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Unsatisfying forecast of a Mediterranean cyclone: a verification study employing state-of-the-art techniques

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Abstract. On 16–17 November 2000, a relatively intense precipitation event on the north-western Italy was heavily underestimated, mainly due to shifting error, by three operational 10-km limited area models (LAMs) which differ about basic equations, domain size, and parameterisation schemes. The scope of the work is to investigate possible common error-sources independent from the single model, in particular the effect of initialisation. Thus, the complex evolution over the western Mediterranean Sea of the cyclone responsible for the event was investigated. Several objective and subjective verification techniques have been employed to check one of the LAMs' forecast against the available observations (precipitation from rain gauge and retrieved from ground-based radar, and satellite-retrieved atmospheric humidity patterns). Despite a clear statement is not achieved, results indicate that high sensitivity to the initial conditions, and the inadequacy of the observational network on the southern Mediterranean area, can play a major role in producing the forecast shifting error on the target area.

1 Introduction

This work focuses on the diagnosis of numerical forecast errors and their sources in the Mediterranean environment, with particular emphasis on the effects of mesoscale processes. In an operational flood alert system, relying on quantitative precipitation forecast (QPF), relatively minor forecast error as a 50–100 km shift in precipitation pattern may result in a system's failure. This is the case of the event presented here. A fairly intense precipitation event occurred in the Italian Liguria and Piedmont regions on November 2000 (Casaioli et al., 2004) has been strongly underestimated by three operational 10-km limited area models (LAMs): the Limited Area Model BOlogna (LAMBO), the Fifth-generation Mesoscale Model (MM5) and the Quadrics BOlogna Limited Area Model (QBOLAM). These models differ about basic equations, parameterizations and domain extension, though they use the same initial and boundary conditions.

Rainfall was associated to a cutoff cyclone which, after traveling across the western Mediterranean during the previous days, is reinforced by the cyclogenetic effect of a synoptic trough approaching the Alps. In this environment, mesoscale motions forced by local features (orography, heat exchanges) can strongly affect the evolution of such disturbances (Homar and Stensrud, 2004). In this sense, we speak about meso-synoptic cyclones. So, it is possible that small-scale errors in the initial analysis can affect the precipitation forecast of the three different models, producing a similar forecast error. This is not the only possible explanation of such a "triple miss". Besides, it is quite difficult to verify such a statement: a sub-synoptic scale verification of both the model forecast and the analysis itself should be performed.

Here, QBOLAM forecast have been checked over the Mediterranean Sea against the Total Column Water Vapour (TCWV) values retrieved from Special Sensor Microwave/Imager (SSM/I) data and, over a larger area, against METEOSAT-7 Water Vapour (hereinafter MET7WV) imagery, which is suitable for a thorough diagnosis of the evolution of sub-synoptic structures (López Pérez and Arán Roura, 2004). The latter comparison is possible since, in cloud-free areas, the MET7WV image should be in a good qualitative agreement with the temperature field on the 75 mg kg^{-1} specific humidity isosurface (hereinafter T75Q; Fehlmann and Davies, 2000). This statement derives from the radiation theory, concerning the location of the atmospheric emissivity peak at the MET7WV channel wavelength.

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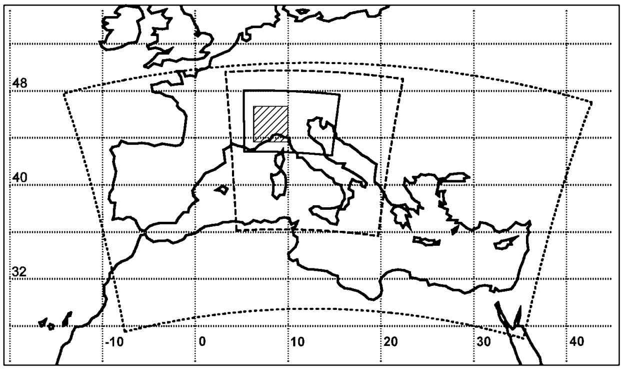

Fig. 1. Extension of the 10-km LAMs' domains. Solid line: MM5. Dashed line: LAMBO. Dotted line: QBOLAM. Shaded area indicates the Liguria-Piedmont area, after Accadia et al. (2003a).

