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Research Paper

The contribution of fine scale atmospheric numerical models in improving the quality of rainfall forecasts during heavy precipitation episodes

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Abstract

The atmospheric numerical models have known great advances with the ongoing development of numerical weather prediction and computing resources. The spatial and temporal resolutions of the global atmospheric models have improved and therefore, the accuracy and reliability of their results have substantially increased. Emphasis was made on the improvement of models dynamics and physical aspects, but also on data assimilation and input data diversification using new numerical schemes and new physical parameterizations that better assess the small-scale weather phenomena. However, these models were not able to overcome their physical limitations and therefore, some small-scale processes are far from being thoroughly apprehended.
To overcome these limitations, new numerical models applied to limited areas and finer scale numerical weather models have been developed including additionally, the microphysics of clouds, atmospheric chemistry and soil characteristics (vegetation index, albedo, roughness property, etc.). The output of atmospheric models, particularly in the field of precipitation, is the main input of hydraulic numerical models and flood warning systems. Better control of the rainfall forecasts, especially during extreme weather events, will have a positive impact in improving the quality of weather early warning systems and thus the quality of numerical hydraulic models predictions.
The present work illustrates, through two recent cases studies, a real demonstration of the contribution of fine-scale atmospheric numerical models in improving the quality of rainfall forecasts taking into accounts that time series of predicted rainfall amounts issued from the fine scale atmospheric models provide more precise information at the scale of water basin and also that these models have demonstrated an ability to better predict stormy situations that are causing floods in many parts of the country.

***Keywords**: AROME, Flash Flooding, Heavy Rainfall Episodes, Numerical Modeling, Weather Forecast.*

1. Introduction

Among the most significant scientific advances of the past century is the ability to simulate complex physical systems using numerical models and therewith to predict their evolution. One outstanding example is the development of general circulation models (GCMs) of the atmosphere allowing, nowadays, the prediction of the weather for several days in advance with a high degree of confidence and the gain of great insight into the factors causing changes in our climate, and their likely timing and severity [1].
Developments in atmospheric dynamics, instrumentation and observing practice and digital computing have made great and rapid advance in the numerical modeling of the atmosphere and, as a consequence, numerical weather prediction models are now at the centre of operational forecasting both in short- and medium-range forecasting and global climate change studies. In this context, the spatial and temporal resolutions of the general circulation models have improved and therefore, the accuracy and reliability of their results have substantially increased. Emphasis was made, during the last decade, on the improvement of GCMs dynamics and physical aspects, but also on data assimilation and input data

diversification using new numerical schemes and new physical parameterizations that better assess the small-scale weather phenomena. In fact, the most important components of any numerical weather prediction model, as reported by Stensrud [2], are the subgrid-scale parameterization schemes, and the analysis and understanding of these schemes is a key aspect of numerical weather prediction.
To overcome these limitations, new numerical models applied to limited areas and finer scale numerical weather models have been developed having higher temporal and spatial resolutions and including additionally processes related to the microphysics of clouds, atmospheric chemistry and soil characteristics (vegetation index, albedo, roughness property, etc.).
The choice of increasing the resolution of the weather numerical model is not sufficient in itself. It introduces new problems related to the need of redefining the description of physical processes not explicitly descried in the model. Corazza et al. [3] stated that it is not only a question of increasing the number of grid points and its related computational cost; the point is to get to a better physical description of phenomena such as the interaction of fluxes with complex orography, convection or microphysical cloud processes. Moreover, the need to describe more detailed flow structures introduces the problem of providing the model with the right initial and boundary conditions.
The same statement was expressed, several years earlier, by Anthes [4] when he noted that the parametrization of cumulus convective effects as a function of the resolvable scale becomes questionable as the grid size becomes smaller than ~100 km. For finer meshes, the separation between resolvable and convective scales becomes less and the model may begin to simulate the same clouds it is also trying to parameterize. For high-resolution models, therefore, it may be preferable to abandon the concept of parametrization in favor of explicit treatments of condensation and evaporation trough the introduction of prediction equations for cloud and precipitation water.
The output of atmospheric models, particularly for the field of precipitation, is the main input of hydraulic numerical models and flood warning systems. Better control of the rainfall forecasts, especially during extreme weather events, will have a positive impact in improving the quality of weather early warning systems and thus the quality of numerical hydraulic models predictions.
To illustrate the contribution of the finer scale weather numerical models in the improvement of the quality of rainfall forecasts and in particular during heavy precipitation episodes, two recent cases affecting Morocco have been studied. The first case concerns the meteorological situation of the October, 30 2012 that has affected the south part of the country known for its semi-arid climate with normal annual rainfall amounts not exceeding 300mm and the second case is more related to a summer deep convective clouds forming in the north part of the country at the vicinity of the Mediterranean Sea. For the purposes of the study, comparison was performed between outputs of two general circulation models ECMWF and ARPEGE (Action Research for Small Scale and Large Scale) and those issued from the limited area weather numerical model ALBACHIR and the finer scale model AROME. Emphasis is also made on the possible impact of the obtained outputs on the quality of weather forecasters' predictions and warnings.

