheme (FBAS) [14]. A fourth-order horizontal hyperdiffusion operator is applied to the prognostic variables and divergence damping of momentum is used to reduce the growth of gravity waves. Both horizontal diffusion and divergence damping are computed using the Euler scheme. An adjustment loop has been implemented, using a forward-backward scheme with reduced time step, for those terms in the primitive equa-

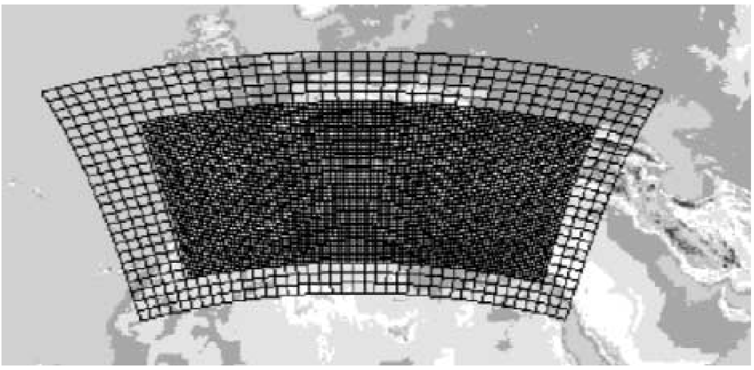

Fig. 2. – Computational domains of BOLAM meteorological model. HR version (outer grid) has 0.3° grid size, while VHR version (inner grid) has 0.1° grid size.

tions describing fast gravity modes. Relaxation to boundary conditions is performed using the Davies scheme [15], modified by Lehmann [16], and is applied to all prognostic variables. The extension of the 30 km outer domain (HR) and the 10 km inner domain (VHR) of BOLAM is depicted in fig. 2.

3˙1.2. The WAM model. WAM is a third-generation wave model [6]. It describes the evolution of the wave spectrum by solving the wave energy transfer equation. It has no constraints on the spectral shape, whose evolution depends on the spatial divergence of the energy flux and on the local sources of energy. The WAM integration is forced by the atmospheric stress computed via the quadratic stress relation:

$$\tau = \rho C_{\mathrm{D}} U^2 \,, \tag{1}$$

where U is the 10 m surface wind predicted by BOLAM, C_{D} is the drag coefficient and ρ is the density. Then WAM calculates the wave contribution to the total stress τ_0 which, in turn, iteratively corrects the total atmospheric stress τ. The resulting stress is used to force the POM-2D integration. WAM is integrated on sea points of the VHR domain (fig. 3), with the 0.1 degrees grid spacing in latitude and longitude.

3˙1.3. The POM-2D model: shallow-water version. The Princeton Ocean Model (POM) [7, 8] is a three-dimensional primitive equations ocean model. In this work, it has been operated in a 2D configuration solving the shallow-water equations to compute surface elevation. We expect this approximation to be sufficient to capture the main features of the storm surges in the Mediterranean, since they are essentially the barotropic response of the basin to the atmospheric forcing [17]. The 2D configuration of the POM model has been used in other studies dealing with storm surges in the Northern Adriatic [18, 19] and with the Indonesian Seas circulation [20, 21]. The horizontal discretisation is performed on the Arakawa C-grid. An explicit Orlanski condition [22] for the elevation, with a restoring to a prescribed value has been selected between the boundary conditions available in the model. However, since the Orlanski scheme [22] does not conserve the total water mass of the basin [25], it is necessary to locate the open boundary where the elevation is close to zero.

