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Numerical simulations of significant orographic precipitation in Madeira island

Flavio Tiago Couto [a,*], Véronique Ducrocq [b], Rui Salgado [c], Maria João Costa [c]

[a] Instituto de Ciências da Terra — Polo de Évora, Departamento de Física, Instituto de Investigação e Formação Avançada — IIFA, Universidade de Évora, Rua Romão Ramalho, 59, 7000-671, Évora, Portugal

[b] CNRM-GAME, UMR3589, Météo-France & CNRS, Toulouse, France

[c] Instituto de Ciências da Terra — Polo de Évora, Departamento de Física, Escola de Ciências e Tecnologia, Universidade de Évora, Évora, Portugal

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ABSTRACT

High-resolution simulations of high precipitation events with the MESO-NH model are presented, and also used to verify that increasing horizontal resolution in zones of complex orography, such as in Madeira island, improve the simulation of the spatial distribution and total precipitation. The simulations succeeded in reproducing the general structure of the cloudy systems over the ocean in the four periods considered of significant accumulated precipitation. The accumulated precipitation over the Madeira was better represented with the 0.5 km horizontal resolution and occurred under four distinct synoptic situations. Different spatial patterns of the rainfall distribution over the Madeira have been identified.

1. Introduction

Heavy precipitation events are one of the major factors inducing floods, which leads to the constant improvement in numerical models and measurement techniques, also reported from several studies worldwide. Accurately representing precipitation systems in atmospheric models is still however challenging, and better forecasts are mandatory to issue early warnings mainly for urban areas. The general environments causing heavy precipitation are well documented for many regions around the world (e.g. Lin et al., 2001), however, the increase of the knowledge about these heavy events on specific regions is needed, for example, over small mountainous and island regions.

The impact of the orography in the formation or enhancement of the precipitation over mountainous islands have been found dependent of the geographic aspects of the island and synoptic conditions associated to each precipitating event (e.g. Wang et al., 2014a; Smith et al., 2012). For example, Wang et al. (2014b), studying two heavy precipitation events over Taiwan showed that the synoptic circulation was dominant over the diurnal effects, and the steep topography of Taiwan was essential to increase the rainfall amount over and near Taiwan. On the other hand, heavy precipitation events may also be induced by several orographic effects. Chen et al. (2010, 2011) identified that orographic lifting and convergence at low-levels caused by the flow deflection due the local orography was related to other precipitation events over Taiwan. In Jeju island, for example, the orographic blocking inducing convergence zones or the intensification of convective cells in the lee side of the elliptical island were some mechanisms favouring heavy precipitation (Lee et al., 2010, 2014).

More attention has been dedicated to the study of precipitation over the Madeira island, a mountainous Portuguese island located in the mid-latitudes (32°75'N and 17°W), after the disaster on February 20, 2010 (e.g., Luna et al., 2011; Levizzani et al., 2013). It was the most remarkable event in terms of heavy precipitation observed in Madeira, with high impact at the surface. The study of the winter 2009/2010 by Couto et al. (2012) highlighted the role of an atmospheric river in six out of the seven cases of heavy precipitation over the island, providing significant amount of water vapour from the tropics for the triggering or enhancement of precipitation by the island terrain. Couto et al. (in press) further examined the characteristics of the synoptic environment by carrying out a 10-year analysis of precipitation over the island and satellite water vapour fields over the Atlantic Ocean during the winter periods. They found that atmospheric rivers when transporting large amounts of precipitable water, are well correlated with heavy precipitation occurrence over the island. However, there are many other heavy precipitation events over the island that are not favoured by atmospheric rivers, but extra-tropical weather systems. In order to further study heavy precipitation over Madeira associated with extra-tropical weather systems, the same approach as in Couto et al. (2012) is followed by simulating all the heavy precipitation events of autumn 2012, the second wettest season in the 10-year period studied by Couto et al. (in press).

The first aim of this paper is to present these high-resolution simulations and their performance. Contrary to Couto et al. (2012), the

* Corresponding author.
E-mail addresses: couto.ft@gmail.com (F.T. Couto), veronique.ducrocq@meteo.fr (V. Ducrocq), rsal@uevora.pt (R. Salgado), mjcosta@uevora.pt (M.J. Costa).

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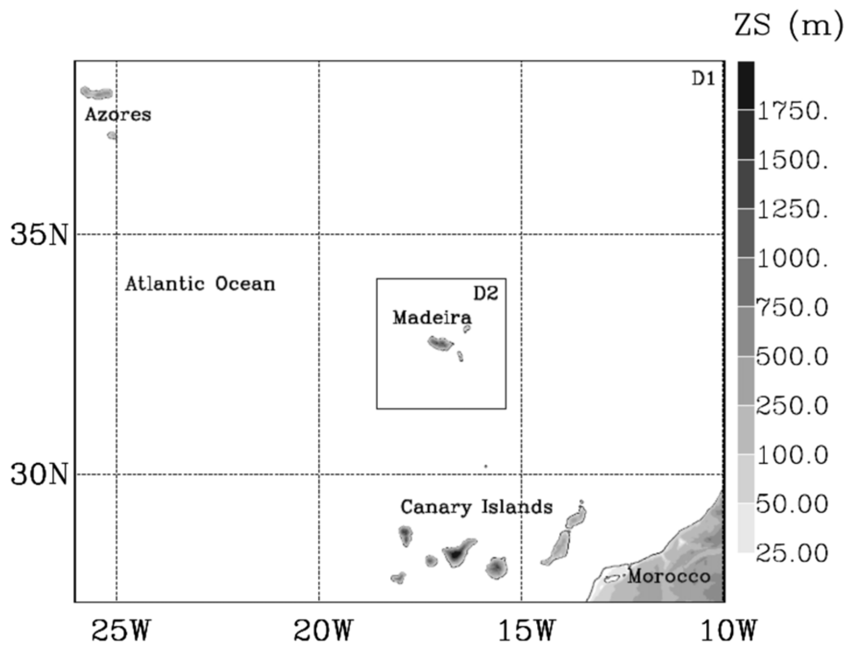

