Parallel Session A:
Advances in regional downscaling

A2: Convection permitting modelling

POSTER PRESENTATIONS

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-01

Multi-model analysis of triggering of precipitation : impact of model resolution and convection representation, and evolution in a warmer climate

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Despite their horizontal resolution higher than global models, regional climate models still present biases for the simulation of precipitation extremes for both sides of the distribution, with a tendency to simulate too often light precipitation and to underestimate heavy precipitation, making them unreliable for the estimation of future extremes (droughts and flash floods) over the Mediterranean area. In this study, we use a multi-variate statistical relationship between temperature, humidity and precipitation - derived from colocated observations at the supersite SIRTA near Paris - to investigate the triggering of precipitation over the site in several regional climate simulations performed in the framework of Hymex/Med-CORDEX, EURO-CORDEX and the FPS Convection. We test the sensitivity of the triggering to the model resolution - from 50 to 3 km, including convection-permitting simulations. In particular, we evaluate how much the spread between models is modified by the absence of parametrization of deep convection in the simulation. We also assess the spatial variability of the relationship and how it evolves in a warmer climate.

Keywords: Triggering of precipitation, Convection-permitting simulation

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-02

Initial results of the CORDEX FPS on extreme precipitation events in Southeastern South America: dynamical downscaling at convection-permitting resolution

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he CORDEX Flagship Pilot Study (FPS) on extreme precipitation events in Southeastern South America (SESA) aims at studying multi-scale processes and interactions leading to extreme precipitation events. It will foster cooperation with the impacts and user community to obtain actionable climate information from different sources, including both statistical and dynamical downscaling. Regarding the latter, we designed an experimental setup exploring the uncertainties arising from the use of (1) different regional climate models and configurations (ETA, RegCM4, WRF3.8, WRF3.9), (2) different resolutions, with an intermediate resolution nest (20km) to reach convection-permitting resolution (4km) over the target area, (3) different heavy precipitation events and (4) different simulation setups, comparing a "Weather-like" mode, benefiting from predictability arising from initial conditions as in NWP, and a "climate mode", where predictability arises only from the lateral boundary conditions. These driving boundary conditions are taken in all cases from the ERA-Interim reanalysis, in order to compare with observations and leave out global climate modelling uncertainty.

In this work, we present some initial results focusing only on precipitation and exploring the above mentioned uncertainty sources. In particular, we focus on the ability of the models to represent the diurnal cycle of precipitation, total precipitation amount and spatial distribution as compared to the driving reanalysis and several station and gridded observational datasets over the region.

Keywords: convection-permitting simulations, precipitation, diurnal cycle, sensitivity study

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-03

Characterization and predictability of rainfall convective systems in the Sahel : focus on Senegal

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In West Africa, rainfall is a determining factor for the global population consists mostly of rural living on agriculture. In this area, the water cycle has a high variability on all spatial and temporal scales and depends on the dynamics of the system of the West African monsoon. Rainfall is generated by Mesoscale convective systems and squall lines (Mesoscale convective systems multicellular), but also with local storm systems of any size, such as isolated thunderstorms. The spatial and temporal distribution of the seasonal cumulative rainfall depends on the number of occurrence of these various convective systems.

This work highlights the rainfall characteristics at a small scale including that of Senegal center area. Using the synoptic observation network of ANACIM (National Agency of Civil Aviation and Meteorology) to and IRD (Institute of Research for Development) to 12 stations in center of Senegal, Thies, Fatick, Kaolack, Diourbel, Mbour, Bambey from 1960 to 2011. We generally observe a high spatial and temporal variability of the annual total and descriptors of the rainy season. including the onset, wet and dry spells and high impact rainfall or extrems events.

This high spatial and temporal variability is observed between separate stations a few kilometers. Indeed, Diourbel recorded a rain deficit in 2007 season, while for the same year was in surplus Kaolack. We showed the high frequency nature for the short dry and wet spells while the long dry and wet spell are low frequencies and strongly modulate the seasonal accumulation of rain. Consequently, to understand this high rainfall variability in the Sahel, it is necessary to distinguish between local systems and meso-scale convective systems (MCSs). Thus, we first made a climatology of different types of convective systems observed in the Sahel from satellite data (TRMM), observations and radar (NPOL). This classification allowed us to properly quantify the contribution of each type of system on the cumulative rainfall in the area. The originality of this study lies in the characterization of convective activity via OLR (Outgoing longwave radiation) data just before and after a long dry and wet spell. Indeed, the duration of such extreme breaks will dry the soil which helps to decrease the latent flux to increase the sensitive flux, which will warm the atmosphere. Thus, the mesoscale convective systems (MCS) and the squall lines can not be supplying moisture and therefore they will dissipate.

