Physics and Chemistry of the Earth 94 (2016) 56–65

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

On the relationship between atmospheric water vapour transport and extra-tropical cyclones development

Juan A. Ferreira [a, *], Margarida L.R. Liberato [a, b], Alexandre M. Ramos [b]

[a] Departamento de Engenharias, Escola de Ciências e Tecnologia, Universidade de Trás-os-Montes e Alto Douro, UTAD, Quinta de Prados, 5000-801 Vila Real, Portugal

[b] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 30 March 2015
Received in revised form
2 November 2015
Accepted 21 January 2016
Available online 3 February 2016

Keywords:
Regional climate modelling
WRF model
Water vapour
Explosive extra-tropical cyclones
Iberia/North Atlantic

ABSTRACT

In this study we seek to investigate the role of atmospheric water vapour on the intensification of extra-tropical cyclones over the North Atlantic Ocean and more specifically to investigate the linkage between atmospheric rivers' conditions leading to the explosive development of extra-tropical cyclones. Several WRF-ARW simulations for three recent extra-tropical storms that had major negative socio-economic impacts in the Iberian Peninsula and south-western Europe (Klaus, 2009; Gong, 2013 and Stephanie, 2014) are performed in which the water vapour content of the initial and boundary conditions are tuned. Analyses of the vertically integrated vapour transport show the dependence of the storms' development on atmospheric water vapour. In addition, results also show changes in the shape of the jet stream resulting in a reduction of the upper wind divergence, which in turn affects the intensification of the extra-tropical cyclones studied. This study suggests that atmospheric rivers tend to favour the conditions for explosive extra-tropical storms' development in the three case studies, as simulations performed without the existence of atmospheric rivers produce shallow mid-latitude cyclones, that is, cyclones that are not so intense as those on the reference simulations.

1. Introduction

One of the major natural hazards in the extratropics are intense winter storms, which represent one of the most costly natural disasters in Europe and are responsible for socioeconomic damages, both on human-built structures and on forested areas. Examples of recent episodes of severe windstorms which caused significant damage and substantial economic losses on south-western Europe are storms Klaus[1] (January 2009; Liberato et al., 2011), Xynthia (February 2010; Liberato et al., 2013), Gong (January 2013; Liberato, 2014) and Stephanie (February 2014; Ferreira et al., 2014a). All these mid-latitude extreme storms crossed the North Atlantic (NA) Ocean, heading towards Europe while experiencing an explosive development[2] at unusual lower latitudes – along the edge of the dominant North Atlantic storm track – thus preventing an early forecast and warning. Most of these storms made landfall on the Iberian Peninsula with an uncommon intensity and consequently with high wind and precipitation impacts. It is worth noting that documentary evidence and historical studies on windstorms affecting Portugal refer to only few events, such as the ones occurring in February 1941 (Muir-Wood, 2011; Freitas and Dias, 2013) and in November 1724, which was one of the most destructive storms ever experienced in Portugal since the early 17th century (Domínguez-Castro et al., 2013).

Some high impact events in western Europe are also characterized by continuous, heavy precipitation and even flooding (e.g. Liberato et al., 2012; Liberato, 2014; Trigo et al., 2014; Stohl et al., 2008; Lavers et al., 2011). This has motivated the investigation on the origin of the moisture responsible for the anomalous continuous rainfall being the atmospheric rivers (ARs) one of the main responsible for this (Liberato and Trigo, 2014; Ramos et al., 2015; Lavers et al., 2013). It was found that ARs are relatively narrow regions of concentrated water vapour (WV) and strong wind responsible for intense horizontal moisture transport in the lower

* Corresponding author.
E-mail address: juan@utad.pt (J.A. Ferreira).

[1] The storm names employed herein are as given by the Institute of Meteorology of the Freie Universität Berlin and as used by the German Weather Service (Source: http://www.met.fu-berlin.de/adopt-a-vortex/historie/).

[2] According to the criterion used by Sanders and Gyakum (1980), a rapidly deepening extra-tropical surface cyclone with a central pressure fall at sea level of at least ($24^*\sin\phi/\sin60^{\circ}$) hPa in 24 h, at latitude ϕ, is classified as explosive cyclone or 'bomb'.

http://dx.doi.org/10.1016/j.pce.2016.01.001

atmosphere (Newell et al., 1992; Ralph et al., 2006). More than 90% of the meridional WV transport in the midlatitudes occurs in these ARs, although they cover less than 10% of the area of the globe (Zhu and Newell, 1998).

Moreover in previous studies it has been shown that the explosive development at such low latitudes is also driven by the presence of an AR (e.g. Kuo et al., 1991; Zhu and Newell, 1994; Ralph and Dettinger, 2011), that is, by a (sub)tropical moisture export over the western and central (sub)tropical Atlantic which converges into the cyclogenesis region and then moves along with the storm towards Europe in addition to favourable jet stream conditions resulting from the southerly displacement of a strong upper-air stream (Liberato, 2014).