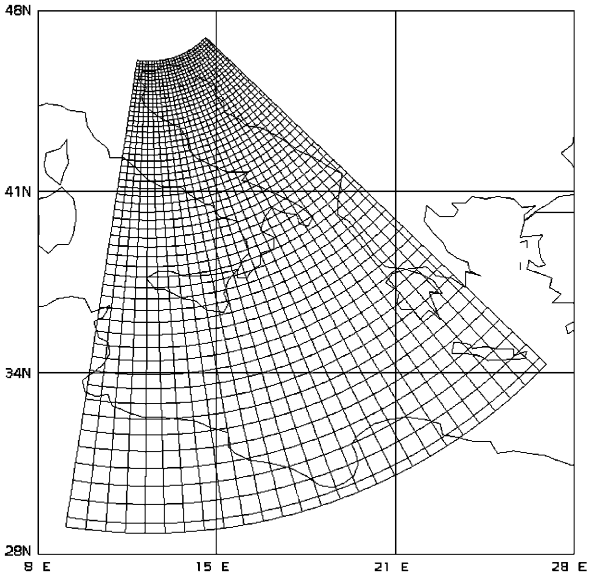

Fig. 3. – Finite-Difference Arc2 grid for POM-2D model, including the Adriatic and central Mediterranean Sea.

3˙1.4. Venice Lagoon Finite Elements Model. A very high-resolution model (VL-FEM) solving the depth-integrated shallow-water equation is used to predict water levels in the lagoon of Venice. The model uses finite elements in the horizontal and a semi-implicit time resolution algorithm [26]. Finite elements allow great flexibility in the subdivision of the basin in triangles varying in form and size, their use is particularly useful in this application due to the complicated geometry and bathymetry of the lagoon. In input the model has the levels at the three entrance of the lagoon, evaluated by POM-2D and the stress in the interior of the lagoon derived from the WAM integration. The mesh used by this model consists of about 7500 elements, with a spatial resolution varying from 1 km along the mud flats down to 40 m inside the channels.

3˙1.5. Operative chain settings. The aim of the operative system is to obtain 48 hours simulations at the resolution of 0.1 degrees both in longitude and in latitude. The main products are meteorological fields and wave heights on the entire Mediterranean domain and sea levels in the lagoon of Venice. The meteorological model with 0.3 degrees grid spacing is initialized using ECMWF analysis fields at 1200 UTC, boundary conditions come from the ECMWF forecast every 6 hours (see fig. 1). The run is 60 hours long. The outputs of this run are used as initial and boundary conditions for the higher resolution run. The VHR-BOLAM run start with a delay of 12 hours from the coarser and produces wind and mean sea level pressure field to force WAM, POM-2D and FEM models. Both the integration domains (HR and VHR) cover the entire Mediterranean basin (fig. 2).

As to the POM-2D setting, by using a boundary condition located at Otranto the oscillation that involves both the Adriatic basin and the eastern basin cannot be entirely represented. For this reason an integration domain including at least the Adriatic and the eastern basin should be considered. The domain used includes the Adriatic and the central part of the Mediterranean Sea (Arc2 area in fig. 3), the Levantine sea is not included, since it accounts for a small part of the total water mass of the eastern basin. The initial elevation and current are set to zero. The domain is characterized by an extensive open boundary on which outflux of energy is allowed and the initial mean elevation is kept almost constant. Therefore, an initial perturbation of the elevation field with a low projection onto the main normal modes of the basin is rapidly radiated out of the boundary (in about 36 hours for an experiment without forcing).

In defining the grid we had to take into account the need of very high-resolution (about 1 km) in the northern part of the Adriatic sea, which derives from the fact that sea surface levels at the three close locations of Chioggia (12.3E, 45.23N), Malamocco (12.32E, 45.33N) and Lido (12.42E, 45.44N) have to be predicted. To define the domain we adopted a polar, non-uniform grid. The center of the reference frame is located at (Lon_0, Lat_0) = (12.43E, 48.73N). The distance of a generic point P is obtained via the equation $\eta_\mathrm{P}^2 = (\mathrm{Lon}_\mathrm{P} - \mathrm{Lon}_0)^2 + (\mathrm{Lat}_\mathrm{P} - \mathrm{Lat}_0)^2$, while the angle is defined as $\xi_\mathrm{P} = \arctan\left[(\mathrm{Lat}_\mathrm{P} - \mathrm{Lat}_0) / (\mathrm{Lon}_\mathrm{P} - \mathrm{Lon}_0)\right] + \alpha_0$, where α_0 is defined using $\tan(\alpha_0) = (\mathrm{Lat}_\mathrm{sw} - \mathrm{Lat}_0)/(\mathrm{Lon}_\mathrm{sw} - \mathrm{Lon}_0)$ and (Lon_sw, Lat_sw) = (28.9E, 9.4N).

