Numerical modeling of heavy rainfall event over Madeira Island in Portugal-Sensitivity to Microphysics

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Abstract — Madeira Island, Portugal, faced an intense heavy rainfall on 20 February 2010 which lost more than 40 lives and caused great damage. This event is recorded as one of the major flash flood events during the past three decades. Keeping this in view, in the present study a series of numerical experiments using the Weather Research Forecasting model and MESO-NH model at very high resolution of 1 km are performed. Lateral and boundary conditions are updated every 6 hours using NCEP FNL data for WRF model and with ECMWF IFS data for MESO-NH model, available at 1 degree and 0.25 degree resolutions, respectively. The WRF model is designed with four nested domains and an inner domain with 1 km resolution centered on the island, which is the area of interest. MESO-NH model is integrated with 3 domains and inner domain at 1 km resolution located over Madeira Island.

Both models show that the extreme rainfall event was originated by the effect of orography on the prevailing large scale flow of a conditionally unstable moist air. Experiments for other heavy rainfall events over Madeira show the same mechanism, indicating the capability of high resolution mesoscale models in reproducing this type of events. At higher resolution, convection parameterization schemes are not so important to resolve mesoscale cloud features but microphysics schemes are important. In this aspect we performed a series of sensitivity experiments with different microphysics schemes. Different cloud microphysical properties are examined and discussed. These cloud microphysical parameters are compared with satellite retrievals. Results indicate that the model is sensitive to different microphysics schemes.

Keywords — Heavy rainfall, mesoscale model, microphysics

1 INTRODUCTION

In Numerical Weather Prediction (NWP) Models, representation of precipitation physics is crucial in predicting precipitation. Rainfall prediction with NWP models is made by representing grid resolvable processes through an explicit representation of clouds and precipitation processes, and by the parametrization of sub-grid scale precipitation due to convection and cumulus At very high resolution (order of 1 km) the cumulus parametrization is not needed as most of the convective precipitation may be explicitly represented. In high resolution NWP models, grid resolvable precipitation algorithms are important for improving rainfall forecasts. As grid distance decrease, the explicit representation of microphysical processes plays an increasingly important role in NWP models. There are two broad types of microphysics schemes, bin or spectral microphysics and bulk microphysics parameterizations. In the bin schemes, tens of mass bin represent the particle spectra and the evolution size distribution is explicitly calculated [1 to 9]. In bulk schemes, the cloud particle size distribution is prescribed and the mixing ratio and number concentration for each type of particle are predicted [10 to 18]. These bulk schemes predict the number concentrations and mixing ratios of hydrometeor species, which increases the degrees of freedom and potentially improves the particle size distributions. Bulk parameterization methods are commonly used in NWP models [11, 13, 15, 16] due to computational advantages. Most of these schemes assumes the hydrometeor size spectra to follow a prescribed exponential or gamma distribution [14, 19]. Many studies tried

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to understand the variations in precipitation species parameters and their variations on precipitation [14, 15, 16, 20]. These studies show the impact of cloud microphysics on global radiative convective quasi-equilibrium in a constant SST at 1 km grid spacing. On complex orography Grubsic et al, 2005 examined the skill of MM5 model at 1.5 km resolution, during heavy rainfall over Sierra Nevada and they studied the sensitivity of different microphysical parameterizations and horizontal resolution. The sensitivity of summertime convective predictions to bulk microphysics parameterizations at fine grid spacing was studied by Liu et al, 2007 [22]. The relative importance of ice-phase microphysics and sedimentation velocity for hydrometers are reported by Hong et al, 2009 [20] in two bulk microphysics schemes, the single momentum 6-class Microphysics scheme (WSM6) and Purdue-Lin scheme for heavy rainfall event over Korea. This study shows the role of ice-phase microphysics and fall velocity for ice particles in bulk type parameterizations approach of clouds and precipitation.

