The Role of Meteorological Models in the Prediction of Weather Hazards – the European Approach

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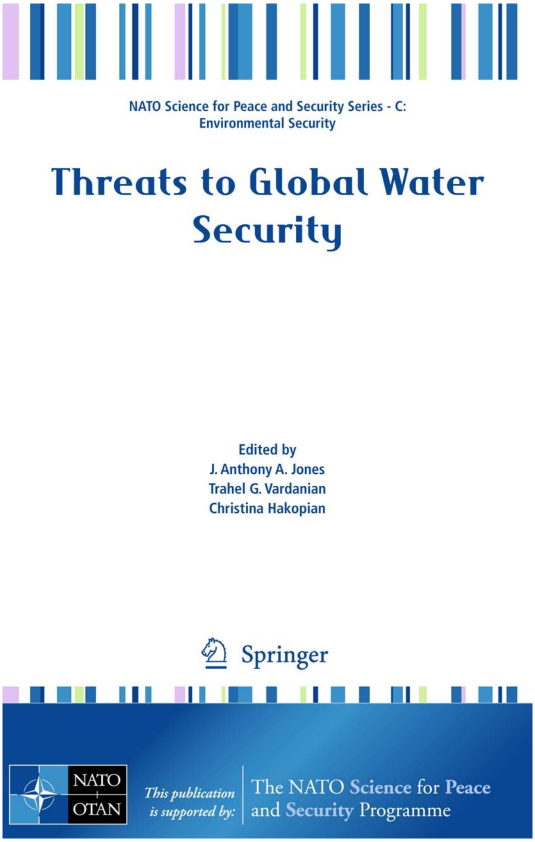

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Edited by
J. Anthony A. Jones
Trahel G. Vardanian
Christina Hakopian

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THE ROLE OF METEOROLOGICAL MODELS IN THE PREDICTION OF WEATHER HAZARDS – THE EUROPEAN APPROACH

C. Cassardo[*]
Department of General Physics "Amedeo Avogadro",
University of Torino, Italy

Abstract. It is a matter of fact that the economic damage and the casualties provoked by extreme meteorological events have dramatically increased in the last few decades, and that, in the last 30 years, a remarkable part of this increment is caused by the increased frequency of extreme meteorological events. The reasons for such an increase are not simply related to the climatic changes, but also to the intensive exploitation of the land areas, like unauthorized building, diffuse urbanization, river canalization, intensive agriculture etc., which has made them much more vulnerable today than in the past. In this context, the use of advanced meteorological instruments could surely give help in the forecasting and in the prevention of extreme phenomena and of their consequences. However, the greatest improvement in extreme events prediction can be achieved by the use of numerical models, which constitute an essential means in the aim of improving both the forecast of the extreme events and the correlated hydrogeological risk assessment. The paper, after a short introduction on the numerical models, contains some considerations on the importance of land surface conditions and of surface layer parameterizations in order to produce a reasonably good prediction of some extreme dry (droughts or heat waves) and wet (floods) events. Among the surface layer parameterizations, the representation of the orographic influences on the atmospheric flow is quite important for estimating the quantity and the intensity of the precipitation. It is explained that for extreme wet events the final objective would be to couple high-resolution meteorological and hydrological models, creating a "meteo-hydrological chain". A detailed discussion will examine the role of the seasonal meteorological predictions, with a part dedicated to the Ensemble Prediction System, and to their utility for forecasting the hydrological variables. Finally, a reflection in the last section is dedicated to the problem of the communication of meteorological and hydrological risks to the public.

Keywords: Flood, drought, heat wave, GCM, LAM, LSPM

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[*] To whom correspondence should be addressed. e-mail: cassardo@ph.unito.it

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1. Introduction

Numerical weather prediction can be considered as an application of the experimental Galilean method (Pasini, 2005) in which, due to the complexity and the uniqueness of the terrestrial atmosphere, and thus the impossibility of conducting real experiments, the computer can be seen as a *virtual laboratory*. This idea allows us to develop numerical models in which single differential equations, each one representing a portion of theory describing a portion of reality, are composed in a mathematical model constituted by one or more coupled system of equations. The variables of these equations have a correspondence in the real system where they can be measured. Thus, giving some realistic initial values to each model variable, indicating the boundary conditions, and numerically solving these equations, it is possible to get a prediction of the most relevant thermodynamic and dynamic parameters in the atmosphere.

