Large scale moist dynamics and sub-synoptic processes relevant for flood forecasting

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ABSTRACT

This study demonstrates that, at least in some cases, the source of moisture for some Mediterranean floods is in the Altantic Inter Tropical Convergence Zone (ITCZ). Early-recurving Atlantic tropical cyclones, after exiting the African easterly jet, can carry in the proximity of the Iberian peninsula, France or the British Isles, noticeable amounts of moisture and leave isolated maxima of low-level convergence and vorticity. The other requirement for heavy precipitation to occur in the Mediterranean region is often related with sub-synoptic scale processes, the most efficient of them are probably the small scale convective cyclones, noticeable for their "hurricane-like" structure. These systems are generated in low-level convergent, and upper-level divergent, environments; they need strong latent and sensible heat fluxes, and the simultaneous presence of strong horizontal shear in the mid-troposphere and small vertical shear between the upper and lower troposphere. In this study it will be shown that low-level vorticity anomalies left from former Atlantic tropical systems, can interact with mid-latitudes systems, producing tropical-like cyclogenesis in the Mediterranean. Some relevant Mediterranean extreme events are analyzed with the aid of the National Center for Environmental Predictions (NCEP) operational gridded analyses, observations, the NCEP Medium range forecast (MRF) global model output and with the Eta model. The main results demonstrate strong sensitivity to initial and boundary conditions. A correct representation of the large scale forcing, and therefore a very large domain of integration, is important to forecast precipitation.

1 INTRODUCTION

Regional modeling over the Mediterranean region reveals strong sensitivity to initialization. The well-tested Eta model (Mesinger et al., 1988; Black et al., 1994) operationally used by the US weather service, displays remarkable changes in performance when shifting the domain, using different sets of gridded boundary conditions, or changing the resolution. Two physical reasons for this sensitivity are analyzed and identified to be important factors in the the atmospheric dynamics leading to floods in the Mediterranean region.

To produce high precipitation rates and/or high cumulated rainfall, the basic requirement is the concentration of large amount of atmospheric moisture into small columns of the atmosphere. In general, the mid-latitudes weather systems are much less efficient than the tropical ones in building up large amounts of precipitable water in the atmosphere. The largest amount of precipitation occurs in the inter-tropical convergence zone (ITCZ) and the highest recorded rainfall intensities are related to tropical weather systems (Anthes, 1982).

Locally intense precipitation rates can be occasionally detected in the mid-latitudes also, and quite often in the Mediterranean. Baroclinic lee cyclones (Buzzi and Tibaldi, 1978; Speranza et al., 1985; Buzzi and Speranza, 1986; Alpert et al., 1996), when anomalously intense, may provide heavy precipitation over the Mediterranean region, particularly if orography can locally enhance the atmospheric uplift, the low-level convergence, and thus the precipitable water. If orography and "complex terrain" were the dominant causes of heavy precipitation in the Mediterranean region, then the crucial requirement for a good regional precipitation forecasting would be just the resolution.

However, the existence of small-scale convective cyclones, generated in the Mediterranean, but totally different from the ordinary baroclinic lee cyclones, was noted by Ernst and Matson (1983) and Billing et al., (1983). Their dynamics was found similar to the tropical cyclones (Reale, 1998): large-scale low-level convergence and simultaneous presence of strong horizontal shear and lack of vertical shear thoughout the entire troposphere (Reale and Atlas, 1999). In spite of their small scale, the modeling of these events requires a large-scale forcing which is not related to resolution. A case of a high-resolution regional model failure is displayed as a part of this study.

The main goal of this work is to show that, beyond the small-scale processes, the large scale dynamics involving the equatorial moisture originated in the Inter Tropical Convergence Zone (ITCZ) was important for two floods which occurred over northwestern (30 September 1998, Sanremo) and northeastern (4-7 October 1998, Friuli) Italy.

The fact that the source of atmospheric moisture needed to produce some major floods in the Mediterranean region does not necessarily come from the Mediterranean was already found to be true by Krichack and Alpert (1998). These authors demonstrate, for the famous November 1994 flood, a tropical-extratropical interaction between convection over equatorial Africa, the upper northward branch of the Hadley cell and moist air-masses over the Indian Ocean. This interaction leads to propagation in the Mediterranean of significant amounts of moisture originated in the ITCZ over the Indian Ocean.

This study, by using a highly refined water vapor back-trajectory technique developed by Dirmeyer and Brubacker (1999) shows a mechanism through which a significant amount of moisture can be carried into the Mediterranean Sea from the equatorial region by the Atlantic Tropical Systems (TSs).

2 IS HIGHER RESOLUTION ALWAYS BETTER?

A well-established "dogma" among the forecasting community in the Mediterranean region tells that the higher the resolution, the better the results. As a consequence, high resolution regional models should perform better than general circulation models (GCMs).