In this study the advanced Research Weather Research and Forecasting (ARW) model [23] is used to test the sensitivity in of four bulk microphysics schemes include (Kessler, Purdue-Lin, Ferrier and Thompson) for heavy rainfall event over Madeira on 20 Feb 2010. The Kessler scheme [19] is called a simple warm rain scheme as it has no ice phase. This includes water vapor, cloud water and rain. Purdue-Lin [24] is a relatively sophisticated scheme, which includes water vapor, cloud water, cloud ice, rain, snow and graupel. The Ferrier [13] scheme predicts changes in water vapor and condensate in the form of cloud rain, cloud water, cloud ice and precipitation ice. The individual hydrometeor fields are combined into total condensate and it is the water vapor and total condensate that are advected in the model. Thompson scheme [25] assumes that snow size distribution depends upon both ice water content and temperature and both are represented as a sum of exponential and gamma distributions. In this scheme snow assumes a non-spherical shape with a bulk density which differs from all other bulk schemes, assuming spherical snow with constant density. A summary of options indicating the number of moisture variables and whether ice-phase and mixed-phase processes are included are shown in Table 1.

2. DESCRIPTION OF THE MADEIRA AND ASSOCIATED RAINFALL EVENT:

Madeira is a Portuguese archipelago situated in the North Atlantic Ocean around 700 km off the African coast, at a distance of 980 km from Lisbon, with roughly 250000 inhabitants. Madeira is the largest island of the group, with a surface area of about 741 km^2, a maximum length of 57 km, a width of 22 km at its widest point, and a coastline of about 150 km. Its longer axis presents an east-west orientation, along which a mountain chain with a mean altitude of 1220 m extends, considered the backbone of the island from which many deep ravines radiate outward to the coast. The highest point on the island is Pico Ruivo, at 1,862 m and the capital is Funchal, a city located in the southern coast of the island. Madeira Island was recently affected by the overpass of a very strong tempest, with severe consequences for the population and territory, turning out to be one of the worst flash floods in the history of the Portuguese archipelago. The heavy rainfall that occurred in a relatively short time, combined with Madeira's geography of steep slopes slanting towards the coast and the urban land use much connected to tourism, the main subsistence income of the island, as well as the saturated soil caused by a rigorous winter, complicated the water runoff and ground drainage, leading to the formation of mudslides and flooding that swept up everything in their path. The observed rain fall at different stations on Madeira Island are: at Funchal is 150mm, 400mm at Areeiviro and 103mm at Ponta Sol. The disaster caused more than 40 deaths, several missing and wounded people, as well as a vast range of material losses, including the destruction of houses, industries, roads, bridges and several thousands of vehicles, the interruption of water and power supplies, as well as of telecommunications, and the devastation of cultivated fields, which will strongly impact local agriculture.

Scheme	Num. of Variable	Ice Phase proc.	Mixed-Phase Proc.
Kessler	3	N	N
Purdue Lin	6	Y	Y
Ferrier	2	Y	Y
Thompson	7	Y	Y

Table 1: Summary of options considered in different schemes

An official report from National Weather Service [26] showed that the heavy rainfall was associated with a plume of deep moisture which came across the Atlantic Ocean and took aim at the Islands. The precipitable water (PW) anomalies from the “rum-runner express” were on the order of 4 to 5 SD deviations above normal. This atmospheric river of deep moisture was associated with this devastating rainfall event. Meteorologically, there were several factors which contributed to this heavy rainfall event. This included the high latitude block over Greenland and the southward shift of the westerlies. A deep cyclone was located over the central Atlantic basin. The plume of high PW air with values over 42 mm and anomalies over 4SDs above normal took aim at the Island.