2. Material and methods

For the purpose of the study, both atmospheric general circulation models and limited area atmospheric numerical models are used. Numerical weather models results are compared to surface and remote sensing observations obtained from the national meteorological observing network and, precisely, from meteorological stations located in the study area.

2.1. General circulation atmospheric models

The formulation of these models is based on a set of basic equations, of which some are diagnostic describing the static relationship between the pressure, density, temperature and height. Other are of prognostic types and describe the time evolution of the horizontal wind components, surface pressure, temperature and the water vapor content of an air parcel. Additional equations are taken into account to describe the changes in hydrometeors (rain, snow and cloud liquid water and ice contents). The processes of radiation, gravity wave drag, vertical turbulence, convection and clouds and surface interaction are, due to their relatively small scales unresolved by the model's resolution and thus described in a statistical way as parameterization processes that are arranged in entirely vertical columns.

2.1.1. The ARPEGE model

The French numerical model ARPEGE (Action Research for Small Scale and Large Scale) is a stretched global atmospheric circulation model using a variable horizontal grid mesh whose focal point is centered in the French territory with a horizontal resolution of about 10km in France, 15km in North Africa and 60km to the antipodes. The vertical resolution of the model is 70 levels. The first one is located at 17 meters above the surface and the higher level is greater than about 70km above the ground. The time step is 600 seconds. The ARPEGE model uses a hybrid vertical coordinate "pressure -sigma", a finite element representation in the vertical and it uses a two levels semi- Lagrangian scheme for time integration.

The initial conditions of the ARPEGE model are determined by a four-dimensional variational data assimilation (4D-Var) incorporating a large amount and variety of conventional observations (upper air observation, aircraft measurements, ground stations, ships, buoys…etc) and also observations obtained from satellite and remote sensing (ATOVS, MCH, AIRS, IASI , SEVIRI, GPS, SATOB, etc...).

2.1.2. The ECMWF model

The atmospheric general circulation model of the European Centre for Medium-Term Weather Forecast is a deterministic model using a grid of 91 vertical levels and a regular horizontal spatial resolution of 0.25°. The model describes the dynamical evolution on the resolved scale and is augmented by the physical parameterization, describing the mean effect of sub-grid processes and of the land-surface model. ECMWF model is also coupled to ocean wave model and it is providing numerical weather products all over the globe for 144H. The model equations are discretized in space and time and solved numerically by a semi-Lagrangian advection scheme. It ensures stability and accuracy, while using as large time-steps as possible to progress the computation of the forecast within an acceptable time.

2.2. Limited area and finer scale numerical models

2.2.1. The model ALBACHIR

The ALBACHIR model is an operational version of the ALADIN Model running twice a day in the national meteorological service of Morocco (DMN). It is a limited area atmospheric numerical model centered on Morocco built and developed as a declination of ALADIN numerical weather model resulting of joint efforts of a consortium of a number of countries including Morocco. This atmospheric model produces weather numerical predictions at a finer spatial scale and at short-term (3 days). ALBACHIR model works with 60 vertical levels and a spatial resolution of 10km.
The initial conditions of the model are determined by a variational data [5] incorporating all conventional and remote sensing observations available on the area of study. The boundary conditions are derived from the regional weather numerical model NORAF itself receiving at boundary conditions from the ARPEGE model as illustrated in Fig.1.

2.2.2. The model AROME

The atmospheric numerical model AROME was designed to improve short-term forecasting of hazards such as strong Mediterranean rainfall, thunderstorms, fog or urban heat islands during heat waves [6]. Indeed, the physical parameterizations of the model are largely inherited from the research atmospheric numerical model MESO-NH (MESOscale and Non-Hydrostatic), while the dynamic part is adapted for fine-scale dynamics of ALADIN core model. The model AROME is operational at the DMN with a spatial resolution of 2.5km and 60 vertical levels. The boundary conditions are obtained from ALBACHIR model at a coupling frequency of 1 hour.