In Figure 1 an event described in detail in Reale and Atlas (1999) is modeled with the Eta model and with the GCM operationally used by the National Center for Environmental Predictions (NCEP, USA), called Medium Range Forecast (MRF) model. This event is a small-scale tropical-like cyclone and is characterized by a perfect alignment of surface low with upper-level cutoff, a cylindrical wind structure with a virtually wind-less column at the storm's center, and a warm core. It produced substantial precipitation, up to 480 mm at Santuario di Polsi (southern Calabria, Italy) between 3 and 5 October 1996. Observed rainfall is displayed in Figure 1e; the small-scale cyclone responsible of the event is shown at 12 UTC 5 October 1996 as it appears in the NCEP operational analyses (Figure 1f).

We selected this case because it is one of the most dramatic examples of failure of a high resolution limited area model when not properly forced: the regional model cannot reproduce the event, and its performance is much worse compared to that of the GCM's one.

Figure 1a shows the 72 hour cumulated rainfall predicted by the Eta model, run at 0.5^0 resolution, forced by the NCEP 2.5^0 reanalyses, and initialized at 00 UTC 2 October 1996. There is no hint of the high precipitation observed over Calabria, and the reason is obviously due to the complete lack of the meso-cyclones seen in Figure 1f: the Eta predicted sea level pressure field (60 hour forecast) at 12 UTC 5 October 1996 is about 12 hPa higher than the analyses.

Conversely, the NCEP operational MRF forecast, in spite of the poorer resolution (1^0), predicts very well, 60 hours in advance, a mesocyclone in the right place. The correct cyclogenesis to the south of Sicily on 3 October, and the right trajectory in the following 60 hours, lead to a well placed precipitation maximum over southern Calabria. Its value (80 mm) is remarkably high, considering that it is a 1^0 gridded precipitation.

The reason for the Eta failure is not obviously in the model, but in the initial and boundary conditions, which do not reproduce the horizontal shear produced by an upper-tropospheric jet which is the causative mechanism of the cyclone (Reale and Atlas, 1999). In other words, even though the resolution of the Eta is higher than that of the global model, there is some information coming from *outside* the Eta domain that is missing in the boundary conditions, thus leading to this poor performance.

Therefore, even given an adequate set of initial and forcing boundary conditions, the Eta model can exhibit strong changes in performance according to the size of its domain.

A good example is the case of 30 September 1998: an intense baroclinic cyclone is located to the southwest of Cornwall (Fig. 2a). Its huge cold front spans from the Canary islands to Denmark and enters the Mediterranean on 30 September. High precipitation was recorded over the Ligurian coast, and it appeared to be related with a small-scale convective cyclone, originating in proximity of the Balearic islands and tracking northwestward. At 12 UTC the small-scale cyclone is over the southeastern France coast; its intense low-level vorticity (Fig 2a) and low-level convergent (Fig. 2b) fields are perfectly centered with the cyclone, suggesting some similarity with the tropical-like storms described in Reale and Atlas (1999). In general, baroclinic, mid-latitude systems have the maximum vorticity in the mid-troposphere (500 hPa), and the maximum low-level convergence along fronts away from the center, whereas tropical and tropical-like storms display centered low-level vorticity and convergence maxima. Occasionally, a tropical system developing into a baroclinic environment (see hurricane Diane, Bosart and Bartlo,

1991) must convert upper level vorticity into low-level vorticity. Whatever the case, the creation of low-level vorticity is crucial for tropical cyclones. Moreover, the cross sections across the small-scale cyclone, perfectly centered with the convective system observed from satellite, display impressive upward vertical velocities, comparable to the ones detected at the onset of hurricanes (not shown).

The performance of the Eta model for the precipitation produced by the cyclone appears to be very sensitive to changes in the boundary conditions. Two of the several experiments performed are shown: in Fig. 2c, the 24-hour cumulated precipitation for 30 September 1998, obtained by a 72-hour simulation (domain shown in Fig. 2e), is compared with the precipitation predicted by the same model at the same resolution of 25 km (Fig. 2d), but run over a much larger domain (Fig. 2f). Although both runs are not satisfactory and underestimate the actual precipitation, the experiment 2 is more realistic. Another experiment run with the same domain of experiment 1, but replacing the above-normal observed sea surface temperature (SST) over the Mediterranean, with lower, climatological values, does not affect the model performance (not shown). This fact, and the improvement obtained by enalarging the domain (from 2e to 2f) might suggest that the large-scale forcing was more important than the high SSTs recorded in the Mediterranean Sea.

A similar result was found for the Friuli event. The Mediterranean SST did not appear to have any role in changing the modeled precipitation, whereas the rainfall appeared to be sensitive to changes in domain's size (not shown).