4. – Post-processing and post-events

It is clear that a system like the above-described one can serve many practical purposes and the numerical output must usually undergo some post-processing procedure in order to fulfil the task in question. The first applications devised in the context of our system are: fitting of wave measurements by buoys; tidal propagation fitting; coupling of numerical precipitation with river flow models for purposes of flood forecasting; forecast of extreme events, like frosts; real time evaluation of risk of land-slide occurrence. Here following we briefly describe these applications.

4·1. *Waves.* – The statistical and deterministic verification and post-processing of sea-state forecasts is a fundamental step necessary to the development of applications with high potential economical impact. Some preliminary results are presented in subsect. **5·1**. A future example of such an activity is the marine routing project in western Mediterranean Sea (INTERREG MEDOCC - project Weatherrouting dans la Méditerranée, WERMED).

4·2. *Tides and sea-elevation.* – The activity of sea-elevation and tide verification is currently ongoing. The POM-2D model will be verified against marigraphic data available from the instruments located in the Adriatic Sea. The same verification study will be performed for VL-FEM model using sea-elevation observations in the Venice Lagoon. An important effort is being made in order to perform an adequate data quality check.

4·3. *Flooding forecast.* – A preliminarily study about possible hydro-meteorological applications of precipitation forecast was developed in the recent past [23]. The serial version of BOLAM code (horizontal grid step: 30 km) was applied to a lumped rainfall-runoff watershed model, calibrated to produce a local river discharge forecast starting from rain gauge observation. The study area (the upper Tiber Valley) has the optimal size according to the model resolution (not too small) and the actual needing of a hydro-meteorological forecasting approach (not too large). Results were encouraging, but the optimization and implementation in cascade with the parallel BOLAM system requires further studies.

4·4. *Frosts*. – In general, numerical prediction of local, extreme surface temperature events as frost events requires the application of some post-processing scheme to the model forecast, due to the strong inhomogeneity of the temperature field (*e.g.*, due to local orographic details). A preliminarily study on suitable post-processing schemes applied to ECMWF two-meter temperature forecast was carried out [24]. Simple post-processing schemes (altitude correction, linear regression), Kalman Filtering (KF) and an advanced Neural Network (NN) algorithm are tested against a 1 year observation database over four stations in Italian Puglia region. On the whole, NN is found to overpass the performance of the other methods. Among the latter, KF is the most effective in reducing the error. Further development is required to fully exploit the potential of the NN method and to implement an NN-based post-processing scheme in cascade with the parallel BOLAM model.

5. – Preliminary evaluation of model performance

The question of how to evaluate the performance of numerical models is, it is well known, an open and controversial one. First of all there is no unique way to define a measure of the model skill. This can (and, sometimes, does!) generate a tendency to establish and use *ad hoc* criteria. Moreover, even once adequate evaluation criteria are agreed upon, difficult technical questions invariably emerge; typically:

1. values of variables on numerical grids are not statistically independent;
2. statistical distributions of variables dealt with are not parametric;
3. available observations are insufficient for determining the truth concerning the field in question.

In view of the above general problems and of the practical applications of our system, we adopted operationally oriented verification criteria [27]. Detailed discussions of the adopted approach and the results obtained so far are reported elsewhere in literature. Here we just summarize the main knowledge acquired in the different areas of operation.

5·1. *Sea-state: surface waves*. – At present is ongoing a thorough verification of WAM 2000-2002 sea-state forecasts against buoy data from the Italian National Buoy Network (Rete Ondametrica Nazionale, RON; see fig. 4). This analysis is needed in order to evaluate the forecasting capabilities during different events. A first assessment is presented in fig. 5 in the form of scatterplots of 3-hourly 24 h forecasts against coincident significant height observations at Alghero, Crotone, La Spezia and Mazara buoys, for a time period from 1/6/2000 to 1/5/2002. The agreement is quite good, although data were not post-processed, showing that the POSEIDON system has a good forecasting capability in the considered areas. It must be also pointed out that 3 hours verification might be insufficient to represent in a satisfying way the time evolution of fast sea-storms (9–12 hours).