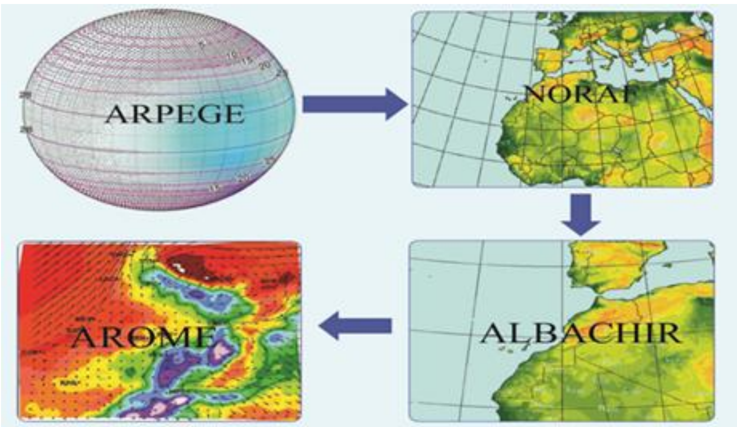

Fig. 1: Diagram of the Boundary Condition Transition from the GCM ARPEGE to the Fine Scale Model AROME

2.3. Surface and remote sensing observations

For this study, images from the weather radar located at Agadir Al-Massira airport (images are available every 10 minutes), Meteosat Second Generation satellite images (available every 15 minutes in multiple channels) and hourly cumulative rainfall and weather observations made by the meteorological stations of Agadir airport and Taroudant are used.

3. Results and discussion

3.1. Case of heavy rainfall episode in the souss valley (october 31, 2012)

The region of Souss-Massa experienced a heavy rainfall episode during the night of 30 and the morning of October 31, 2012 which reached about 100mm in the station of Taroudant as shown in Fig. 2 and 84mm in Agadir airport meteorological station. The recorded quantities of rainfall during this short time episode (less than 15 hours from October 30th, 2012 at 21h00 to October 30th, 2012 at 12h00) accounts for the equivalent of 30% of the annual rainfall normalized average (300 mm) observed in the Souss Valley known generally for its semi-arid climate [7].

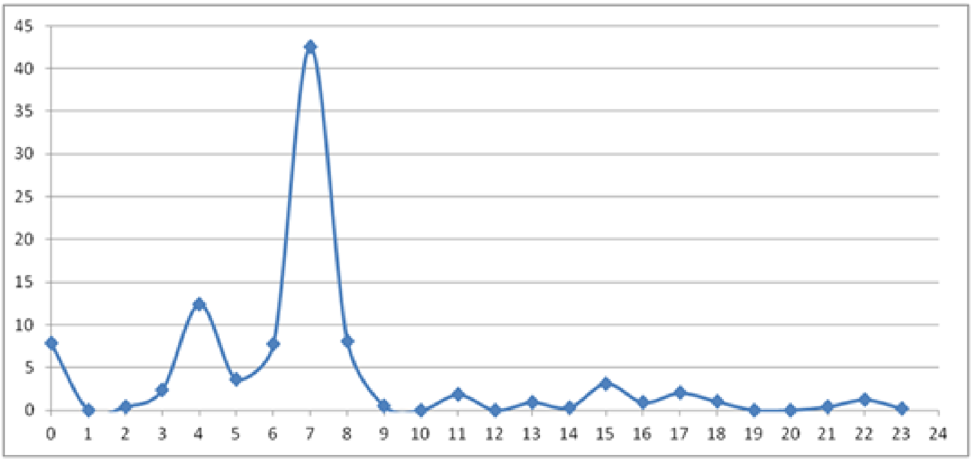

Fig. 2: Hourly Rainfall Amounts Observed At the Meteorological Station of Taroudant at October 30, 2012

The meteorological situation prevailing in the day of October 30, 2012 was characterized on the surface level by the presence, over Morocco, of a relative minimum of the thermal field and also of the field of atmospheric pressure promoting the formation of a cloud cluster on the south west of the country moving to east. This cloud cluster, visible in Fig. 3, consists of low cumulus clouds having an averaged vertical extension of 4km altitude above the ground as observed by the weather radar of Agadir airport meteorological station reported in Fig. 5.

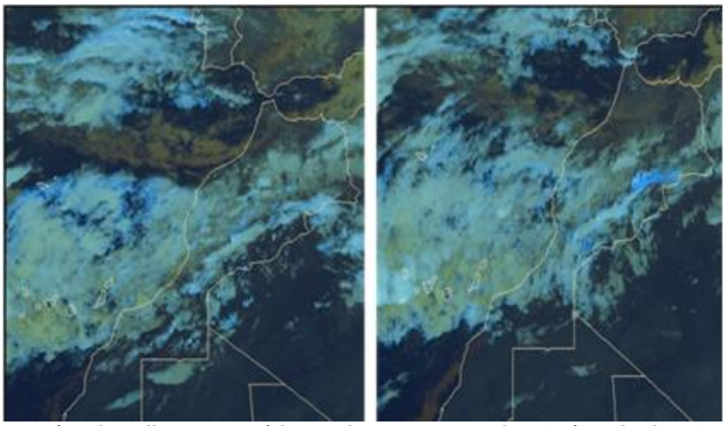

Fig. 3: Infrared Satellite Images of the October 31, 2012 at 03h00 (Left) and 06h00 (Right)

The cloud cluster include convective clouds with important water content materialized by high reflectivity exceeding 30 dbz observed in the weather Radar image of 07:00 am (Fig. 5) indicating the presence of precipitating clouds that were at the origin of more than 40mm of rain recorded at the station Taroudant between 07:00 am and 08:00 am.