Keywords: Rainfall, MCSs, Squall lines, Dry and Wet Spell

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-04

Assessment of the capability of the WRF-ARW model at convective permitting resolution to reproduce extreme precipitation events over Southeast South America: A Case Study Approach

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Southeastern South America (SESA) is one of the regions in the world most affected by extreme mesoscale convective systems and their associated extreme precipitation. Many authors have studied the mesoscale forcings that trigger convection on the region, being the Andes mountain range and the South American Low Level Jet key factors in the development of convective storms. The small spatial scale of these systems and the fact that the intensity of extreme precipitation has been increasing over SESA due to global warming during the last decade, reveals the importance of understanding how these systems may change in the future. Several studies show that high resolution convective permitting Regional Climate Models (RCMs) improve the representation of the diurnal cycle and intensity of precipitation associated with deep convection, compared to coarser convection parameterized RCMs. In this context, the aim of this study is to assess the capability of the WRF-ARW at convective permitting (CP) resolution in representing the precipitation associated with these events over SESA, compared with RCMs, in two ways. First, in order to determine if the CP improves the results of RCMs and second, if increased spatial resolution in a CP model improves the results, taking into account the computational cost of high resolution simulations. Three extreme precipitation events have been selected over the region and three simulations have been carried out, one with parameterized convection at 12 km spatial resolution, and two simulations at 4 km and 2.4 km in which convection was not parameterized but resolved explicitly. The simulated precipitation was compared against CMORPH satellite estimations and the ability of the simulations was measured using the Fractional Skill Score. The results show that CP simulations have better agreement with the observations (diurnal cycle and intensity) than RCM simulations. No significant difference was found between the 4 km and 2.4 km simulations.

Keywords: SESA,Convective permitting simulations,extreme precipitation events,high resolution

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-05

Exploration of new insights of land-atmosphere interaction unsing FPS Alps convection permitting experiment

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The CORDEX FPS Alps experiment establishes a first-of-its-kind in regional climate dynamic downscaling experiments by using the models at cloud resolving resolution. This should enable the study of the land-atmosphere interaction under the unprecedented paradigm of the very high resolution for a multi-year period. This resolution should allow the study of different land-atmospheric processes which were unresolved at previous similar lower resolution exercises.

In this study we present a preliminary exploration of the suitability of this new paradigm to study various land-atmosphere interaction processes. The main focus is to analyze the impact of the heterogeneity of the surface fluxes on the development of convection during summer, while other subjects are the representation of katabatic/anabatic winds and the land/sea-breeze. The study attempts to analyze some of these different features in terms of: (1) how they are represented in the simulations, (2) fit-for-purpose of the resolution (3) and suitability of the complexity of the physical parameterizations.

This study aims to explore, open and discuss the new opportunities that (should) arise from this kind climate exercises. Which land-atmosphere dynamics or other interactions can be expected to be properly resolved and which aspects are still required to be improved from the modeling community in order to properly represent and analyze the unresolved ones.

Keywords: Convection Permitting, Land-atmosphere interaction

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-06

Soil moisture-temperature coupling in a CORDEX FPS convection-permitting WRF RCM ensemble

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High-resolution, convection-permitting regional climate models (CPRCMs), with a more detailed representation of land surface properties and an explicit treatment of deep convection, have shown improvements in the simulation of meteorological and climate system processes. Using an ensemble of CPRCM evaluation simulations for a central European domain, this study investigates results from the application of drought- and heatwave-related indices in the context of soil-moisture temperature coupling as part of the terrestrial segment of the land-atmosphere coupling. Analyses focus on differences (i) between the nested convection-permitting resolution 3km runs and their reference 15km driving runs, and (ii) among 11 members of a multi-physics evaluation experiment. A higher resolution leads not only to different precipitation timings, distributions and amounts; the larger heterogeneity at the surface and subsurface, as well as the larger orographic variance, lead, e.g., to altered terrestrial water cycle processes, which in turn affect the coupling. The CPRCM base data used in this study are from an ERA-Interim driven evaluation experiment from 2000 to 2009 that is part of the WCRP CORDEX Flagship Pilot Study (FPS) "Convective phenomena at high resolution over Europe and the Mediterranean". Here we use 11 WRF ensemble members from 11 international FPS participant groups, as a subset of the overall FPS ensemble. The WRF models are run in a one way double-nesting setup, with a joint 15km European and a FPS 3km Alpine domain. To allow for a clear separation of cause and effect relationships, these runs were done in a highly constrained setup, using the same spin-up, initial and boundary condition files and a common model configuration with systematically altered microphysics, boundary layer, surface layer, aerosol, and shallow cumulus convection schemes as well as different land surface models.