The forecasting capability of the model can be also assessed verifying the significant height time series using 24 hours forecasts. Three different examples are reported, at Crotone, La Spezia and near the Island of Ponza (fig. 6).

An important issue to be considered in the analysis of the strongest events is the increasing influence of the bathymetry near to the coasts. In such cases WAM forecasts might be significantly different from what observed, because the model is not ideal for use

Fig. 4. – Distribution of the Italian Buoy Network.

in shallow water conditions. Open sea forecast should be more close to the observations, where available.

5˙2. *Sea-state: tidal waves.* – As mentioned before, the actual verification of operational tidal waves forecasting is currently ongoing. However, a preliminary assessment and description of the POM-2D pre-operational version is presented in Bargagli *et al.* [28]. The outcomes of this work were used for the design of the current operational forecasting system.

5˙3. *Precipitation.* – Precipitation is obviously a quantity of great interest, from everyday life to hydrological applications. An important future development of the integrated system is the coupling of the meteorological model with hydrological models over the sensitive Italian basins. This is a very demanding task, partly due to the hydrological modeling complexities. Another important point is that hydrological forecasting may require an adequate statistical post-processing of the necessary meteorological fields to bridge between different phenomenological scales. Finally, many basins have small spatial extension, hence hydrological forecasting may be very sensitive to small forecast displacement errors, just to mention one.

In this context, an innovative statistical non-parametric skill score intercomparison exercise among different LAMs, including BOLAM, of 24 h precipitation forecasts has been performed over Liguria and Piedmont regions by Accadia *et al.* [29] using 8 months forecast and rain gauge observation data, starting from the 1/10/2000. This dataset included the Piedmont flood event of 13-16 October 2000. This work has been done in the framework of the EU project INTERREG IIC: Land Management and floods prevention-Intercomparison of Limited Area Models.