The comparison between the outputs of general circulation atmospheric models (ARPEGE- ECMWF) and those of the small-scale numerical models (ALBACHIR- AROME) reveals that the latest provides most accurate forecasts of some meteorological parameters in particular fields of temperature and rainfall. The same comparison between the outputs of the two models ALBACHIR with a spatial resolution of 10km (Fig. 2) and AROME with meshes of 2.5 km (Fig. 4) shows the ability of the model AROME to better predict nighttime temperatures over the Anti-Atlas mountains in the south part of the country and also over the eastern part the Atlas mountains. Furthermore, accurate precision were indicated for the atmospheric pressure field showing a relative minimum of 1006 hPa to the south east of the country.

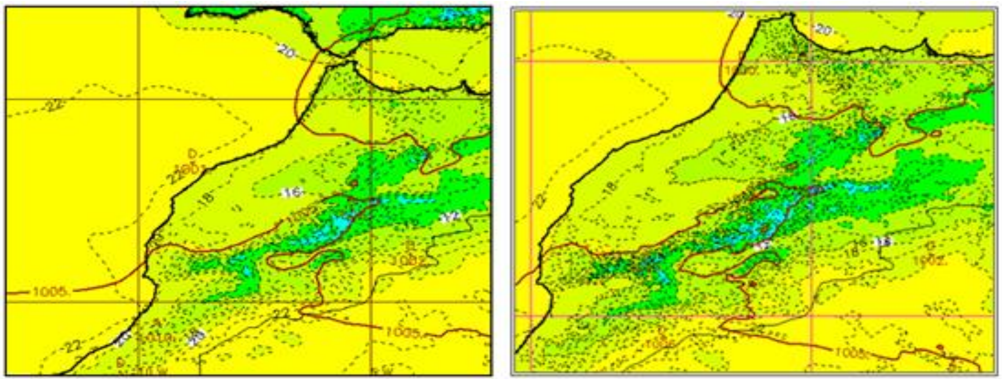

Fig. 4: Analysis Charts of the October 31, 2012 At 00h00 Issued from the Model Albachir (Left) and Arome (Right) Illustrating the Field of Temperature at the Surface and of the Field of Mean Seal Level (Msl) Atmospheric Pressure (Continuous Line).

The comparison between the outputs of general circulation atmospheric models (ARPEGE- ECMWF) and those of the small-scale numerical models (ALBACHIR- AROME) reveals that the difference between the two types of models becomes clearer when comparing the rainfall results provided by the different numerical models used. Indeed, the ECMWF model fails to isolate the cloud cluster that affected the region of Souss-Massa (Fig. 6) showing weak to moderate rainfall quantities not exceeding 10mm, while the ARPEGE model manages to highlight this cloud cluster laying from Agadir to Taroudant with predicted values rainfall quantities reaching the ground exceeding 15mm near Agadir city.

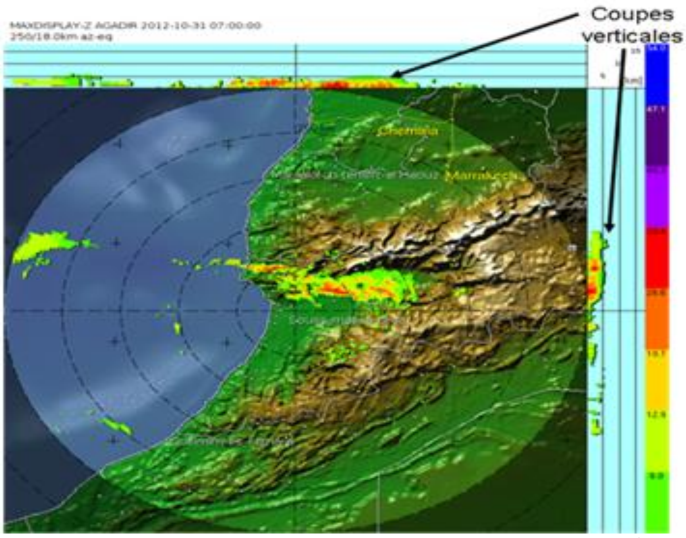

Fig. 5: Weather Radar Image at 07h00 Am Giving Indications on Clouds Reflectivity

ALBACHIR numerical model provides more precisions concerning the geographical position of the precipitating clouds and of the amount of predicted rainfall (Fig. 7). ALBACHIR model succeed to mark the spatial extent of the maximum of rainfall which is approaching the shape and the position of cloud reflectivity reported by the weather radar of Agadir (Fig. 5). The predicted amount of rainfall exceeds 20mm over the axis Agadir-Taroudant which is still less than real quantities reaching the ground.