This approach was used for the first time by Lewis Richardson in 1927, but at that time computers did not exist and also the theory to ensure the numerical stability of the solutions was not yet discovered, thus his attempt was not successful. At the beginning of 1950, John von Neuman and Jule Charney pioneered the use of the electronic computer for weather forecasting at the Institute for Advanced Study at Princeton University. They used a primitive computer, much less powerful that today's personal computers, but they succeeded in forecasting the horizontal air geopotential height pattern at 500 hPa over Northern America.

A meteorological model consists of a series of prognostic differential equations for the main meteorological variables (wind velocity, temperature, humidity and pressure): conservations of momentum, energy and water, state and continuity equations. Some numerical computer models of the atmosphere are designed to operate over different spatial scales depending on the forecast range. For example, a model for short-range forecasts (up to 3 days) can cover an area extending to a continent and needs as initial data the observations carried out only in that restricted area. On the other hand, a model designed for medium-range forecasts (up to 10 days) is generally a global model and thus needs observational data from all over the globe, since within such a forecast range, a weather system can travel over distances comparable to the Earth's radius.

The equations included in the first generation models were simplified and the resolution was very coarse, thus these models were able to diagnose only some large-scale phenomena affecting continental areas. With the continuous increase in computer power, the equations used became more complete, the resolution was increased and the dataset used for the model initialization was also more dense both in time and space. Furthermore, some numerical techniques were developed to assess more stable and detailed solutions. In 1979, the European Centre for Medium-range Weather Forecast

(ECMWF) was created in Reading, UK, with the aim of providing medium-range forecast data for the northern hemisphere. Another very important component of the model forecast chain which has been considerably improved is the data initialization. Actually, the ECMWF model can provide the meteorological data on a grid whose size at the latitude of 45° is approximately 25 km, while in 1979 the grid size was only about 120 km. This means that the ECMWF GCM (General Circulation Model) can actually be used to initialize a mesoscale model able to run over a grid size of few kilometres. The correctness of the predicted fields also increased almost regularly over the years (see Figs. 1 and 2). The accuracy of the weather forecasts provided by the mesoscale models is even greater, but is normally limited to the next 2–3 days, because the domain is too small to allow longer runs.

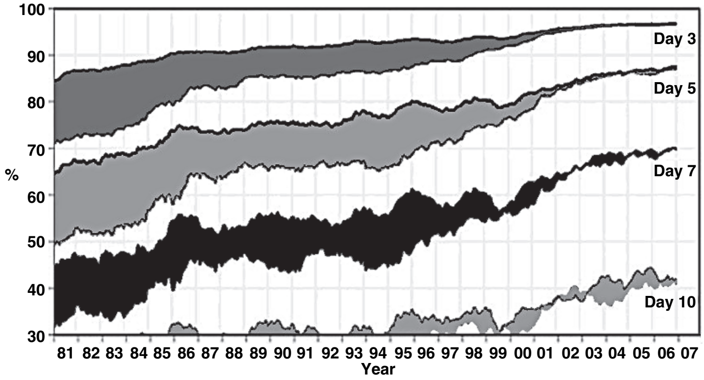

Figure 1. Improvement of the anomaly correlation of the 500 hPa geopotential height depending on the forecast day for the two hemispheres in the period 1981–2007 for the ECMWF GCM (adapted from CSAEOS, 2008)