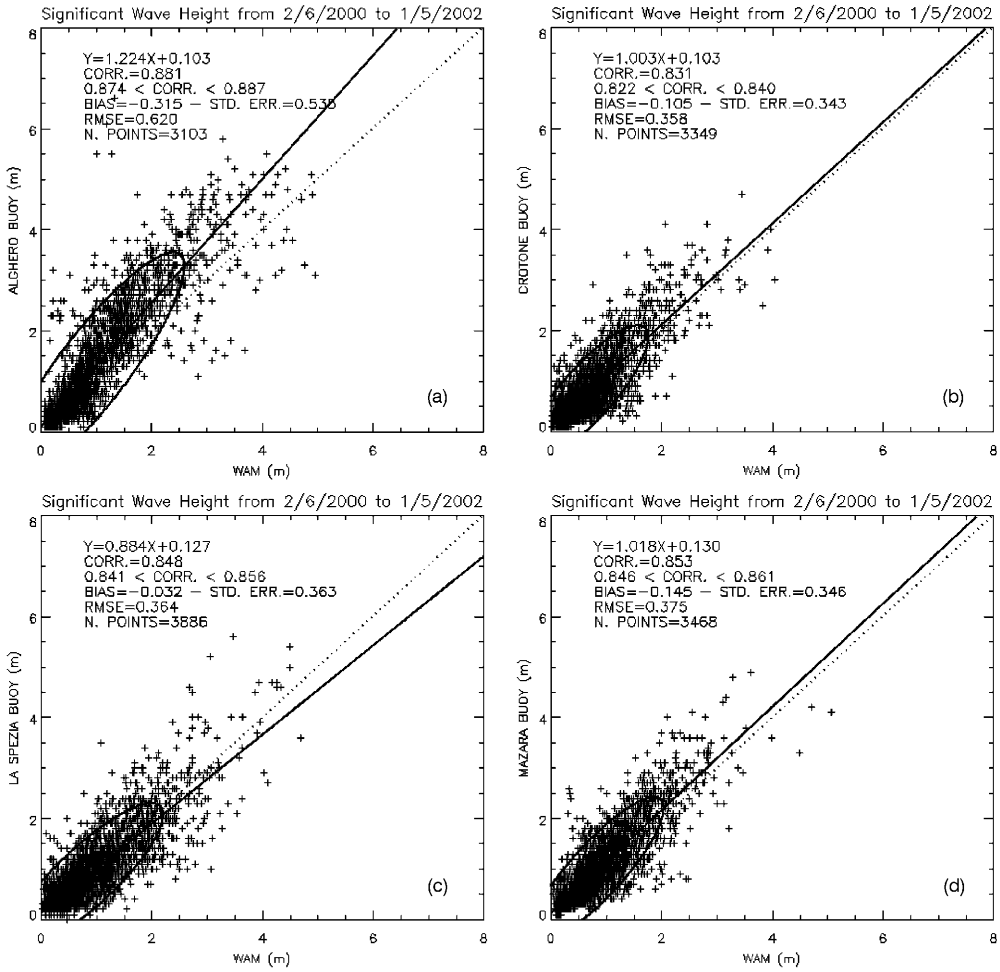

Fig. 5. – Significant wave height scatter diagrams of 24 h WAM forecasts against buoys observations, from 2 June 2000 to 1 May 2002. a) Alghero buoy; b) Crotone buoy; c) La Spezia buoy; d) Mazara buoy.

The skill score differences among the considered models have been assessed using the resampling technique proposed by Hamill [30]. BOLAM showed a fair forecasting capability of strong precipitation events, statistically equivalent to that of the others considered LAMs. This study has been recently extended to the whole Italian territory, using and extended dataset with 2 years worth 24 h precipitation forecasts and corresponding raingauge observations, from 1 October 2000 to 1 October 2002 [31]. The BOLAM implementation on Quadrics machine (also known as QBOLAM) shows some difficulties in forecasting precipitation during summer season. One of the drawbacks of the present parallel computational system is an actual stiffness in code changes, which has been developed in TAO language (see Appendix). This work indicates that some parameterizations (convection in particular) have been overly simplified, reducing the precipitation forecasting capability. This assessment backed the decision to migrate BO-

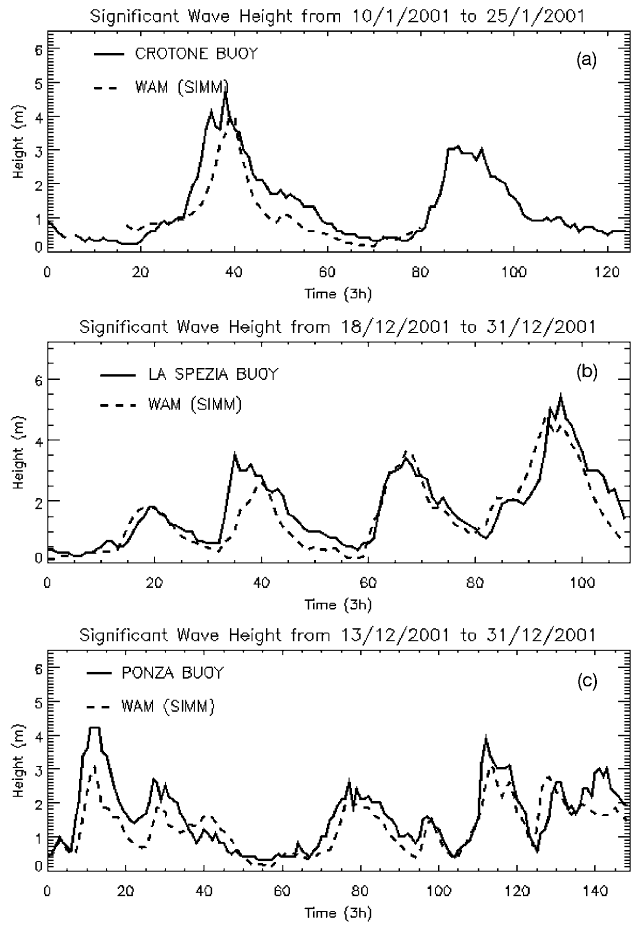

Fig. 6. – Significant wave height measured by buoys and forecast by WAM during sea-storm events. Solid lines indicate buoy measurements, whereas dashed lines indicate WAM forecasts. a) Crotone buoy—from 0000 UTC of 10 January to 2300 UTC of 25 January 2001. b) La Spezia buoy—from 0000 UTC of 18 December to 2300 UTC of 21 December 2000. c) Ponza buoy—from 0000 UTC of 13 December to 2300 UTC of 31 December 2001.