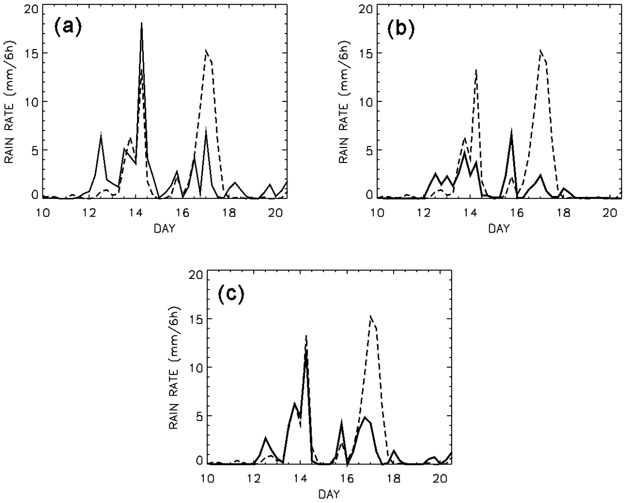

Fig. 2. Mean 6-h observed and forecast rainfall over Piedmont and Liguria, from 10 to 20 November 2000. Observations (dashed line): average on working rain gauges. Models (continuous line): average on grid points with at least one working rain gauge. **(a)** QBOLAM. **(b)** LAMBO. **(c)** MM5. Forecast curves are obtained joining 24-h fragments (from 00:00 UTC to 24:00 UTC) taken from subsequent daily runs. After Casaioli et al. (2004).

Paper is organised as follows. In Sect. 2, the observational and model data are presented. Rainfall verification is described in Sect. 3. Section 4 provides a synoptic analysis of the lower tropospheric circulation systems, which led to the precipitation event. In Sect. 5, TCWV satellite observations are used to characterize QBOLAM forecast error on a wider scale. A comparison of two subsequent QBOLAM runs, also verified against MET7WV imagery, is shown in Sect. 6. Conclusions are finally outlined in Sect. 7.

2 Model and observational data set

The 8-month data set collected by Accadia et al. (2003a) includes 3-hourly forecast precipitation fields from the MM5 (Grell et al., 1994) operating at Parco Scientifico e Tecnologico d'Abruzzo (PSTA; L'Aquila, Italy), from LAMBO (Paccagnella et al., 1992) operating till June 2004 at Agenzia Regionale Prevenzione e Ambiente–Servizio Idro-Meteo (ARPA–SIM; Bologna, Italy), and from QBOLAM (Speranza et al., 2004) running at Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici (APAT; Rome, Italy). It also includes a 390-rain gauge data set over Italian Liguria and Piedmont regions. Models were chosen, among ones operating in Italy, in order to share a comparable grid step (about 10 km). All models employ the European Centre for Medium-range Weather Forecast (ECMWF) analysis and forecast as initial and boundary conditions, respectively. These are imposed on lower resolution ("outer") domains which are nested to the 10-km ("inner") ones.

Beside this, models differ markedly each other. The "inner" domains (Fig. 1) range from the whole Mediterranean Sea (QBOLAM) to only the northern Italy (MM5). MM5 is the only non-hydrostatic model, although the effect should not be appreciable on a 10-km grid. Parameterisation schemes implemented in MM5 are the most advanced ones. Conversely, very simple convection and radiation schemes are present in QBOLAM: this is because the model is implemented on a massively-parallel computer (QUADRICS), whose synchronous architecture puts severe constraints on the parallel code (see Appendix in Speranza et al., 2004). For QBOLAM the complete model output was available, too.

The observational data set includes also ground-based radar and satellite data. Data from three operational C-band Doppler radar of the MeteoSwiss network have been used. The stations are: Monte Lema (46.042° N, 8.833° E; 1625 m), La Dole (46.426° N, 6.100° E; 1680 m) and Albis (47.285° N, 8.513° E; 928 m). Data are corrected for visibility, profile and gaseous attenuation. In addition, a sophisticated clutter suppression algorithm is used (Germann and Joss, 2003). For a further description of the radar data see Joss et al. (1998). Precipitation is derived from the composite data from all three radars.

Satellite data include SSM/I brightness temperatures and MET7WV imagery. The SSM/I sensor is a seven-channel, four-frequency, linearly-polarized, passive microwave radiometer flown onboard the Defense Meteorological Satellite Program (DMSP) satellites. This sensor measures microwave brightness temperatures at 19.35, 22.235, 37.0, and 85.5 GHz (Hollinger, 1989). The 22.235 GHz channel frequency is at the peak of a weak water vapour absorption line. Over ocean, this allows the retrieval of TCWV using a statistical algorithm (Alishouse et al., 1990). Retrievals over land are impossible because of the high and varying emissivity of land surfaces. In addition, the Ferraro and Marks (2000) precipitation retrieval method is used as screening procedure to remove data affected by precipitation. SSM/I brightness temperatures from DMSP satellites F13, F14 and F15 were used in order to cover, as much as possible, the

Mediterranean Sea. Observations are available with best coverage over the Mediterranean area mainly around 06:00 UTC and 18:00 UTC, considering only data available within 3 h. Few overpasses are at 12:00 UTC, with partial coverage.