Within the framework of the STORMEx project (Mid-Latitude North Atlantic Extreme Storms Variability: Diagnosis, Modelling Dynamical Processes and Related Impacts on Iberia) research has been performed in order to understand which dynamical mechanisms favour the development and explosive intensification of extra-tropical cyclones at such lower than usual latitudes, thus preventing an early forecast and warning. In this study the development of the above mentioned storms is analysed with simulations from the mesoscale Weather Research and Forecasting (WRF) Model, forced by ERA Interim input data. We present a numerical simulation experiment applied to three recent extra-tropical storms (Klaus, 2009; Gong, 2013 and Stephanie, 2014) which aims at understanding the role of ARs on the explosive development of NA storms. The paper is organized as follows. In Section 2 the details of the methods, datasets and model setup design are presented. Results from the several numerical experiments are shown in Section 3 and finally main conclusions are presented in Section 4.

2. Methods and data

2.1. Numerical experiments

The mesoscale model used in the present work is the Weather Research & Forecasting Model – Advanced Research model (WRF-ARW) version 3.5 (Skamarok et al., 2008). The initial and boundary conditions for the large-scale atmospheric fields of pressure, wind, humidity and temperature, as well as initial soil parameters (soil water, moisture and temperature) and sea surface temperature (SST), are given by the 0.75° × 0.75° ERA-Interim reanalysis data (Dee et al., 2011) from the European Centre for Medium-range Weather Forecasts (ECMWF) for the periods summarized in Table 1.

In order to have a good representation of the complete genesis and development of the explosive storms that affected Europe as well as the structure of the ARs we need to include both the NA basin extension from the Gulf Stream region to the Iberian Peninsula and most of the subtropical NA Ocean. Thus, the model domain configuration consists of a domain with relatively coarse 27 km horizontal resolution and 32 vertical levels, with the model top at 50 hPa.

The main physical parametrizations (Table 2) were chosen after the works of Ferreira et al. (2008) who performed a sensitivity test to 24 combinations of physical parametrization schemes (short wave radiation, cumulus, microphysics and surface-planetary boundary layer) in 36 periods during 2006, comparing model results of temperature, mean sea level pressure (MSLP), humidity and wind speed with observations along the continental Portuguese area. This parametrization setup was then used to study two extreme precipitation events: Lisbon (February 2008) and Madeira (February 2010) (Ferreira et al., 2014b and Luna et al., 2011; respectively) with satisfactory results in terms of model representation of the observed precipitation. Thus, the parametrization setup used in the present study include the WRF Single-Moment 6-class microphysics scheme (Hong and Lim, 2006), Duhdia shortwave radiation (Dudhia, 1989), Rapid Radiative Transfer Model (RRTM) longwave radiation model (Mlawer et al., 1997), the Noah Land Surface Model (Chen and Dudhia, 2001), the Yonsei University (YSU) boundary later parametrization (Noh et al., 2003) and the Grell-3D scheme (Grell and Devenyi, 2002).

Table 1
Simulation period for each storm.

Storm name	Simulation period
Klaus	06 UTC 22/01/2009–06 UTC 24/01/2009
Gong	12 UTC 17/01/2013–12 UTC 19/01/2013
Stephanie	00 UTC 08/02/2014–00 UTC 10/02/2014

Table 2
Physical parameterization schemes.

Physics	Parameterization
Microphysics	WSM6
Cumulus	Grell3D
L. W. Radiation	RRTM
S. W. Radiation	Dudhia
Boundary Layer	Yonsei University
Surface Layer	Monin-Obukhov
Surface Model	Noah land-surface model

In some applications of models to extra-tropical storms, the use of a nudging technique to constrain the large scale features of the model to the analysis fields is performed (Ludwig et al., 2013). However, as the objective of this research is to analyse the response of the system to modifications made in the initial and boundary conditions of WV, with the aim of removing the effect of ARs from these conditions, the grid nudging capability of WRF was not applied. Thus the model is used as in a numerical weather prediction simulation, in runs starting 48 h before the maximum intensification instant of each storm.

In order to investigate the effect that atmospheric WV has on the development of extra-tropical storms, 11 experiments with modified initial and boundary conditions of humidity were made. First, the control run simulation consists of specifying the undisturbed initial and boundary conditions from the ERA-Interim reanalysis for the initial time of each storm (see Table 1); this serves as reference run (CNTRL). Subsequently, 10 sensitivity experiments are performed, consisting of simulations with modified humidity initial and boundary conditions. These were defined as fractions of the control run humidity, ranging from 90% to 0% of the control run humidity, by increments of 10%. These resulted in 11 simulations per storm. However, for the sake of clarity, only results from the control run (CNTRL) simulations as well as from 80% (SH80), 50% (SH50) and 0% (SH00) of relative humidity are shown.

The numerical experiments described above were applied to the 3 explosive extra-tropical storms that recently affected the weather conditions and had significant socio-economic impacts in the Iberian Peninsula (see Table 1): Klaus (January 2009; Liberato et al., 2011), Gong (January 2013; Liberato, 2014) and Stephanie (February 2014; Ferreira et al., 2014a).

2.2. Observational data

The first goal of this study was to validate the simulations of the 3 storms. Comparison of model precipitation with observed data and in particular with gridded precipitation data that enables the analysis of spatial patterns are of prime importance in the