LAM on a new parallel machine, which will allow a more flexible and updated Fortran 90 implementation.

BOLAM has also been used in the framework of the EU project Hydroptimet (INTERREG IIIB-MEDOCC Programme) [32] and VOLTAIRE project (5th Framework Programme) [33].

The principal aim of Hydroptimet was to advance in the knowledge of intense hydrometeorological events, which produced many damages in the Mediterranean area, by optimization of current hydro-meteorological forecasting techniques. Hence BOLAM simulations have been placed at partners' disposal both for case-study model intercomparison and to initialize selected hydrological models for the corresponding hydrological simulations. Moreover, within VOLTAIRE, BOLAM precipitation forecasts, rain gauge data and radar observation are used to determine possible forecast error sources.

6. – Conclusions

At the time when the project was started the main motivation was to prove the *feasibility* of running in *service configuration* an atmospheric model covering all the scales of motion from *global* (*i.e.* comparable with the Earth's radius) to *local* (in the case of Italy, typically that of a hydrological basin), together with a *complete set of linked*, in the sense of "one-way forecasting", *models* (waves, tides, runoff, etc.).

Over the years, the system has been enriched with many *post-processing* chains based on both statistical and deterministic methods. These operational post-processing procedures are an important part of the system, both for diagnostics of the system itself and for immediate use and application of forecasting products.

In our opinion this "system approach" to the problem of regional forecasting in a complex area like the Mediterranean region is still valid. Actually, systems of the size and complexity of the one described here are essential for assimilating remotely sensed observations from orbital platforms. In fact, the use of new kinds of observations from space and the study and development of new assimilation methods is a "big science" task, since it involves the scientific, engineering and industrial communities at national and international level.

On the other hand, a dominant tendency is, nowadays, that of setting up finer and finer grid models in order to bring the output of the models themselves nearer to the "human world time and space scales". This may result in a dangerous tendency in the context of forecasting, in which the really important point is to *capture the time-space scales on which the derivatives of state variables of the system are "written"*.

Moreover, in the context of current studies on assimilation (in particular of observations from space) it emerges that even larger domains, like the one presented in fig. 7, are needed. Two are the main motivations:

- controlling the modes of error growth (mostly baroclinic waves) in the process of assimilation implies full representation of the modes themselves [34]: such modes typically are of full Euro-Atlantic scale;
- As the model variables (typically 10^7–10^8 real variables) are compressed in ever smaller domains, the ratio observations/variables becomes ever smaller. Just to give an idea, in each assimilation cycle only 10^3 (independent?) observations are assimilated.

The above considerations and motivations, together with the operational experience from the POSEIDON project, should be considered thoroughly before the development of any future regional forecasting system is started. Anyhow, the POSEIDON system, for the region covered, for outputs of operational chain, for analyses performed and for available database still remains a high quality system.

Appendix

The development of the parallel version of BOLAM code for the Quadrics supercomputer, called QBOLAM, started in 1997. At that time, the operational requirement of a meteorological code running at more than 2 GFlops sustained could be effectively satisfied using the parallel computer Quadrics, also known as APE100.