3. MODEL DESIGN AND DATA USED FOR THIS STUDY

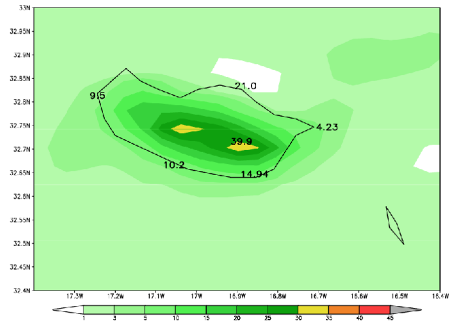
Advanced Research Weather Research and Forecasting model (ARW) developed by NCAR, USA is used in the present study. It is a limited area, primitive equation, non-hydrostatic and terrain following sigma coordinate model. The description of the model is given in Skamarock et al. 2008 [23]. The model is highly flexible to choose the domain, horizontal/ vertical resolution, interactive nested domain and incorporates several parameterizations for different physical processes such as convection, radiation, microphysics, surface fluxes and boundary layer turbulence. The physics used for this study in the model includes the Dudhia shortwave radiation scheme, RRTM longwave radiation scheme, YSU non-local scheme for PBL turbulence, 5 layer soil thermal diffusion scheme for surface processes and the Kain-Fritsch scheme for convection and four different explicit moisture schemes were used to assess the sensitivity of different microphysical processes. The model is integrated with four nested domains with the horizontal resolutions of 27, 9, 3 and 1km. The initial and boundary conditions are adopted from NCEP FNL analysis data available at 1 degree resolution. The model is designed with 41 vertical levels in which 30 levels are below 500 hPa to resolve reasonable boundary layer fluxes. Four sets of experiments are performed with different microphysics schemes and model experiments are integrated for 72 hours starting from 12UTC of 19 Feb 2010. Model results were compared with the observations collected from Institute of Meteorology, Portugal and also from satellite retrievals. Results from these comparisons are shown in Fig. 1.

The MESO-NH model [27] was run on three nested grids with horizontal resolutions of 9, 3 and 1 km, respectively, and 45 stretched vertical levels. MESO-NH was initialized and forced by the European Centre for Medium-Range Weather Forecast (ECMWF) IFS model analysis (for initialization) and forecast (for boundary conditions), updated every three hours. The model For the representation of stratiform clouds and explicit precipitation, the mixed-phase microphysical scheme developed by Pinty and Jabouille (1998) [28] was used, which distinguishes six classes of hydrometeors (water vapour, cloud water, liquid water, ice, snow, and graupel). The Kain-Fritsch convection scheme type [30] was activated in the two coarser grids (9 and 3 km), while convection was assumed to be explicitly resolved for the 1-km grid. The MesoNH radiation scheme treats successively the longwave and shortwave radiative transfer equations for independent air columns [30, 31]. The exchange flux between the atmosphere and the surface was taken into account using the physical parameterizations included in the externalized surface (SURFEX) package as described in Salgado and Le Moigne (2010) [29].

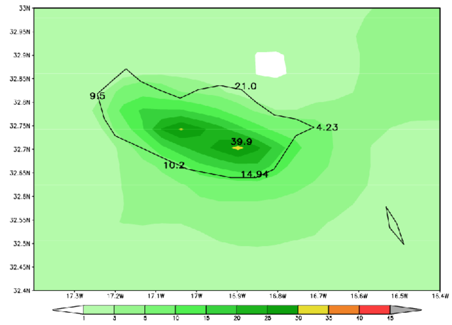
4. RESULTS AND DISCUSSIONS:

Four experiments with different explicit moisture schemes were performed with ARW model. Each model produced rainfall distribution for the period 00UTC of 20 to 00UTC of 21 February, 2010, which were presented in Figure 1 for analysis. From the results, it is very interesting to note that each scheme produced heavy rainfall with different intensities. The experiment with Ferrier scheme produced more rainfall of nearly 45 cm/day than the observation which was of about 40 cm/day and location is are well agreeing with the observations. This result is in reasonably good agreement with the observations but with slight over estimation of the values. Other three experiments are shown with maximum values of 30 cm/day but indicating almost the same location for the maxima. In these three experiments, the location of maxima rainfall is approximately the same but the extension area is quite different. From Figure 1a, obtained with Kessler scheme, the maximum of rainfall is located at two sites with an extent of nearly 5km over the top of the mountains. Experiment with Purdue-Lin scheme (Figure 1b) give as location of maximum rainfall over two places but the extension areas are a little less comparatively with the Kessler scheme, especially in the south of the domain. With Thompson scheme (Figure 1d) the maximum amount of rainfall is also located over two places like with the Kessler scheme, but with a lower area. Interestingly in all three schemes, the maximum locations are almost at the same place, only varying the extent of rainfall area. From Figure 1c, results with Ferrier scheme are different from all other three experiments. The model simulated rainfall value with Ferrier scheme is much higher than all other three experiments. It is of about 45 cm/day and it is over estimated with the observations. In addition, the extent of area is quite large comparatively with the other three experiments. These results indicate the importance of each cloud resolving schemes used for this study.