3 THE ATLANTIC TROPICAL SYSTEMS

The Atlantic tropical weather systems are often related with the so-called "easterly waves" which appear to be reversed troughs on the southern flank of the African tropical easterly jet. If the environment is favorable for develompment, (i.e., lack of vertical shear, strong horizontal shear, SST greater than 26.5^0 and pre-existing convection), a tropical wave can generate a sea level pressure minimum (tropical depression) which may or may not go through an intensification process (Charney and Eliassen, 1964; Emanuel, 1986; Rotunno and Emanuel, 1996; Craig and Gray, 1996) leading to the stages of tropical storm and hurricane.

In general, the Atlantic tropical cyclones track westward in the easterly flow and then either hit the American continent or recurve northward and then northeastward along the Gulf Stream. Very few tropical cyclones behave differently: they exit the African tropical easterly jet, at latitudes varying from 10^0 to 30^0 latitude North, and immediately recurve northward and eastward (like Erika in 1997 and Ivan, Karl and Jeanne in 1998), 'back' across the Atlantic. These "early recurving" tropical cyclones are usually neglected by the Tropical Prediction Center and by the National Hurricane Center because (a) they do not have landfall over mainland US and because (b) they enter the highly baroclinic environment of the central Atlantic, become affected by cooler waters and lose their tropical structure. Of these storms, some become partly or totally baroclinic (and thus, by definition, "extratropical"), some dissipate, some are absorbed into larger scale frontal systems, moving as vortices along the frontal line. Whatever the epilogue, they have two effects in the atmosphere:

- they leave impressive amounts of moisture concentrated in small columns of atmosphere
- they leave very high values of low-level vorticity

In this study, the role of early recurving Atlantic tropical systems for Mediterranean weather is investigated. The questions addressed are: (a) how much moisture they can carry in the proximity of the Iberian peninsula, France or the British Isles? (b) How much they can affect Mediterranean weather systems?

Particularly, the very intense baroclinic cyclone located to the south of Cornwall at 12 UTC 30 September 1998 (Fig. 2a) is nothing but the extra-tropical remnant of the former tropical cyclone Karl (Fig. 3a). Similarly, once the tropical storm Jeanne entered the baroclinic environment, it became a small-scale, intense convective cyclone approaching the coast of Portugal (Fig 3a).

4 WATER VAPOR BACK-TRAJECTORIES

In order to quantify the importance of various evaporative sources and to understand the transport of water vapor, the water vapor back-trajectory method developed by Dirmeyer and Brubacker (1999), hereafter DB99, is applied. The authors use a quasi-isentropic back-trajectory technique, based on the fully implicit algoritm of Merril et al. (1986), to investigate evaporative sources during the drought of 1988 and the flood of 1994 over the US. In this study the same method is used to investigate the water transport for the two relevant cases of the 30 September 1999 (Sanremo) flood and the 5-8 October (eastern Friuli) flood.

The DB99 method is adapted to our case. Gridded 6-hourly precipitation at a 1.875^0 resolution is obtained from the NCEP surface reanalyses. Two boxes are selected (Figure 3) to comprise the two events: north-western Mediterranean (NW) and north-central Mediterranean (NC). The method consists in throwing parcels from each box at a rate proportional to the precipitation rate. Parcels keep being launched for 5 consecutive days *before* the rain occurs, and they are traced back, using 3D NCEP 1.875^0 reanalyses wind field, for 15 days or when the parcel humidity is reduced to 10% of the original value (whichever comes first). Parcels are randomly distributed in the vertical of the gridbox, and their probability of being launched is weighted with the the precipitable water $PW = (p_s/g)\int_\sigma^1 q d\sigma$ (where p_s is surface pressure, q the specific humidity and σ the vertical coordinate) by giving a cumulative distribution function such that the probability of being launched decreases with height (details in DB99). The horizontal position at each time-step is calculated by

$$x^{n-1} = x^n + \frac{\tau}{2}[u^{n+1} + u^{n-1}] \quad (1)$$

$$y^{n-1} = y^n + \frac{\tau}{2}[v^{n+1} + v^{n-1}] \quad (2)$$

where n is the timestep number, τ the time interval, and u, v the wind components. At each timestep, surface evaporation is computed and potential temperature is calculated assuming that the parcel will be in equilibrium with the potential temperature of the gridbox. By calculating the sum of all evaporative contributions of all parcels within the given time-window, the result provides an indication of the moisture sources for the precipitaion within a given box.