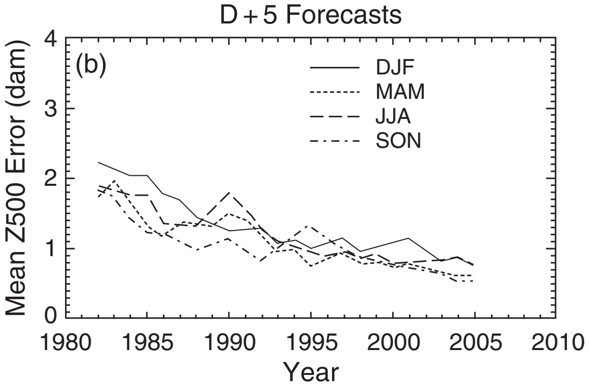

Figure 2. Reduction of Northern Hemisphere systematic 500 hPa geopotential height error for the fifth day of forecast in the period 1981–2006 for the ECMWF GCM (courtesy of ECMWF)

With the availability of these kinds of products, it is actually possible to have highly accurate weather predictions at the large-scale and also accurate predictions at the mesoscale and at the local scale. Thus, in principle, it can be possible to provide some alerts in the case in which some extreme or hazardous events are predicted in the medium-term. In the category of the hazardous or extreme events are included floods or severe rainfalls, typhoons, hurricanes or tropical cyclones, extreme winds, but also prolonged drought episodes or heat waves.

The normal period of time in which a deterministic weather forecast has an adequate validity is normally 3–5 days, depending on the weather situation and on the local characteristics, but using some methodologies, such as the Ensemble Predictions Systems, it is possible to have an idea about the probability of occurrence of a determinate forecast even for the next 5 days. Forecasts over longer periods are currently experimental in some Meteorological Services.

In this paper, the reader will find some information on the most recent developments regarding some characteristics of the numerical models used in meteorology, and a conclusive note showing their importance in the predictions of natural hazards.

2. The prediction of heat waves and drought conditions

During June, July and August 2003, an exceptional heat wave affected western and central Europe. The extreme drought and heat had heavy social, economic and environmental impacts, among them the death of thousands of the elderly. Other serious consequences were the destruction of large forest areas by fire, the depletion of aquatic ecosystems, the retreat of glaciers, power cuts and transport restrictions, and a decrease in agriculture production. In recent years, the number of such extremes was increasing, according to the Intergovernmental Panel on Climate Change (IPCC, 2001), and Meehl and Tebaldi (2004) also said that is possible that the number of heat waves similar to that of 2003 will increase in the future. As the long-range forecasts (greater than 1 month) for this phenomenon were not successful, it is thus important to try to understand which mechanisms can exacerbate or guide this kind of event.

In the specific case of the European heat wave in the summer of 2003, it has been shown that the synoptic circulation induced by the persistence of an anomalously strong anticyclone extended over Western Europe for most of the period May–August 2003 drove hot air from North Africa, producing strong subsidence motions on the right-hand side of the anticyclone (i.e. over central and Western Europe) during most of the time (see for instance Cassardo et al., 2007). The enhancement of the adiabatic compression related to these synoptic motions contributed to the observed temperature increments. A second enhancing factor that exacerbated the heat wave effects was the precipitation deficit recorded during the preceding spring, which caused low soil moisture values to be observed already at the beginning of the heat wave. This fact is not surprising as, according to Black and Sutton (2007), the soil water content in Europe's Mediterranean regions plays a critical role in the climate regulation across Europe and in the development of climate anomalies over Europe.

A thorough understanding of the physical mechanisms of climate is a baseline for their subsequent incorporation in the meteorological and climatological models. For instance, the ECMWF short-, medium- and long-range (up to 30 days) forecasts were successful in inferring the main features of the large-scale flow as well as the temperature anomalies, while the seasonal predictions were a failure, even considering the EPS (see Section 5). Grazzini et al. (2003) suggested that this problem could be due to a combination of (i) failure to predict the observed large Sea Surface Temperature (SST) anomalies in the Indian Ocean, and (ii) the above mentioned dependence on the soil moisture. The continuous refinement of the physical processes in the numerical atmospheric models could allow a more accurate prediction of such extreme phenomena.