3 Precipitation verification

The event was firstly identified as an outstanding triple miss on the 8-month (from October 2000) model precipitation verification over the Liguria and Piedmont target area (see Fig. 2; Casaioli et al., 2004).

The sharp rainfall peak observed on days 16-17 November 2000 (with a maximum value of 16 mm $(6\,\mathrm{h})^{-1}$) is strongly underestimated by the forecast from QBOLAM $\left[7\ \mathrm{mm}\,(6\,\mathrm{h})^{-1}\right]$, MM5 $\left[5\ \mathrm{mm}\,(6\,\mathrm{h})^{-1}\right]$ and LAMBO $\left[\text{less than } 3\ \mathrm{mm}\,(6\,\mathrm{h})^{-1}\right]$. However, the peak timing is correct, and a good forecast is provided by LAMBO and MM5 in the first 12 h of the event. Note that, in the 8-month series, other events comparable to this one were usually predicted with fair or good accuracy, as, for instance, the first rainfall peak (14 November) visible in Fig. 2.

A qualitative verification of radar images against forecast precipitation patterns gives more insight on the different models' error. Due to the experimental design, for each model two runs for days 16 and 17 November, respectively, are involved: one starting on 12:00 UTC 15 November (RUN1), and one starting on 12:00 UTC 16 November (RUN2; see Fig. 2). The LAMBO and MM5 runs extend 36 h ahead, whereas the QBOLAM runs extend 60 h ahead. For all the models, only the portion from +12 h to +36 h is discussed in this section. The first 12 h of all the runs have been discarded (model spin-up).

In RUN2, all the forecast fields display an eastward shifting of the precipitation patterns with respect to the radar ones (Fig. 3). This is evidenced by the hook-shaped structure visible both in the radar and in the models' pattern. Concerning RUN1, a similar eastward shifting is displayed by the LAMBO and QBOLAM predicted patterns, but not by the MM5 one (not shown). In other words, a non-rainy area, observed over the Italian-French border is forecast over the target area by all three models in two subsequent runs, with only one exception. These results seem to support the idea that a common error mechanism affects all three models, despite the differences among them, and results in the event miss.

4 Synoptic analysis

The event is associated to the passage of a meso-synoptic Mediterranean cyclone, which undergoes a complex evolution in the previous days. On day 14 November (00:00 UTC; not shown), a NE-SW elongated trough is present at 500 hPa level over the Iberian Peninsula, easterly blocked by a high pressure over the eastern Mediterranean Sea. At the end of the day, the trough tip evolves in a weak cutoff cyclone west of Gibraltar (Figs. 4a, b). In the following 48 h, the cyclone moves rotating around the Iberian Peninsula: in the first 24 h it moves over the Atlas mountain range and along the Algerian coast (see Figs. 4c, d for 00:00 UTC 16 November); then it moves north-eastward towards Genoa Gulf. In the meanwhile, a new mid-tropospheric trough approaching the Alps from west (Fig. 4e) forces the deepening of the cyclone by the effect of Alpine cyclogenesis mechanism (Tibaldi et al., 1990). This is evidenced by the reduction of tilting of the "rejuvenated" cyclone (Fig. 4f). On day 18 November the cyclone is stationary on Genoa Gulf; finally, in the following days, it dissipates (not shown).

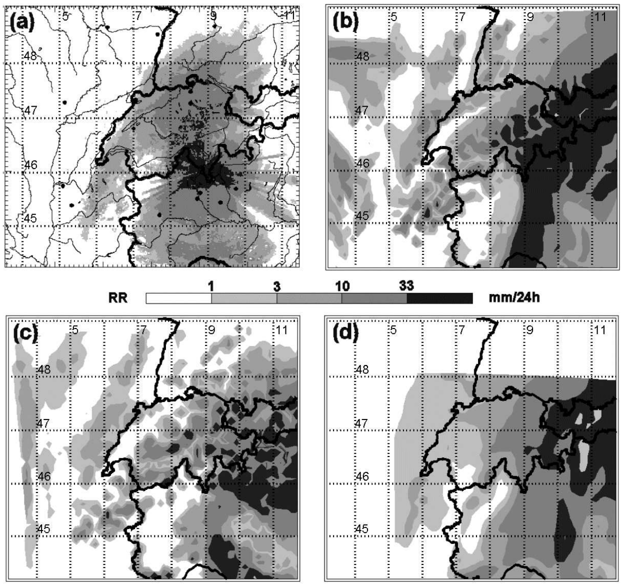

Fig. 3. 24-h accumulated rainfall over the western Alpine region, during day 17 November 2000, from 00:00 UTC to 24:00 UTC. **(a)** Radar precipitation estimate, mosaic from three MeteoSwiss radar stations. **(b)** QBOLAM forecast. **(c)** LAMBO forecast. **(d)** MM5 forecast.