The results of the water vapor backtrajectories for box NW are displayed in Fig. 4. During 20-29 September 1998, most of the precipitation in box NW seems to have been originated in the Mediterranean. In the following ten-day period, from 30 September to 9 October, the situation is totally different (Fig. 4b): the area integral reveals that 70% of the precipitated water originated in the Atlantic. The correspondence of the recurved map of cumulative evaporation (Fig 4a), collected in the 15 days preceding the time interval of 30 September - 9 October, with the trajectory of the hurricane Karl, is remarkable. Therefore, it is not unreasonable to believe that an important fraction of the moisture needed to produce the Sanremo event orginated in the Atlantic and advected into the Mediterranean by the tropical system Karl, or by the southernmost part of its baroclinic remnant.

Fig. 5 displays the result of the back-tracing done for box NC. The precipitation between 20 and 29 September over the box NC seems to have been originated mostly over the Adriatic Sea, although a significant contribution comes from the moisture source over continental Europe (Fig. 5a).

The water vapor back-tracing performed in the following ten-days interval (Fig. 5b) provides a noticeable analogy with Fig. 4b. Considering the high precipitation recorded over northeastern Italy and Slovenia between 5 and 8 October, and considering the trajectory of the tropical system Jeanne (Figure 3a) another good correspondence is found. For the Friuli case, approximately 50% of the moisture seems to have been produced in the Atlantic.

5 CONCLUSIONS

The large scale forcing is ineffective, if not corroborated by a sub-synoptic scale process that concentrate precipitable water in a small column. Beyond the large amounts of moisture entering the Mediterranean, the low-level vorticity maxima left by dissipated tropical systems can be also advected into the Mediterranean.

For the Sanremo case, the low-level wind field tells that it is quite likely that the low-level vorticity maxima left by the former tropical system Karl contributed to create the small-scale cyclone over the western Mediterranean.

For the Friuli event, the small-scale process is completely baroclinic: a lee-cyclone of the well-known Alpine type. However, it was shown that part of the moisture was provided by the remnants of the tropical storm Jeanne. Water vapor tracing reveals a reverse "C-shape" path from Equatorial Africa westward, northward and eastward. Once in the Mediterranean region, the moisture gets concentrated over northeastern Italy by an intense low-level moisture flux convergence.

Our study demonstrates that an important requirement for precipitation forecasting with regional models over the Mediterranean region can be the size of the domain. The horizontal resolution of integration is probably less important: tropical-like (i.e., small-scale) cyclones can be generated by a global model at 1^0 and can be missed by a regional model at 0.25^0 of resolution, if not properly forced.

Particularly, the role played by decayed Atlantic tropical systems might be important for some floods and cannot be reproduced correctly with regional models run on very small domains.

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LIST OF FIGURES

Fig 1 Eta model, Global model and observations for a tropical-like cyclone in the Mediterranean (Reale and Atlas, 1999): (a) 72 hour cumulated rainfall (mm) predicted at 00 UTC 6 October 1996 by the Eta model; initialization time: 00 UTC 3 October 1996; (b) Sea level pressure (hPa) at 12 UTC 5 October 1996 (60 hour forecast) predicted by the Eta model; (c) 72 hour cumulated rainfall (mm) predicted at 00 UTC 6 October 1996 by the NCEP operational global model MRF; (d) Sea level pressure (hPa) at 12 UTC 5 October 1996 (60 hour forecast) predicted by the NCEP MRF; (e) Observed 72 hour cumulated rainfall (mm) at 00 UTC 6 October 1996; (f) NCEP Analyses sea level pressure (hPa) at 12 UTC 5 October 1996.

Fig 2 Eta model and analyses for the Sanremo event: (a) Sea level pressure (hPa) at 12 UTC 30 September 1998 and 925 hPa vorticity; the light shading indicated cyclonic vorticity $> 10^{-4}s^{-1}$; (b) 925 hPa Wind ($m\ s^{-1}$) and divergence (shaded, s^{-1}) at 12 UTC 30 September 1998; The dark (light) shading indicates negative (positive) divergence $<(>)-(+)3\times 10^{-4}s^{-1}$; (c) 24 hour cumulated rainfall (mm) predicted at 00 UTC 1 October 1998 by the Eta model (experiment 1); (d) 24 hour cumulated rainfall (mm) predicted at 00 UTC 1 October 1998 by the Eta model (experiment 2); (e) Domain of experiment 1; (f) Domain of experiment 2.

Fig 3 (a) Official tracks of tropical systems Karl and Jeanne (from the National Hurricane Center); (b) "Boxes" from which the water-vapor backtracing is started.

Fig 4 Sources of moisture ($kg\ m^{-2}$) for the NW Box: (a) 20-29 September 1998; (b) 30 September-9 October 1998.

Fig 5 Sources of moisture ($kg\ m^{-2}$) for the NC Box: (a) 20-29 September 1998; (b) 30 September-9 October 1998.

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