3. The importance of land surface conditions and of surface layer parameterizations

In the last 2 decades, it has been recognized that a necessary boundary condition for all Numerical Weather Prediction (NWP) modeling is the representation of the land surface processes. They are crucial in short-term weather forecasts as well as for climatic predictions, as the Earth surface can influence the partition between sensible and latent heat fluxes and consequently the atmospheric stability is related to the surface properties. In this respect, leaving aside the surface and land characteristics, which also are a key factor for the surface processes, soil temperature and especially soil moisture constitute very important parameters. In fact, the Earth surface is the main source of energy and moisture, which regulate the atmospheric motions. Wrong estimates of those parameters lead to wrongly simulated variables in the surface layer, especially for the phenomena related to convection, and thus the forecasts of atmospheric stability and precipitation amount could have a low reliability. Nevertheless, the soil temperature and moisture, as well as sensible and latent heat fluxes, are not measured extensively or for long periods, and also satellite estimates are difficult to generalize over areas with different vegetation cover or types. Thus, a key problem in weather forecasting is the initialization of soil temperature and moisture for the model simulation. Therefore, in the last few years, there have been many attempts to evaluate these parameters in the absence of direct observations, both for weather forecasting and for climatic simulations. One methodology, presented in Cassardo et al. (1997), consists in running for a sufficiently long time a SVAT model over a multitude of synoptic meteorological stations included in a mesoscale area, and in averaging the model predictions of soil moisture and temperatures. This method proved successful in improving the rainfall maxima during an episode of strong convection that occurred near the Alps (Cassardo et al., 2002a), showing that the initial soil moisture field can affect precipitation predictability in short-term weather forecasts. Another method, which uses a linearized variational technique for the analysis of total soil water content via the assimilation of screen-level observations (Balsamo et al., 2003), has been applied to the European data and also showed the importance of the soil moisture initialization for improving the skill of model predicted precipitation at large scale.

4. The role of the seasonal meteorological predictions and the ensemble prediction systems (EPS)

Until recent years, climate prediction had been viewed as a speculative and largely unproven venture. In fact, deterministic forecast lengths are limited by the Lorenz deterministic chaos theory to 2–3 weeks, and by the scarcity of data for the initialization to not more than 7 days, sometimes less. Thus, deterministic predictions of seasonal mean climate based on the mean anomaly are not always accurate for individual cases, even when a perfect atmospheric global circulation model and perfectly represented boundary conditions are used. More recently, when the meteorological models have been coupled with the oceanic models in order to better quantify the effects of interannual variability phenomena like the El Niño–Southern Oscillation – ENSO, seasonal forecasts of 3-month-average surface temperature or precipitation have been demonstrated to have some skill in particular seasons, regions, and circumstances (see for instance Shukla et al., 2000). This is the reason why some meteorological services and research institutes started few years ago to publish some climatic prediction maps referring to the future 1–3 months. However, as it is not yet clear why seasonal predictions succeed in some instances but fail in others. These forecasts are still regarded as research products and are not routinely used by the forecasters in their decision-making process, especially for the predictions related to the hydrological variables. On the contrary, their dissemination on the web sometimes causes some confusion for the public, who suppose that they have validity similar to the deterministic predictions (i.e. 5–7 days), and when these predictions fail the public tends to lose confidence in the quality of all meteo-hydrological predictions.

Thus, until now these products must still be regarded as a sort of very preliminary attempt to evaluate the performances of the models over so long a timescale, and, in my opinion, greater effort should be made in trying to explain to the general public that these products cannot be used in the same way as the short-term forecasts. From the point of view of the research, as our current knowledge about the relationships between boundary conditions and climate is still incomplete, many efforts will be required to fill this gap. For instance, Barnston et al. (2005) suggest that, for improving the quality of the climate predictions, a *two-tiered* prediction system is required: (i) to obtain a best prediction for the future boundary condition anomalies, and (ii) to specify the true probability distribution function corresponding to this boundary condition. Only when the accuracy of the seasonal climate predictions have increased, could they begin to be valued for meteorological and hydrological forecasts.