Quadrics is a massively parallel Single Instruction Multiple Data (SIMD) computer based on a three-dimensional cubic mesh of Processing Elements (PEs) with periodic

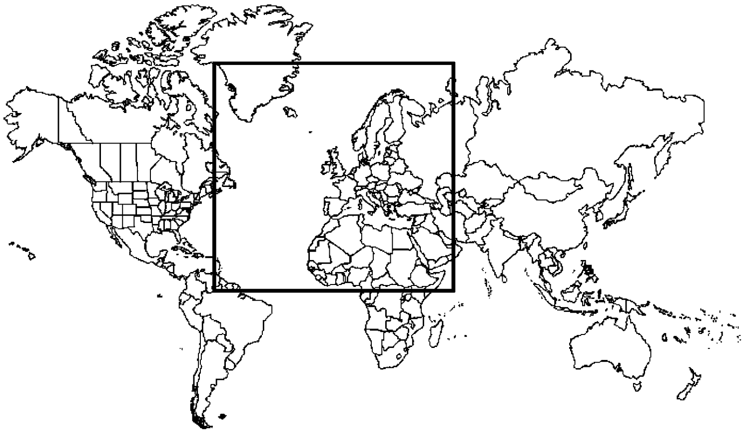

Fig. 7. – A possible computational domain (bolded area) for a future integrated forecasting system.

boundary conditions and it is scalable from 8 to 2048 PEs. Each PE contains a floating point pipelined processor called Multiplier and Adder Device (MAD) with 50 MFlops of peak power and a memory bank of 4 MBytes. It is important to stress two important features of this architecture: the first one is that all PEs execute the same code, synchronized by a single master controller that also performs integer data operations and memory addressing; the second is that each node exchanges data with its six nearest neighbours in the three spatial directions.

The BOLAM code has been redesigned for the SIMD platform and completely rewritten in TAO language, which is a proprietary high level language able to manage the parallel features of the machine and to perform data communication.

The adopted parallelization strategy was based on static domain decomposition. The whole computational domain ($N_{\mathrm{Lon}} \times N_{\mathrm{Lat}} \times N_{\mathrm{Lev}}$) has been divided into P subdomains of same shape and size ($M_{\mathrm{Lon}} \times M_{\mathrm{Lat}} \times N_{\mathrm{Lev}}$), each assigned to one of the P machine's PEs. Since the number of subdomain vertical levels remains N_{Lev}, this solution allows to keep the whole vertical extension inside the single processor. This decomposition has been realized via a custom library that transforms the *real* 3D topology of Quadrics supercomputer into a *virtual* 2D topology. Moreover, considering that the prognostic variables are stored in three-dimensional arrays, with the fastest index running along the vertical direction, it was possible to define a *column-type* data structure. Therefore, other two *ad hoc* libraries have been developed in order to efficiently communicate *columns* among processors and to execute arithmetical operations between *columns* exploiting the processors' internal pipeline.

The parallel code QBOLAM can now execute the same computation (Single Instruction) working on data of different subdomains (Multiple Data). We can say that the Quadrics supercomputer runs concurrently P meteorological models each limited to the area of its subdomain. A frame has been added to each local processor's subdomain to allow the connection between the subdomains (frame method); thus, boundary data of the neighbouring subdomains can be copied into the frame of the local subdomain before any computational phase requiring communications with the first neighbours. Then, the *submodels* proceed altogether linked each other. The dynamics routines for horizontal/vertical advection and diffusion of the prognostic variables have the features to be adapted for a SIMD architecture; but the same routines are the most critical in terms of parallel implementation, because they require interprocessor data transfer.

On the other side, if the algorithms used in the physics routines involve only computations along the vertical direction (avoiding communication), some of them (especially convection and radiation) require an intricate mechanism in order to be adaptable to the SIMD machine.

The resulting parallel model QBOLAM, is a code executable on Quadrics machines with any number of nodes. The choice of the machine dimensions depends on the size of the global domain and on the computational power required. The maximum performance measured is of 8.72 GFlops sustained on a 512 nodes machine, corresponding to 34% of the peak power. In the operational configuration on a 128 nodes machine, the VHR model (10 km of resolution) runs at 2.12 GFlops sustained (33% of peak power), taking about 90 minutes for a two days simulation.

Finally, the technical evolution in computer science makes any processor obsolete in little time. From this point of view, Quadrics is not any more one of fastest supercomputers, hence the POSEIDON system is currently being migrated to a new parallel machine. The system is also being updated taking into account all the previously accumulated operational experience.

* * *

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