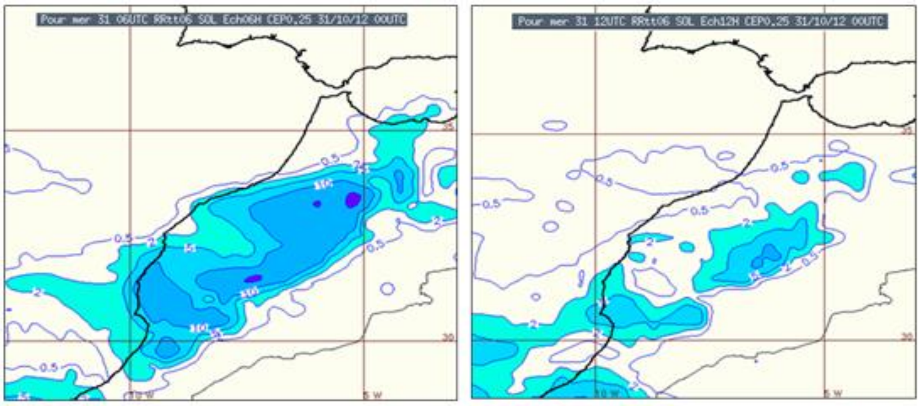

Fig. 6: Predicted Rainfall Amounts for 06h00 Am (Left) and 12h00 Am (Right) as Predicted by the Ecmwf Model

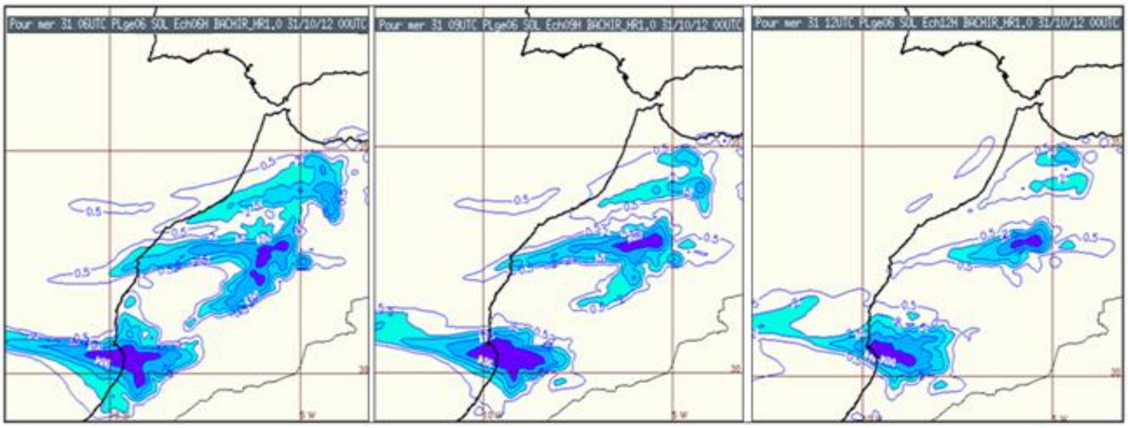

Fig. 7: Predicted Rainfall Amounts Issued from the Model Albachir for 06h00am (Left), 09h00am (Middle) and 12h00am (Right)

The model maintains this area of maximum of rainfall throughout the period from 03:00am to more than 12:00 as shown in Fig. 7. Based on this information, a severe weather warning for heavy rainfall exceeding 40mm over 24 hours was established but, in reality, the numerical model ALBACHIR failed to predict the end of the rainy period since the observations have shown that heavy rains weakened after 09:00 am (Fig. 2).

The finer scale numerical model AROME (2.5km) provides, as illustrated in Fig. 8, more accurate information on the period of persistence of these heavy rains showing its beginning after 03h00 am and its declination beyond 09h00 am. Comparing these outputs with weather radar images, presented in Fig. 9, indicates a good match, in terms of geographical localization, between the high reflectivity area and the area of heavy rains predicted by the model AROME.