Regarding meteorological forecasts, one of the most recent and promising techniques in NWP is the development of the Ensemble Prediction Systems (EPS). These models have been recently developed in an attempt to overcome the problem of the limited temporal validity of deterministic forecasts (Ehrendorfer, 1997). As is known, these models generate an ensemble of predictions using the same model and different initial conditions, or, more recently, using the same initial conditions but different models or parameterizations (Buizza et al., 2005). To deal with the increased computational demand caused by running the models several times for the same prediction, normally EPS operate at a coarser grid scale compared with the deterministic model, but the advantage of this technique is that the generation of an ensemble of forecasts, rather than a single deterministic forecast, provides a way of quantifying the uncertainty about them, because it can be converted into a probability distribution function. The EPS has been part of the ECMWF operational suite since December 1992, when it has been gradually upgraded with the implementation of the Variable Resolution Ensemble Prediction System (VAREPS). This is designed to increase the ensemble resolution in the early forecast range and to extend the forecast range covered by the ensemble system to 1 month (Buizza et al., 2007).

At present, the vast majority of flood forecasting systems are deterministic in design and input, but this is changing fast, and new programmes are currently in development in Europe and in the US with the explicit aim of developing and producing ensemble forecasts that allow a reliable hydrological capacity (Demeritt et al., 2007). Examples in this sense are the expectation of an EPS for forecasting floods to be fully operational in the USA by 2013 (US National Weather Service, 2001), and the Hydrological Ensemble Prediction Experiment (Schaake et al., 2006) sponsored by the World Meteorological Organization (WMO).

5. The need of interfacing meteorological and hydrological models for flood forecasting

Flood forecasting is an important factor that can reduce the negative effects of flood events. A few years ago, the traditional method used to predict real-time flood events was to use a semi-distributed rainfall-runoff model (Bartholmes and Todini, 2005). Recently, to improve flood-forecasting capacity, more accurate methods are in process of development. For instance, the strategic plan for the US National Weather Service (2001) is investing strongly in the development of an Advanced Hydrologic Prediction System.

Nowadays, the continuous increase in computer power has allowed the utilization of distributed hydrological models with higher resolution (mesh size of 10–1,000 m). Also, meteorological models have increased their resolution in the recent years and now GCMs can run with a grid scale of 10–20 km or even less using nesting techniques. Mesoscale meteorological models can produce forecasted fields at a higher resolution (some hundred meters), but in normal operative conditions only for 2–3 days. Thus, since the aim of each meteo-hydrological system is to extend the forecasting horizon to 1 week or more, the GCMs are taken into consideration.

The gap between the resolutions required by hydrological models for the precipitation field and that furnished by the GCMs does not allow a direct coupling of the two models for an accurate prediction of the floods, especially for small- and medium-range basins. Cassardo et al. (2006) have indeed shown that it is possible to get some rough estimates of the river-flow increases for a large basin, such as that of the Po River in the Italian Piedmont region, during the exceptional flood of the October 2000, by taking into consideration the runoff evaluated by a SVAT (Soil Vegetation Atmosphere Transfer) scheme (in that case, the LSPM, Land Surface Process Model, has been used) coupled with a LAM (Limited Area Model). Nevertheless, the results reported by Ferraris et al. (2002) show that a direct coupling of meteorological and hydrological models might be considered not particularly useful, even in catchments showing scales that allow this direct coupling, because of the wrong location of high precipitation clusters in the meteorological model, which could have dramatic consequences on hydrologic modelling. Incidentally, the results of Cassardo et al. (2002b), who also studied the same flood episode in November 1994 in Piedmont, have shown some problems of the meteorological model in correctly locating the predicted precipitation cluster, which produced the flood in the Tanaro river basin.

Two techniques are currently used with the aim to improve the quality of the forecast. One is the Ensemble Prediction System (EPS – see Section 4), currently used by ECMWF and many other meteorological services, like the German DWD (see for instance Ferraris et al., 2002, or also Bartholmes and Todini, 2005), in order to better assess the spatial and temporal variability associated to the deterministic forecast. The second one is the downscaling of the rainfall data provided by the meteorological model prior to using the hydrological model. At this regard, one of the most used methods is the multi-fractal theory, that, according with Gupta and Waymire (1993), can be considered a very powerful approach to nonlinear and intermittent processes like precipitation, and can reproduce simultaneously the statistical properties of real rainfall in space and time.