Such a scenario is common in the Mediterranean autumn (Pinto et al., 1999; Trigo et al., 1999), and it can be associated with disastrous floods (e.g., the Algerian flood on 10 November 2001; Homar and Stensrud, 2004). The analogy suggests that local mesoscale forcing due to orography and latent heat release may play a significant role in the evolution of the studied cyclone, its trajectory and its structure.

5 TCWV verification

The availability of retrieved TCWV values, even over a reduced domain (the Mediterranean Sea, in non-rain conditions and far from the coastline) gives an observational basis to verify the meso-synoptic features of the QBOLAM forecasts (Accadia et al., 2003b) and the respective initial fields.

Figure 5 is representative for day 16 November. Observations (Fig. 5a) are used to cross-check QBOLAM RUN1, the

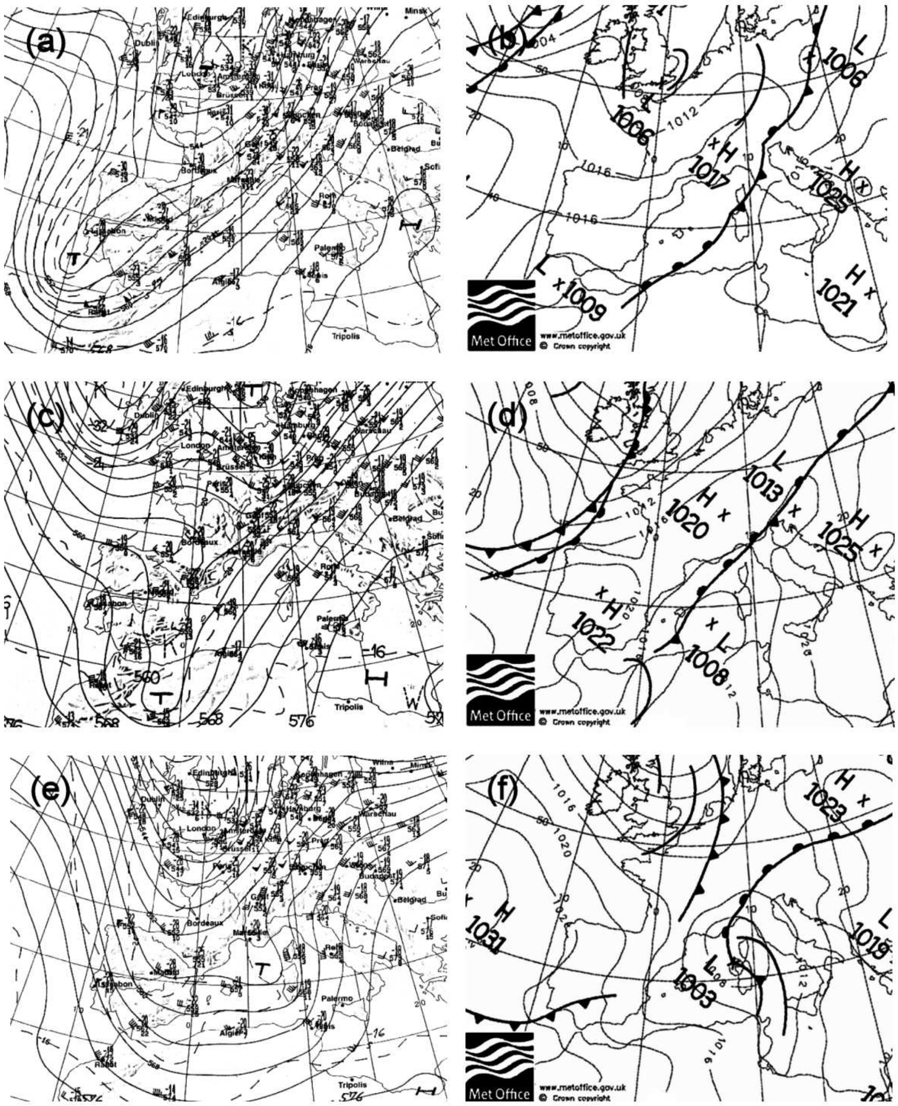

Fig. 4. 500-hPa geopotential height and temperature (left column, from Deutsche Wetterdienst weather maps) and surface analysis (right column, from UK Met Office weather maps) over southern Europe at 00:00 UTC of days: **(a–b)** 15 November 2000; **(c–d)** 16 November 2000; **(e–f)** 17 November 2000.