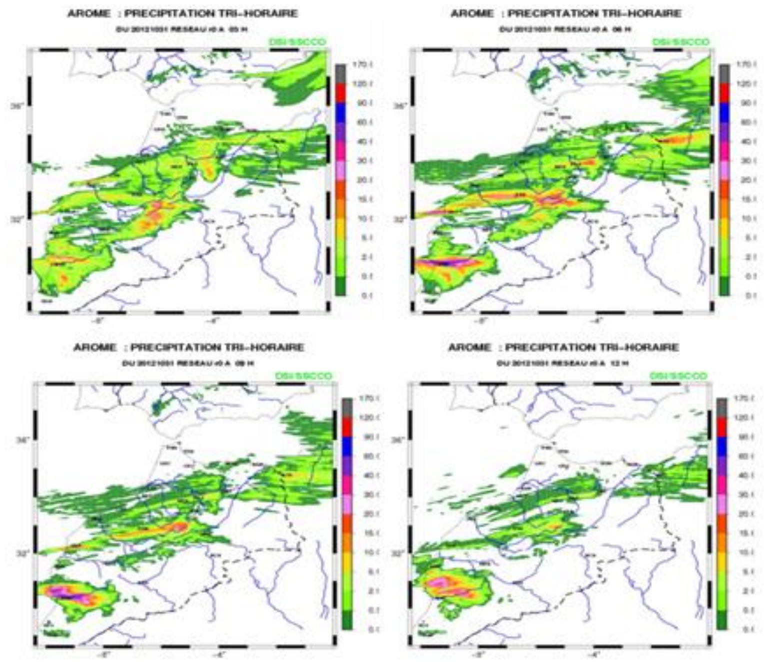

Fig. 8: Predicted Rainfall Amounts Issued from the Arome Model for the October 31, 2013 at 03h00 (Hl), 06h00 (Hr) 09h00(Ll) and 12h00 (Lr).

3.2. Case of the convective clouds in the region of tetouan (August 29, 2013)

The summer stormy meteorological situation of the 29 August 2013 was particularly interesting. Unstable weather conditions prevail in southern Spain and northern Morocco leading to the development of thunderstorm cloud cells. Those thunderstorms produce intense precipitation in many locations in the northern part of Morocco leading to some floods and material damages in urban regions as was the case in the cities of Tetouan and M’diaq.

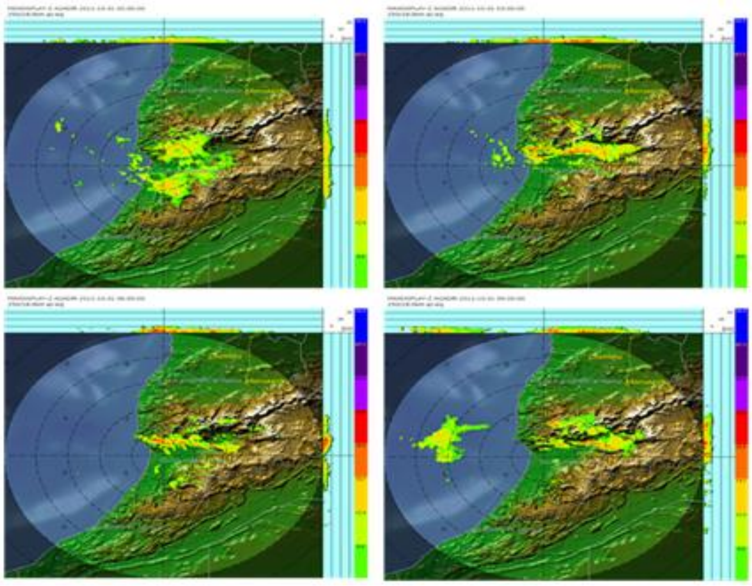

Fig. 9: Weather Radar Images of October 31, 2012 at 00h00 (Hl), 03h00 (Hr), 06h00 (Ll) and 09h00 (Lr)

Fig. 10: Urban Damages Caused by Heavy Rainfall during the Morning of the August 29, 2013 in City Of Tetouan

Since 01:30 am, three stormy cloud cells grew on the region of the Tetouan bay: the first cell forms and grows between 01:00 am and 03:30 am over the Mediterranean sea at the immediate vicinity of the town of M'diq, the second forms also over the Mediterranean sea from 04:00 am to 07:00 am between the two cities of Fnideq and M'diq and the third consisted on a cluster of thunderstorm cells which grew since 09:00 am to cover the entire region from Ksar Sghir to Oued Lao as shown in Fig.s 12.