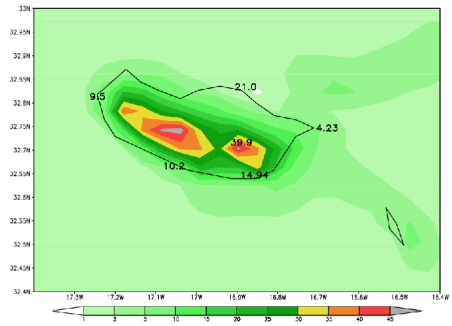
(a)



(b)



(c)



(d)

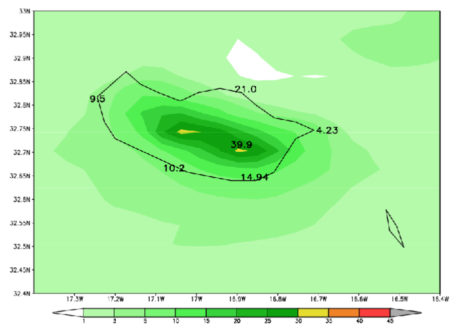
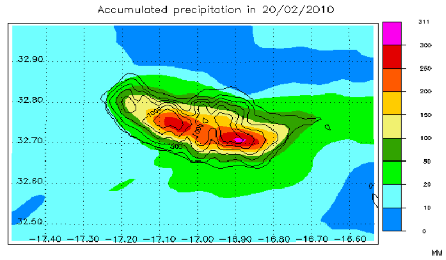


Figure 1: ARW Model produced daily rainfall (cm) with different explicit moisture schemes during 00UTC of 20 to 00UTC of 21 Feb, 2010. (a) Kessler (b) Purdue Lin (c) Ferrier and (d) Thompson schemes. Numbers indicates observed rainfall values at that station.

(a)



(b)

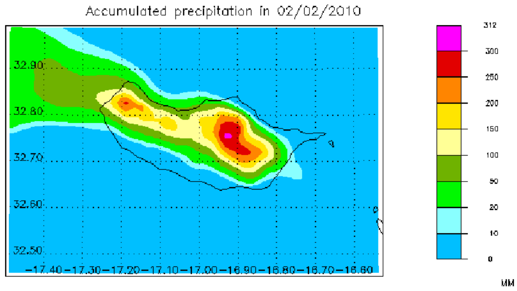


Figure 2: MESO-NH Model produced daily rainfall (mm) along with topography.

The results of the MESO-NH simulations confirm the possibility of obtaining accurate rainfall forecasts over isolated mountains with current atmospheric models at high horizontal resolution. Regarding the simulation of 20 Feb. 2010, the simulated values of accumulated daily precipitation (Fig 2a), with a maximum of 31 cm, are similar to the rainfall collected at surface stations, except in those situated in the southern slope, near Funchal city, where the model underestimates the precipitation. However the model shows a delay of about 2 to 3 hours on the onset of the precipitation event.

In order to strengthen this conclusion, other MESO-NH simulations were conducted, with the same design, for other case studies of heavy precipitation events occurring in Madeira Island in the winter of 2009 and 2010. The results in terms of daily accumulated precipitation on 2 Feb. 2010 are shown in Figure 2b. The model also reproduces the accumulated precipitation that occurred in this "case study", on a different synoptic situation characterized by an east flow.