ECMWF analysis and the corresponding ECMWF forecast, started at 12:00 UTC 16 November. It is remarkable that in both ECMWF analysis (Fig. 5b) and ECMWF forecast (Fig. 5c) the observed humid band is correctly located, whereas it is shifted eastwards in the QBOLAM forecast (Fig. 4d). It is also interesting that the QBOLAM run on the outer domain (with a 30-km grid step) displays a smaller shifting than the 10-km run (not shown); in other words, the shifting error seems to increase with the model resolution. This seems to be an "anomalous" behaviour, since usually LAMs are able to improve forecast, especially with respect to mesoscale features. See for example the 14 November rainfall peak visible in Fig. 2, which was due to the passage of a broad synoptic front, less sensitive to Mediterranean local forcing (not shown). Verification of the TCWV forecast reveals a shifting error which progressively decreases from the ECMWF forecast, to the 30-km QBOLAM forecast, up to the 10-km QBOLAM forecast (not shown).

A possible explanation relies on the difficulty in predicting complex interactions among the secondary cyclone, the synoptic forcing and the local forcing. Note that this "anomalous" behaviour is found during the development phase of the secondary cyclone. Theory (Speranza, 2001) shows that, in the Alpine cyclogenesis mechanism, the orography forcing is dominant in the onset phase, whereas the latent heat release may play a major role in the following development phase. Since both the synoptic pattern and the local forcing are more complex in the 17 November event than in the "classic" Alpine cyclogenesis, it is not trivial to discriminate the key factors which can affect the cyclone development.

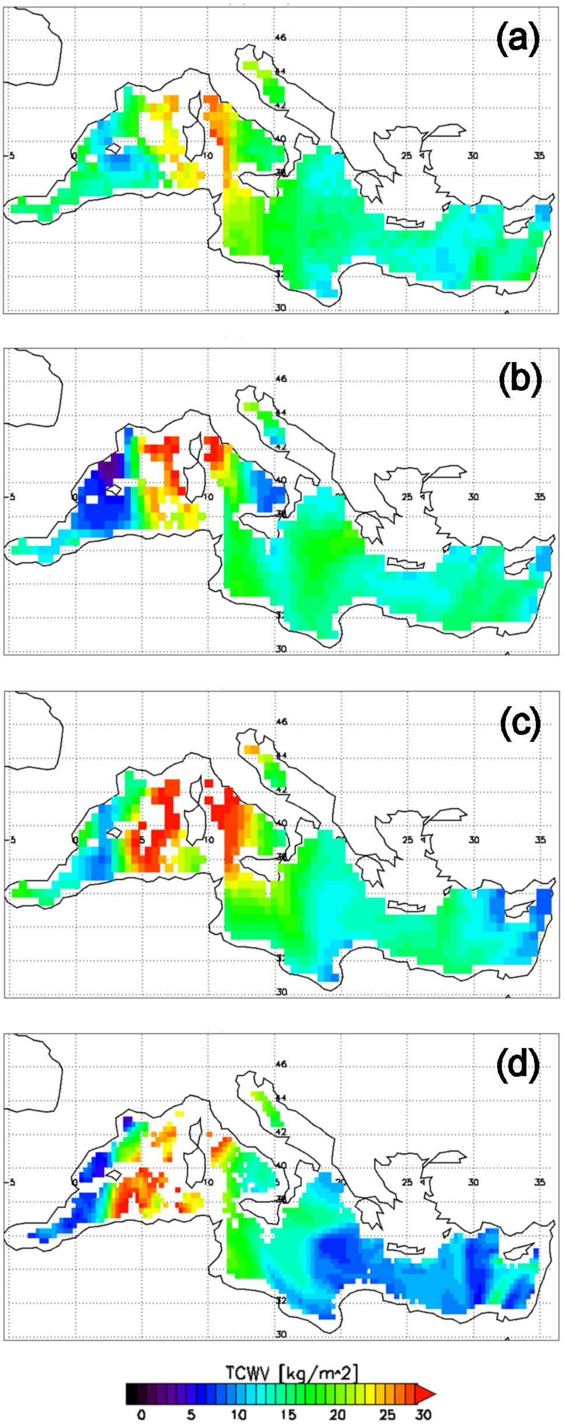

Fig. 5. TCVW satellite estimate, analysis and forecast over the Mediterranean Sea, for 18:00 UTC 16 November 2000. Data are masked over the area where SSM/I retrieved TCWV is available. **(a)** SSM/I retrieved estimate. **(b)** ECMWF analysis. **(c)** ECMWF forecast. **(d)** QBOLAM forecast. ECMWF and QBOLAM runs started at 12:00 UTC 15 November 2000.