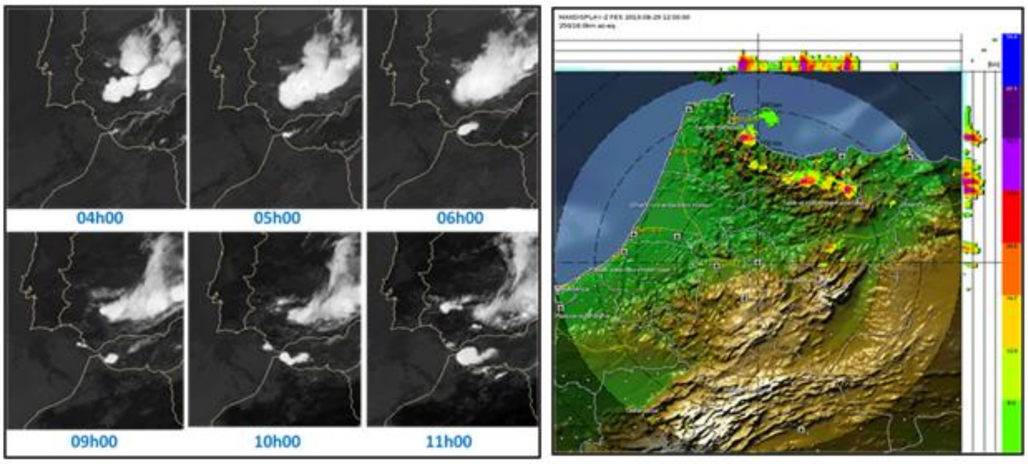

Fig. 11: (Left) Infrared Satellite Images (Ir) and (Right) Weather Radar Image of 12h00 –Situation of the August 29, 2013

The observed amounts of rainfall reaching the ground were highly variable but quite interesting in terms of rainfall intensity: M'diq: six hours cumulative rainfall amount of 58mm between 00:00 am and 06:00 am, Tetouan Airport: 31mm between 09:00 am and 12:00 am, 41mm recorded at a location 20 km far from Tetouan airport, 16mm in Capo Negro and 13mm in the Smir Dam near M'diq recorded between 06:00 am and 12:00 am. The analysis of the weather

Radar images, recorded every 10 minutes by two weather radars located in Fes airport and in Larache city, shows the existence of stormy cells extending vertically over 8 km above the ground and having very high reflectivity exceeding 40 dbz indicating intense rainfall as indicated in Fig. 11.

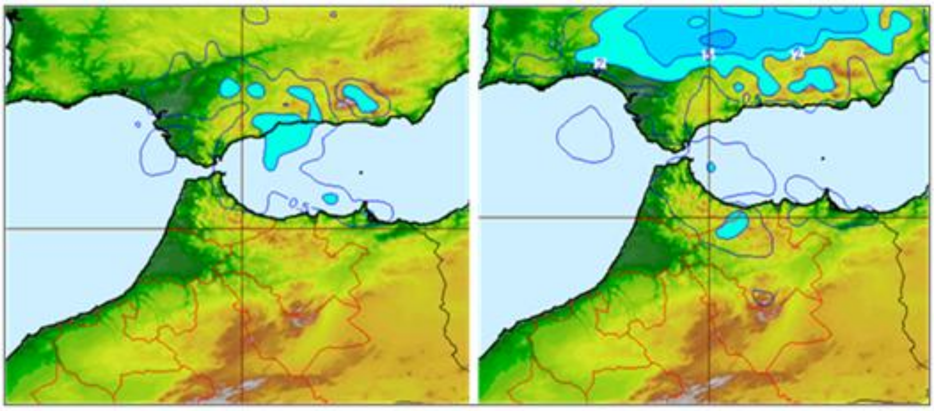

Fig. 12: Six Hours Predicted Rainfall Amounts Issued from the Ecmwf Model for the Periods 00h00-06h00 (Left) and 06h00-12h00 (Right) at August 29, 2013

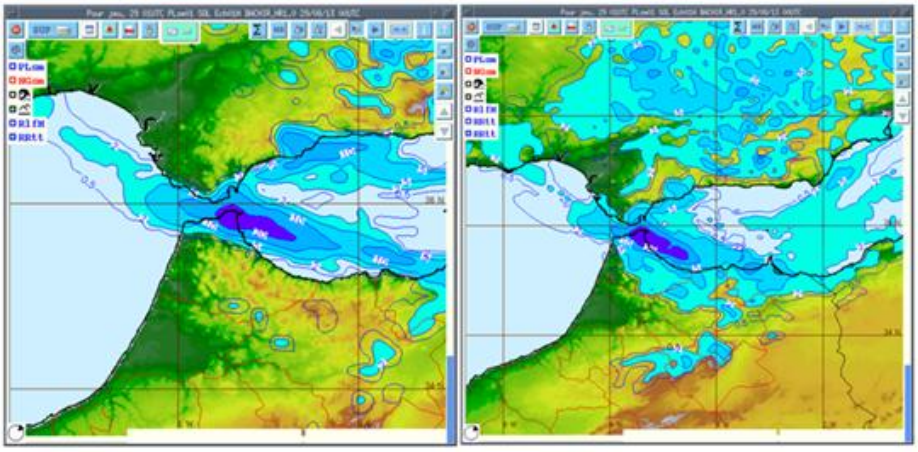

Fig. 13: Six Hours Predicted Rainfall Amounts Issued from the Albachir (10 Km) Model for 00h00-06h00 (Left) and 06h00-12h00 (Right) at August 29, 2013