5. Summary:

Results obtained with ARW and MESO-NH models show that both the models are able to reproduce the heavy rainfall event formed over Madeira Island, with very high resolution of 1km. These results show also the model sensitiveness to different cloud resolving schemes. Experiments with ARW model using different explicit moisture schemes show that the Ferrier scheme produces more rainfall than the other three schemes, presenting a greater spatial extent as well. Almost all four experiments produced maximum heavy rainfall in the same approximate location. MESO-NH model also reproduced the heavy rainfall event with a pattern similar to those obtained in the ARW model experiments. Another Feb 2010 case study was simulated with MESO-NH, which confirms the possibility of obtaining good precipitation predictions in isolated mountains with high resolution models (~ 1 km).

References

[1] JHall, W. D., 1980: A detailed microphysical model within a twodimensional dynamic framework: Model description and preliminary results. *J. Atmos. Sci.,* 37, 2486–2507.W.-K. Chen, *Linear Networks and Systems.* Belmont, Calif.: Wadsworth, pp. 123-135, 1993. (Book style).

[2] Feingold, G., B. Stevens, W. R. Cotton, and R. L. Walko, 1994: An explicit cloud microphysical/LES model designed to simulate the Twomey effect. *Atmos. Res.,* 33, 207–233.

[3] Khvorostyanov, V. I., 1995: Mesoscale processes of cloud formation, cloud-radiation and their modeling with explicit microphysics. *Atmos. Res.,* 39, 1–67.

[4] Reisin, T., Z. Levin, and S. Tzvion, 1996: Rain production in convective clouds as simulated in an axisymmetric model with detailed microphysics. Part I: Description of the model.*J. Atmos. Sci.,* 53, 497–519.

[5] Reisner, J., R. J. Rasmussen, and R. T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 Mesoscale Model. *Quart. J. Roy. Meteor. Soc.,* 124B, 1071–1107.

[6] Harrington, J. Y., T. Reisin, W. R. Cotton, and S. M. Kreidenweis, 1999: Cloud resolving simulations of Artic stratus. Part II: Transition-season clouds. *Atmos. Res.,* 51, 45–75.

[7] Yin, Y., Z. Levin, T. Reisin, and S. Tzivion, 2000: Seeding convective clouds with hygroscopic flares: Numerical simulations using a cloud model with detailed microphysics. *J. Appl. Meteor.,*39, 1460–1472.

[8] Jiang, H., G. Feingold, W. R. Cotton, and P. G. Duynkerke, 2001: Large-eddy simulation of entrainment of cloud condensation nuclei into the arctic boundary layer: May 18, 1998 FIRE/ SHEBA case study. *J. Geophys. Res.,* 106, 15 113–15 122.

[9] Rasmussen, R. M., I. Gersedi, G. Thompson, K. Manning, and E. Karplus, 2002: Freezing drizzle formation in stably stratified layer clouds: The role of radiative cooling of cloud droplets, cloud condensation nuclei, and ice initiation. *J. Atmos. Sci.,*59, 837–860

[10] Koenig, L. R., and F. W. Murray, 1976: Ice-bearing cumulus cloud evolution: Numerical simulation and general comparison against observations. *J. Appl. Meteor.,* 15, 747–762.

[11] Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl.Meteor.,* 22, 1065–1092.

[12] Cotton, W. R., G. J. Tripoli, R. M. Rauber, and E. A. Mulvihill, 1986: Numerical simulation of the effects of varying ice crystal nucleation rates and aggregation processes on orographic snowfall. *J. Appl. Meteor.,* 25, 1658–1680.

[13] Ferrier, B. S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Part I: Description. *J. Atmos. Sci.,* 51, 249–280.

[14] Walko, R. L., W. R. Cotton, M. P. Meyers, and J. Y. Harrington, 1995: New RAMS cloud microphysics parameterization. Part I: The single-moment scheme. *Atmos. Res.,* 38, 29–62.