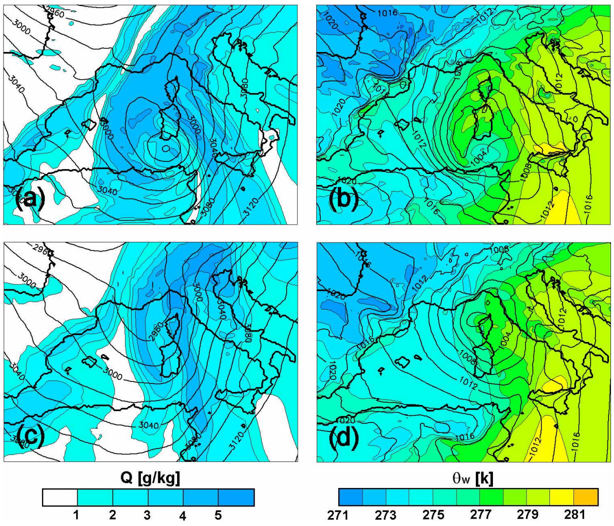

Fig. 6. QBOLAM forecasts valid for 00:00 UTC 17 November. **(a)** 700 hPa geopotential height (solid line) and specific humidity (colour); run started at 12:00 UTC 15 November (RUN1). **(b)** mean sea-level pressure (solid line) and 850-hPa wet-bulb potential temperature (Kelvin), RUN1. **(c)** As in (a), for the run started at 12:00 UTC 16 November (RUN2). **(d)** As in (b), for RUN2.

6 Looking for possible initial error: a comparison of subsequent runs

A well-posed sensitivity test on the effect of the initialisation changes is quite difficult to perform, as well as a thorough verification of the mesoscale details of the ECMWF analysis fields. The simplest way to assess the role of initialisation is to compare two subsequent runs for the same instant. Thus, the simultaneous portion of QBOLAM RUN1 (validity time from +36 h to +60 h) and RUN2 forecast (validity time from +12 to +36 h), valid for day 17 November, have been compared. It should be kept in mind that a large enough initial error in one of the runs (or both) produces an outstanding discrepancy between the two forecasts, whereas the inverse is not necessarily true. In other words, when such discrepancies are evident, a major role of initialisation error is likely but not proven. Anyway, strong differences between the two runs are present: these are evident, for example, at 00:00 UTC 17 November (Fig. 6). In RUN1, a well-developed secondary cyclone is centred between Sardinia and Tunisia. In RUN2, the pressure minimum is centred about 500 km north, on Genoa Gulf, and the cyclone is significantly weaker. It is noticeable that the differences are much smaller outside the central Mediterranean area. These differences tend to attenuate in the following 24 h of forecast time.

Verification is needed in order to assess whether one of the run is closer to the real atmosphere and, if yes, which one. Moreover, the use of direct observations, rather than ECMWF analysis, is more appropriate for our purposes, since the analysis accuracy (and its effects on the forecast