Fig. 1. Location of the Madeira island and the MESO-NH configuration. The larger domain (D1) at 2.5 km horizontal resolution, and the inner domain (D2) at 0.5 km grid spacing. The orography was obtained from the SRTM database.

convection-permitting simulations are performed in the present study over large model domains (Fig. 1) in order not only to describe at high-resolution convection and precipitation enhancement over the Madeira island but also the associated larger-scale cloudy weather systems over the surrounding ocean region.

The Madeira island is a small island (58 km × 23 km), characterized by an east–west mountain chain with peaks above 1800 m. It is thus expected that the simulation of the precipitation distribution over the mountainous island will require a proper horizontal resolution able to describe the main terrain features of the island. The second aim of the study is thus to verify that increasing horizontal resolution in zones of complex orography, such as in Madeira island, improve the simulation of the spatial distribution and total precipitation.

This article is divided into four sections as follows. The data, numerical experiments and methodology are described in Section 2, followed by the results and discussion in Section 3, and conclusions in Section 4.

2. Data, numerical experiments and methodology

The observed precipitation over the 2012 autumn was characterized using the 12 meteorological stations (Ponta do Sol (986), Quinta Grande (984), Areeiro (973), Santo da Serra (975), Funchal (522), Caniçal (978), Calheta (990), Lombo da terça (980), Bica da Cana (970), São Vicente (967), Santana (965), and Santana/ S. Jorge (960)), and distributed over the island and belonging to the Portuguese Sea and Atmosphere Institute, IPMA (no weather radar covering the island). The Areeiro weather station (see Fig. 5c), located in the south-eastern part of the island (altitude of 1590 m, close to the maximum height), allowed us to highlight the 2012 seasonal distribution of the daily precipitation, and to select the precipitating periods that have been simulated in this study (Fig. 2a). The second part of the season was more propitious to heavy precipitation events, with rainfall exceeding 100 mm day^{-1} in four days. These four events have thus been selected for this study, and simulations of the periods encompassing them have been designed. Table 1 indicates the start and end of each simulation.

The numerical simulations are performed using the non-hydrostatic research model MESO-NH (Lafore et al., 1998). The initial and boundary conditions are provided by the 6-hourly operational ARPEGE analyses (Courtier et al., 1991). A first series of simulations (called hereafter CTRL) are performed using a 1500 km × 1250 km grid domain (D1) at 2.5 km horizontal resolution. For the second series of simulations (called hereafter EXP) a two-way interactive inner domain (D2) at 500 m horizontal resolution is added prior to the start of the heavy precipitation period (Fig. 1). In the CTRL simulations, the model terrain is obtained from the GTOPO30 database, whereas in the EXP simulations it is obtained from the SRTM database. The periods simulated are shown in Fig. 2b–e. The dashed-line rectangles in blue and green represent the simulations with 2.5 km (CTRL and EXPD1) and 0.5 km (EXPD2) resolution, respectively. The inner domain is centred over the Madeira island, covering an area of 300 km × 300 km. The vertical grid is composed of 55 height-based terrain-following levels. With respect to the previous study of Couto et al. (2012), the horizontal resolutions are increased (3 km/1 km comparing to 2.5 km/0.5 km here) but the main difference are mostly the larger model domains considered, with about 100 times more grid-points for each domain. More realistic simulations are thus not only expected for precipitation enhanced by the island orography but also for the larger-scale precipitating systems affecting the island.

The physical package is rather similar to the ones successfully used in past studies of heavy precipitation events over complex terrain (e.g. Ducrocq et al., 2008). The model is also able to correctly reproduce the microphysical pattern and dynamical structure of convective systems (e.g., Cohuet et al., 2011; Pujol et al., 2011). The one-moment microphysical scheme predicts the mass mixing ratios of cloud water, rain, graupel, snow, and ice (ICE3; Pinty and Jabouille, 1998). The turbulence scheme is based on a 1.5-order closure (Cuxart et al., 2000). Verrelle et al. (2015) pointed out the necessity to deal with horizontal turbulent fluxes at kilometric resolutions for grid mesh smaller than 2 km. Then, in the inner 500 m resolution domain, the full 3D turbulent fluxes scheme was activated, while in the 2.5 km domain only the vertical fluxes were considered. Shallow convection is parameterized according to Pergaud et al. (2009) for the 2.5-km domain only. The radiation parameterization is based on the Rapid Radiative Transfer Model (Mlawer et al., 1997).

It is well known that the density of raingauge observations is essential in order to achieve a good quantitative evaluation of the model performance to simulate the complex behaviour of the precipitation over a steep terrain. In our case, there are only observations on the island and with poor coverage in its mountainous interior. Nevertheless, the quality of the simulated accumulated precipitation in each event is assessed