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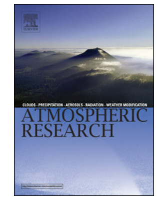

The added value of convection permitting simulations of extreme precipitation events over the eastern Mediterranean

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ABSTRACT

Climate change is expected to substantially influence precipitation amounts and distribution. To improve simulations of extreme rainfall events, we analyzed the performance of different convection and microphysics parameterizations of the WRF (Weather Research and Forecasting) model at very high horizontal resolutions (12, 4 and 1 km). Our study focused on the eastern Mediterranean climate change hot-spot. Five extreme rainfall events over Cyprus were identified from observations and were dynamically downscaled from the ERA-Interim (EI) dataset with WRF. We applied an objective ranking scheme, using a 1-km gridded observational dataset over Cyprus and six different performance metrics, to investigate the skill of the WRF configurations. We evaluated the rainfall timing and amounts for the different resolutions, and discussed the observational uncertainty over the particular extreme events by comparing three gridded precipitation datasets (*E*-OBS, APHRODITE and CHIRPS). Simulations with WRF capture rainfall over the eastern Mediterranean reasonably well for three of the five selected extreme events. For these three cases, the WRF simulations improved the ERA-Interim data, which strongly underestimate the rainfall extremes over Cyprus. The best model performance is obtained for the January 1989 event, simulated with an average bias of 4% and a modified Nash-Sutcliff of 0.72 for the 5-member ensemble of the 1-km simulations. We found overall added value for the convection-permitting simulations, especially over regions of high-elevation. Interestingly, for some cases the intermediate 4-km nest was found to outperform the 1-km simulations for low-elevation coastal parts of Cyprus. Finally, we identified significant and inconsistent discrepancies between the three, state of the art, gridded precipitation datasets for the tested events, highlighting the observational uncertainty in the region.

1. Introduction

While global climate projections for temperature, which indicate a general warming, appear to be reasonably robust, this is not the case for precipitation changes (Collins et al., 2013; Lelieveld et al., 2016). Model results and measurements can vary considerably and depend strongly on the region of interest. Discrepancies, even in the sign and the amount of precipitation changes, can occur among climate models. Accordingly, the uncertainty for future climate change projections is high, especially for extreme weather events (IPCC, 2012).

The broader Mediterranean region is, according to observations and future climate projections, a hot spot of climate change (Diffenbaugh and Giorgi, 2012). This is mainly related to the fact that temperature and precipitation are changing in an opposite direction, intensifying environmental stress in the region (Lelieveld et al., 2012; Zittis et al., 2014a). In this type of arid, water-stressed environments improved knowledge and modelling of the hydrology is needed to provide better projections of the inflow of water to dams and of flood hazards, for the development of water allocation strategies, the sustainable exploitation of groundwater resources, and flood protection. Although a reduction in precipitation and prolonged droughts will likely be a most significant impact of climate change in the region, changes in extremes of rainfall are also expected (Paxian et al., 2015; Kitoh and Endo, 2016). These rare events, which can cause human casualties and significant infrastructure damage, are most of the times difficult to reproduce by models.

The horizontal grid spacing of current global climate models (typically100–200 km) is usually not sufficient for impact studies and further downscaling is required. The most crucial model components for rainfall generation are the parameterization schemes of convection and microphysical processes that occur on sub-grid scales. These processes in atmospheric models are empirically described either because the complexity and small scales involved make them too computationally expensive to be modeled or because there is insufficient knowledge about a specific process to represent it mathematically (Warner, 2011). The widely-used Weather Research and Forecasting (WRF) model has a large number of available schemes for the parameterization

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of each process, which can significantly alter the produced precipitation properties in terms of type, amounts or duration (Skamarock et al., 2008). One of the main reasons for these discrepancies is that different schemes were designed with different conceptual underpinnings and tunable parameters that are not universal and are also quite uncertain (Cossu and Hocke, 2014).

The objective of this study is to evaluate the performance of different convection and microphysics parameterizations of WRF, driven by reanalysis data, for the dynamic downscaling of precipitation extremes over Cyprus and the broader region of the eastern Mediterranean at 12-, 4- and 1-km resolution. Since there is no universal optimum setup, we test a large number of WRF configurations in order to investigate which ones are most skillful in reproducing five extreme precipitation events that have occurred over the region of interest. Each combination of four cumulus and five microphysics schemes was utilized while the rest of the model physics was identical. Our 20-member ensemble includes the Lin (Lin et al., 1983), WSM6 (Hong and Lim, 2006), Thompson (Thompson et al., 2008), Ferrier (NOAA, 2001) and WDM6 (Lim and Hong, 2010) microphysics schemes and the Kain-Fritsch (Kain, 2004), Betts–Miller–Janjic (Janjic, 1994), Grell–Freitas (Grell and Freitas, 2014) and Grell 3-D Ensemble (Grell and Devenyi, 2002) convection schemes. This selection was based on the performance of these schemes in similar applications such as the simulation of exceptionally extreme precipitation events (Luo et al., 2010; Tapiador et al., 2012; Mahbub Alam, 2014; Cassola et al., 2015; Meredith et al., 2015a; Remesan et al., 2015; Spiridonov et al., 2017), precipitation forecasting (Bukovsky and Karoly, 2009; Clark et al., 2009; Ruiz et al., 2010; Givati et al., 2012; Kioutsioukis et al., 2016) or climate applications (Evans et al., 2012; Soares et al., 2012; Ratna et al., 2014; Zittis et al., 2014b; Katragkou et al., 2015). All simulations address a period of 15 days with the rainfall maximum more or less centered within this period. This might not be optimal for some applications, such as weather forecasting. However, we aim to investigate the model skill from a climate mode perspective, i.e. to reduce the dependence on initial conditions.