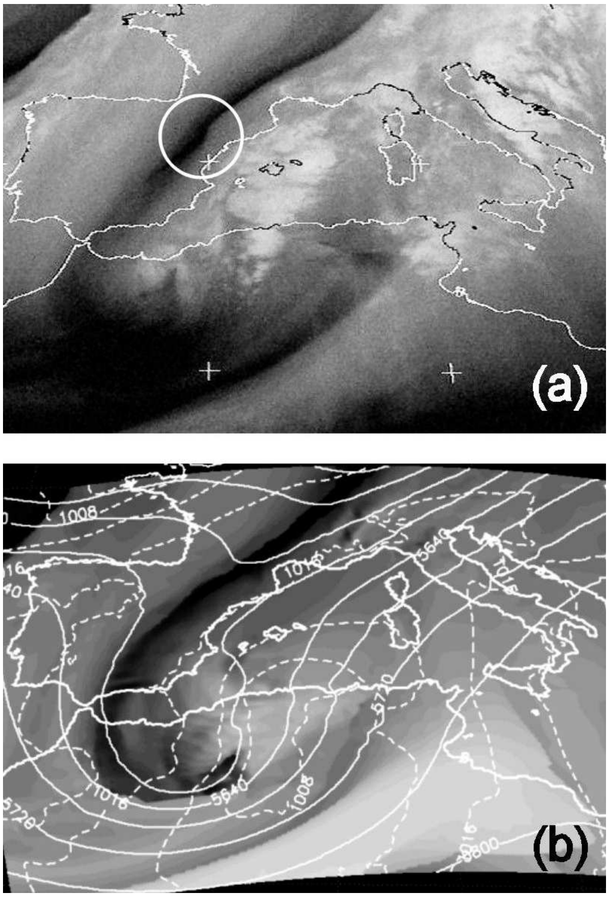

Fig. 7. 00:00 UTC 16 November 2000. **(a)** MET7WV image. **(b)** QBOLAM forecast (RUN1) of the T75Q field (grayscale), 500 hPa geopotential height (solid line), and mean sea-level pressure (dashed line).

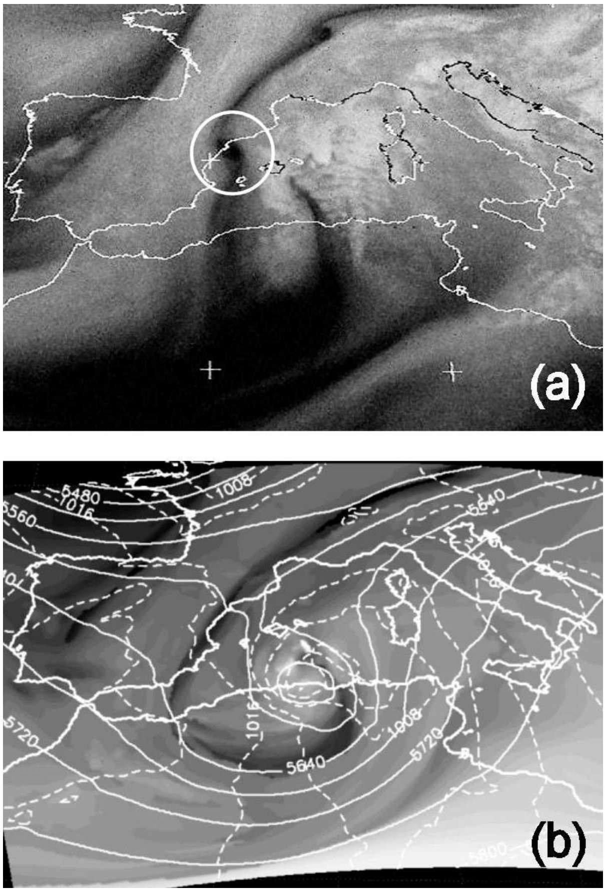

Fig. 8. As in Fig. 7, for 12:00 UTC 16 November 2000. **(a)** MET7WV image. **(b)** QBOLAM forecast (RUN1).

quality) is under discussion in this context. The MET7WV verification technique, mentioned in the Introduction, is able to provide the desired check, and also to give possible hints about the origin of the discrepancies.

The T75Q forecast field, to be compared with the satellite image, is obtained as follows. First, the height of the selected specific humidity isosurface (computed starting from the top, in order to avoid humidity profile inversions) is found by vertical linear interpolation from the surrounding model levels. Then, temperature is vertically interpolated from the surrounding levels to the isosurface height. The resulting pseudo-image is comparable to the satellite one, especially about some dynamically-relevant features: dry air associates with high potential vorticity air intrusion (dark stripes) and clear-air humid bands (light stripes). Sharp boundaries between such areas should represent robust features, suitable for verification of the synoptic-scale and mesoscale details of the analysis and the ECMWF and QBOLAM forecasts.

About RUN1, T75Q fields are quite similar to the satellite images for both the initial analysis (not shown) and the forecast up to 00:00 UTC 16 November (Fig. 7): the disturbance, in forecast and observations, moves eastward along the Algerian coast and becomes deeper.

Suddenly, after that time, a minor cyclonic vorticity centre (barely visible inside the circle in Fig. 7a), growing to the detriment of the old cyclonic centre, is observed, but not forecast. Consequently, at 12:00 UTC, the observed structure (Fig. 8a) is more compact along longitude, and shifted north-easterly, than the predicted cyclone (Fig. 8b), which continues to move along the Algerian coast. Note how these results are coherent with the TCWV comparison shown in Fig. 5, since the predicted cyclone spans westwards much more than the observed one. In the following 12 h, this tendency is enhanced. Eventually, whereas the predicted cyclone is located south of Sardinia (as seen in Figs. 6a, b), the observed one is located northwards; in particular, the south-easterly advection of moisture over Liguria and Piedmont is evident in the observation and absent in the forecast.