[15] Meyers, M. P., R. L. Walko, J. Y. Harrington, and W. R. Cotton, 1997: New RAMS cloud microphysics parameterization. Part II: The two-moment scheme. *Atmos. Res.,* 39, 3–39.

[16] Reisner, J., R. J. Rasmussen, and R. T. Bruintjes, 1998: Explicit forecasting of supercooled liquid water in winter storms using the MM5 Mesoscale Model. *Quart. J. Roy. Meteor. Soc.,* 124B, 1071–1107.

[17] Straka, J. M., and E. D. Mansell, 2005: A bulk microphysics parameterization with multiple ice precipitation categories. *J.Appl. Meteor.,* 44, 445–466

[18] Morrison, H., J. A. Curry, and V. I. Khvorostyanov, 2005: A new double-moment microphysics parameterization for application in cloud and climate models. Part I: Description. *J. Atmos.Sci.,* 62, 1665–1677.

[19] Kessler, E., 1969: On the Distribution and Continuity of Water Substance in Atmospheric Circulations, Meteor. Monogr., No.32, Amer. Meteor. Soc., 84 pp.

[20] Hong, S.-Y., Lim, K., Kim, J., Lim, J., Dudhia, J., 2009. Sensitivity study of cloudresolving convective simulations with WRF using two bulk microphysical parameterizations: ice-phase microphysics versus sedimentation effects. J. Appl. Meteor. Clim. 48, 61–76.

[21] Grubisic, V., R. K. Vellore, and A. W. Huggins, 2005: Quantitative precipitation forecasting of wintertime storms in the Sierra Nevada: Sensitivity to the microphysical parameterization and horizontal resolution. *Mon. Wea. Rev.,* 133, 2834– 2859.

[22] Liu, C., Moncrieff, M.W., 2007. Sensitivity of cloud-resolving simulations of warm-season convection to cloud microphysics parameterizations. Mon. Wea. Rev. 135, 2854–2868.

[23] Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, Xiang-Yu. H, W. Wang, and J. G. Powers (2008), A description of the advanced research WRF Version 3, NCAR Tech. Note NCAR/TN□475+STR, Natl. Cent. for Atmos. Res., Boulder, Colo.

[24] Chen, S.-H. and Sun, W.-Y.: A one dimensional, time dependent cloud model, J. Meteor. Soc. Japan, 60, 99–118, 2002.

[25] Thompson, G., R. M. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Wea. Rev.,* 132, 519–542.

[26]Richard H. Grumm, 2010: The Madeira Island Floods of 20 February 2010, *National Weather Service report, USA*

[27] Lafore, J.-P., J.Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fischer, P. Héreil, P. Mascart, V. Masson, J.-P. Pinty, J.-L. Redelsperger, E. Richard, and J. Vilà-Guerau de Arellano. 1998. The Meso-NH Atmospheric Simulation System. Part I: adiabatic formulation and control simulations. Scientific objectives and experimental design. Ann. Geophys. 16: 90-109.

[28] Pinty, J.-P. and P. Jabouille, 1998: A mixed-phase cloud parameterization for use in mesoscale non-hydrostatic model: simulations of a squall line and of orographic precipitations. *Proc. Conf. of Cloud Physics, Everett, WA, USA, Amer. Meteor. soc., Aug. 1999,* 217 – 220

[29] Salgado, R., and P. Le Moigne. 2010. Coupling of the FLake model to the Surfex externalized surface model, *Boreal Env. Res.,* 15, 231-244.

[30] Bechtold, P., E. Bazile, F. Guichard, P. Mascart, and E. Richard. 2001. A mass-flux convection scheme for regional and global models. *Q. J. R. Meteorol. Soc.*127: 869-886.

[31] Borcrette, J.-J.: Radiation and cloud radiative properties in the European Center for Medium-range Weather Forecasts forecasting system, J. Geophys. Res., 96, 9121–9132, 1991.

[32] ECMWF: 2011, IFS documentation, technical report, Reading, U. K., http://www.ecmwf.int/research/ifsdocs/, last access: 15 Apr 2011.