Following the established success of EPS in weather forecasting, several initiatives are trying to promote the application of such techniques to hydrological modelling, and in particular to real-time flood forecasting.

6. The problem of the orography and the results of the MAP project

The Mesoscale Alpine Programme (MAP) was an international research initiative supported by the WMO (World Meteorological Organization). Scientists from 13 countries all around the world have been directly involved in MAP, which was devoted to the study of atmospheric and hydrological processes over mountainous terrains. MAP started officially in 1994 with the twofold aims (i) to understand and model the physical processes at the basis of the intense meteorological phenomena induced by the topography, and (ii) to refine the instruments to make short-term forecasts. Particular attention was devoted to the mesoscale phenomena, which are at the basis of the floods. The MAP projects and their scientific objectives were subdivided in the following way. Three projects were in direct support of the so-called “wet” part of MAP: the orographic precipitation mechanisms, the upper tropospheric potential vorticity anomalies, and the hydrological measurements for flood forecasting. Four projects came in direct support of the “dry” part of MAP: the dynamics of gap flow, the non-stationary aspects of foehn winds in large valleys, the three-dimensional gravity wave breaking, and the potential vorticity banners. Finally, one project, devoted to the planetary boundary layer structure, came in support of both wet and dry scientific objectives.

In 2007, when most results of MAP were already published (see the MAP website: http://www.map.meteoswiss.ch/), the MAP D-PHASE (‘Demonstration of Probabilistic Hydrological and Atmospheric Simulation of flood Events in the Alpine region’) was launched. This new project, which is a Forecast Demonstration Project (FDP) of the WWRP (World Weather Research Programme of WMO), aims at demonstrating some of the MAP achievements: in particular, the ability of forecasting heavy precipitation and related flooding events in the Alpine region, addressing the entire forecasting chain ranging from limited-area ensemble forecasting, high-resolution atmospheric modelling (km-scale), hydrological modelling, and nowcasting to decision-making by the end users. The MAP D-PHASE will thus summarize the state-of-the-art in the forecasting of precipitation-related high-impact weather, especially concerning the mountainous regions, where hazardous events are most common, most difficult to predict and often have the largest impacts.

7. The problem of communicating the flood risk

An important question is whether and how useful meteorologists and hydrologists actually find the new technologies in making the decision about whether or not to issue a flood warning. The problem of using the innovative technologies in the best possible way has been illustrated well by Morss et al. (2005). In practice, the problem is to find a balance between the desire for issuing a warning as early as possible (Harremoës et al., 2002) and the inevitable trade-off between false alarms and false negatives, that is, unforeseen flood events (see Hammond, 1996). A study by Demeritt et al. (2007) shows that flood forecasters welcome EPS predictions, but that they use mainly these data to confirm their deterministic models, and that, in the case in which there is a discrepancy between EPS and deterministic model predictions, they adopt the technique of "*wait and see*". This seems to indicate that the continuous development of techniques is welcome, but that it is also necessary to invest in explaining directly to the targeted users how to utilize these new technologies.

8. Conclusions

This paper has described some aspects of the currently most important and most recent developments in the field of the prediction of extreme and hazardous event. To pursue this end, a panoramic view of the techniques which are currently in development by the meteo-hydrological community has been described and summarized. The improvement of modelling skills in the prediction of natural hazards can be successful if several aspects of contemporary meteo-hydrological science are improved. Data availability is a key factor, as it allows the models to be tested and intercomparisons to be made. Model parameterizations, especially those related to the surface layer and to the soil surface, must be continuously developed to improve the physical mechanisms embedded in the code (as in the MAP experiment). Moreover, the quality of a deterministic meteorological forecast can be improved by running the same model but over a coarse scale in different configurations (EPS), which will give a better description of the model output.

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