The general circulation atmospheric models ARPEGE or ECMWF and even the first version of ALBACHIR numerical model with spatial resolution of 16km fail to predict the rainfall amounts observed in the northern part of Morocco or to oversee the storm formation in this part of the country. Fig. 12 shows the six hours cumulative rainfall amounts predicted by the model ECMWF illustrating the fact that large-scale numerical models were not suitable for such kind of stormy situations consisting of isolated thunderstorm cloud cells that are smaller than the spatial resolution of the model itself even despite the efforts deployed in terms of research and development for better control of these so-called "sub-grid" phenomena.

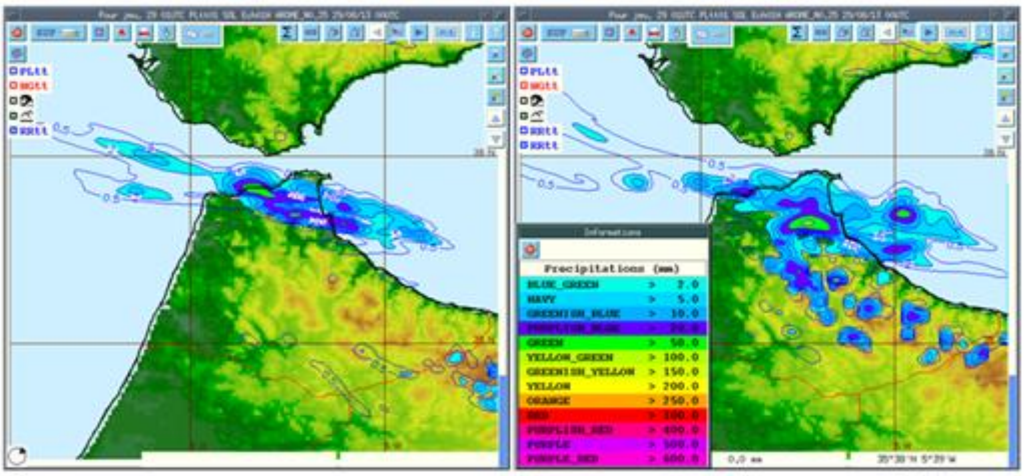

Fig. 14: Six Hours Predicted Rainfall Amounts Issued from the Arome Model for the Periods 00h00-06h00 (Left) and 06h00-12h00 (Right) at August 29, 2013

The ALBACHIR numerical model with spatial resolution of 10km predicted very well this stormy situation either in terms of spatial and temporal distribution (geographical location, beginning and end of the rain episode) or in terms of expected rainfall amounts (Fig. 13). Indeed, a maximum rainfall accumulation (between 00:00 am and 06:00 am) of about 60 mm was forecasted by the model AL-CACHIR near the city of M'diq where 58mm was really recorded during same period. The fine scale numerical weather model AROME with a spatial resolution of 2.5km added some finesse in the spatial representation of boundaries and shape of the thunderstorm cells, as clearly illustrated in Fig. 14, succeeding to represent the isolated thunderstorm cells as observed in the weather radar images of 12h00 am (Fig. 11). Although, the total predicted amount of rainfall for six hours was larger over estimating the observed rainfall amounts with a maximum value exceeding 100mm in six hours in the M’diq city.

4. Conclusion

For these two case studies, the contribution of fine scale models is clearly remarkable as they allow meteorologists and especially weather forecasters to refine their forecasts and thus to improve the early warning system in terms of both spatial location and temporal duration. This contribution of small and fine scale atmospheric numerical models is not only due to their high spatial resolution, allowing them to incorporate more realistic representations of surface characteristics, but also to their physical parameterizations, including all microphysical processes of clouds, cloud-surface interaction, atmospheric chemistry and other processes, and the implementation of data assimilation cycles that integrate all types of available observations. In particular, important work was made aiming to improve the parameterization of deep convection processes in the fine scale atmospheric models as reported by Ducroq et al. [8] and Gérard et al. [9]. The strength of these numerical models also draws the progress experienced by general circulation atmospheric models or limited area numerical models since they provide the boundary conditions.

Acknowledgments

Our thanks go to the staff of the National Meteorological Department for their contribution providing numerical model outputs and observational data related to the studied cases.

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