Concerning RUN2, the event misforecast seems to be linked to the absence of some mesoscale details in the initial analysis. In fact, the 12:00 UTC 16 November analysis pseudo-image (not shown) looks like a smoothed version of

Fig. 8a: in particular, the analysis does not show the vorticity centre marked by the circle in Fig. 8a, although on a larger scale the MET7WV image pattern is well reproduced.

The differences between the observed structure and the forecast one tend to increase during RUN2. At 00:00 UTC 17 November (Fig. 9) the location and the overall structure of the predicted cyclone are coherent with the corresponding MET7WV image, but the cyclone is apparently less developed in the simulation than in the observed reality. It seems reliable that the cyclonic circulation around the evidenced centre (circle in Fig. 9a), which is absent in the forecast fields (Fig. 9b), has strengthened south-westerly moist advection over Liguria and Piedmont. In fact, the predicted moist band over north-western Italy is less evident than the observed one, and it is shifted eastwards.

7 Conclusions

The present study is a work in progress, and it will be soon extended in two directions: a more robust assessment of the results subjectively obtained, and the search for a deeper insight on the physical processes involved. For example, object-oriented method as the contiguous rain area analysis (Ebert and McBride, 2000) can provide a quantitative basis to evaluate the precipitation pattern shifting; instead sensitivity tests are suitable to evaluate the role of mesoscale forcing mechanisms. However, the aforementioned results indicate (although do not demonstrate) a possible role of the detail of initial conditions as a major factor affecting the forecast quality (defined in terms of rainfall integrated over the target area). In particular, the behaviour of the QBOLAM RUN1 seems to suggest the occurrence of a relatively high sensitivity to small error in the initial conditions. In any case, the LAMs' results are found to be less reliable than the ECMWF's ones. This is also coherent with the relatively better performance of MM5 model for this run. In fact this model, having a small domain, is comparatively less able to develop mesoscale circulations different from the ECMWF forecast advected through the boundaries. About QBOLAM RUN2, the MET7WV comparison gives some direct evidence of the effect of initialisation error; in particular, of the lack of specific mesoscale details in the ECMWF analysis.

These results, if confirmed, tend to stress the importance of the issue of data coverage inhomogeneity: in the Mediterranean area, the effects of complex topography are not always resolved by the observational system, due to the lack of observations over the sea and northern Africa. Finally, the physical mechanisms involved in the model error production are still to be investigated and will be the object of future studies.

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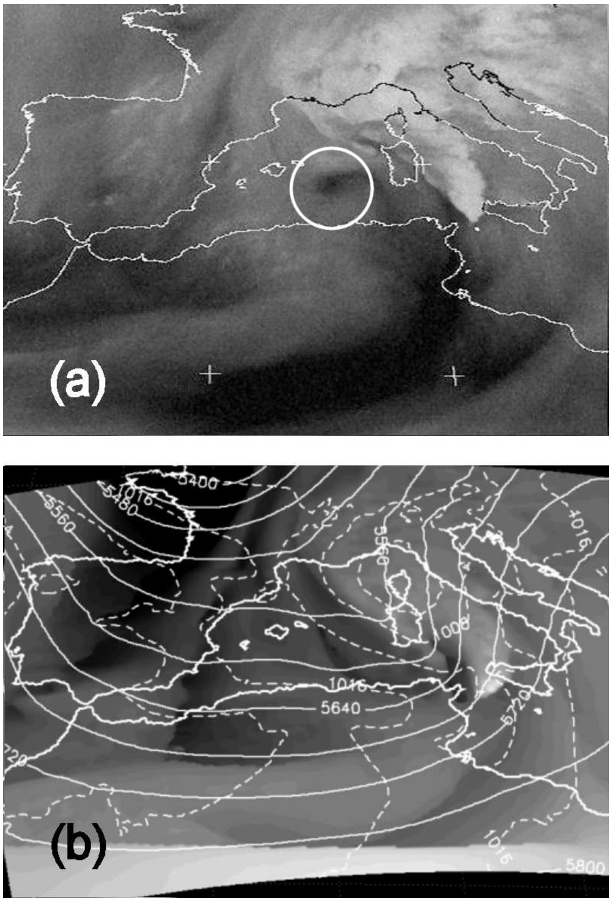

Fig. 9. As in Fig. 7, for 12:00 UTC 17 November 2000. **(a)** MET7WV image. **(b)** QBOLAM forecast (RUN2).

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