An increasing number of studies for various locations and types of experiments, and based on different regional models indicate a relatively realistic representation of precipitation processes in high-resolution convection-permitting simulations (Klemp, 2006; Prein et al., 2013; Cassola et al., 2015; Davolio et al., 2015; Fosser et al., 2015; Meredith et al., 2015b; Prein et al., 2015). Therefore, after applying an objective ranking scheme for identifying the best performing WRF configurations at 4-km resolution, we further downscaled them to 1-km to explore if convection-permitting simulations can reproduce the selected extreme precipitation events more accurately. Accordingly, we quantify the added value of each step of the downscaling.

When it comes to model evaluation the availability and quality of reference observations is of great importance, while it is especially critical for atmospheric variables such as precipitation that can significantly vary in space and time. The sparse network of available meteorological stations over the broader region highlights the issue of observational uncertainty (Gómez-Navarro et al., 2012; Tanarhte et al., 2012). In this context and for the same extreme cases we compare three state-of-the-art gridded observational datasets for the eastern Mediterranean region.

2. Data and methodology

2.1. Model and experimental setup

For our simulations we used the version 3.7.1 of the WRF model. It was driven by the ERA-Interim (EI) reanalysis dataset (Simmons et al., 2006), which provides the initial and boundary conditions. The latter were updated every 6 h. We used the one-way nesting option, downscaling EI ($\approx$80 km) to 12 km (Domain 1: D01) and subsequently to 4 km (Domain 2: D02) and 1 km (Domain 3: D03). The three simulation domains are presented in Fig. 1. The step between the forcing EI data and the coarse 12-km domain is well below the 10:1 ratio that is often referred as a maximum threshold for dynamical downscaling (Giorgi and Gutowski, 2015). Preliminary test simulations of the two-way nesting and nudging options were found not to improve the results for this particular experimental setup and weather events. In particular, we applied a full grid analysis nudging that was found not useful as it was pushing the simulations towards the generally drier ERA-Interim data, at least for the cases the latter was strongly underestimating precipitation. The model was set up with 40 vertical levels and a top at 50 hPa. To be useful for hydro-climatological applications, all model output was saved in hourly intervals. Interestingly, the duration of these simulations was found to be about 20% longer compared to the simulations where daily output was saved. This highlights the fact that input/output (I/O) processes during WRF simulations are not negligible and further optimization might be required.

As described in the Introduction section, our simulations ensemble is based on a combination of five microphysics and four convection parameterizations (Table 1). A brief description of these schemes follows:

Convection (Cumulus) Parameterizations:

- Kain-Fritsch (KF): Deep and shallow convection sub-grid scheme using a mass flux approach with updrafts, downdrafts, entrainment and detrainment processes.
- Betts-Miller-Janjic (BMJ): Column moist adjustment scheme, relaxing towards a well-mixed profile. No explicit updraft or downdraft and cloud detrainment.
- Grell-Freitas (GF): An improved stochastic parameterizations scheme that tries to smooth the transition to cloud-resolving scales. It includes explicit updrafts and downdrafts.
- Grell 3D (G3D) Ensemble scheme with explicit updrafts and downdrafts. It can also be used on high-resolution simulations as subsidence is spread to neighboring columns.

Cloud Microphysics Parameterizations:

- Lin: A sophisticated 5-class scheme (cloud water vapor, rain, ice, snow and graupel processes). It includes ice sedimentation and time-split fall terms. Suitable for real-data high-resolution simulations.
- WRF Single-Moment 6-class scheme (WSM6): A scheme with ice, snow and graupel processes suitable for high-resolution simulations.
- Thompson: A double-moment, 6-class scheme with ice, snow and graupel processes suitable for high-resolution simulations.
- Ferrier: A single-moment, 5-class, efficient scheme with diagnostic mixed-phase processes. It assumes that fractions of water and ice within the column are fixed during advection.
- WRF Double-Moment 6-class scheme (WDM6): Double moment 6-class scheme with graupel. Cloud condensation nuclei (CCN) and number concentration of cloud and rain are also predicted.

Besides the microphysics and cumulus parameterizations, our general configuration includes the Rapid Radiation Transfer Model (RRTMG) short and long-wave radiation (Iacono et al., 2008), the Mellor-Yamada-Janjic (MYJ) Planetary Boundary Layer scheme (Janjic, 1994), in addition to the Noah Land Surface Model (Tewari et al., 2004). Our WRF setup is similar to that of the Cyprus Department of Meteorology, used for operational weather forecasting (Tymvios et al., 2017), at least regarding the radiation and land surface model options. The 20 different setups were tested on the 12 and 4 km resolutions, while only the five best performing configurations were used to drive the 1-km simulations, since the computational cost of the latter was rather high. In this finer grid, the same microphysics scheme was used as for the selected 4-km driving model. However, convection was not parameterized but was explicitly resolved.