Keywords: CORDEX FPS, L-A coupling, convection-permitting,WRF RCM

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-07

Simulated climate extremes in the Yangtze River Basin, using the regional climate model WRF

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Abstract ： A 9-yr(2005-2013) Weather Research and forecast(WRF) Model regional climate simulation was evaluated over Yangtz River Basin (YRB). The analysis assesses the spatial and temporal characteristics of climate extremes, using a selection of climate indices. Two nested domains at 9- and 1.5-km resolution are examined over the research area, using convection parameterization scheme or convection permitting scheme, separately . The simulation results are compared with the observed temperature and rainfall to verify mode suitability. The results show that: 1) At both coarse and fine resolutions, WRF can simulate the temporal and spatial distribution of precipitation and temperature, including extreme climate events; 2) convection permitting significantly improves the simulation results for precipitation; 3) the model has a good reproduction of the average temperature, but the simulation of high temperature and low temperature is not ideal, and high resolution did not show improvement in results. Based on these consequences, the authors believe that the WRF model has reliable climate simulation results in Yangtz River Basin, including the spatial and temporal distribution of climate extremes, and the convection permit model in this region is better than the convective parameterization scheme for precipitation simulation. This study provides a high-resolution climate description for impact studies and will also provide a reference for climate simulation driven by general circulation models.

Keywords: Convection-permitting model, Regional Climate Model, Extreme climate, Yangtz River Basin

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-08

Testing of non-hydrostatic core of RegCM and microphysics over the Carpathians

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This study is about testing of non-hydrostatic core of RegCM and microphysics over the Carpathian Mountains. Carpathians are a mountain range across the Eastern and Central Europe forming an arc of ~1,500 km long, with eastward continuation of Alps. The region of study comprises of the Carpathians with the Hungary-Slovakia domain at 4 km resolution for the years 2006-2015. The two setups with non-hydrostatic dynamical cores and microphysics under moisture scheme were made. Setup 1 used Kain-Fritsch for cumulus convective scheme while it is kept off for the setup 2. Average daily temperature and daily precipitation over the study region (Hungary-Slovakia) for 10 km observations and 20 km coarse domain were observed. Both setups and 20 km coarse resolution shows higher values of daily temperature over the Hungary as compared to observations whereas it shows lower values of precipitation as compared to observations. Similarly, both setups show higher values for daily temperature over Slovakia whereas lower values of precipitation as compared to observations. The results and comparisons show that the model performs better with the Slovakia domain. A larger domain for the high-resolution simulation may improve the results over the Carpathians. The long-time span experiments may show better results.

Keywords: microphysics,non-hydrostatic,temperature,precipitation,Carpathians

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-09

Sensitivity of temperature and precipitation to physical parameterization schemes of RegCM4 over Mindanao, Philippines

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The island of Mindanao, Philippines is key agricultural region of the country known to be vulnerable to extreme climate events whose extent and dynamics are still poorly understood. As part of the Southeast Asia Regional Climate Downscaling/Coordinated Regional Climate Downscaling Experiment-Southeast Asia (SEACLID/CORDEX-Southeast Asia) project, this study first examines the sensitivity of simulated temperature and rainfall of Mindanao using 18 different cumulus parameterization schemes of the ICTP Regional Climate Model (RegCM) version 4.3 at 25km resolution for the period 1990-2007. The best-performing cumulus scheme is then used for simulations using RegCM 4.3.7 over the same domain at a finer 5km resolution and compared with output from the newly-introduced nonhydrostatic configuration. The observation datasets APHRODITEv1808 and CHIRPSv2 was used as basis for temperature and precipitation, respectively. For all configurations at 25km, consistent cold bias (1-4°C) and and large rainfall RMSE values (>5mm/day) are observed over mountainous areas while warm bias (1-2°C) exists over southern coasts of the island. The parametrization that recorded the least bias and best metrics is Grell over land and Emanuel over ocean with Zeng ocean roughness parameter iocnrough=2. On the other hand, configurations using Grell over both land and ocean and the Kuo scheme ranked lowest among all metrics.

Keywords: Philippine climate, cumulus parametrization, nonhydrostatic model, CORDEX SEA

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A2-P-10

Analysis of hazardous events environment in present and future scenario by multi-models approach in convection permitting mode

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Withdrawal

Severe precipitation events in Europe, together with other weather and climate related hazards, have large impact on people's life, economy and ecosystem. This is particurlary true in the Mediterranean area because of its complex morphology, where it is expected that a warmer climate will increase thermal instability and frequency of severe precipitation events.

One method for assessing trends about occurence and intensity of wet hazards is to study environment conditions favorable to their development by using correlated quantities such for example CAPE, available from model simulations.

Even if the dynamical downscaling community made enormous advances to overcome the limitation of too coarse resolution in representing subscale mechanisms, the convection parameterizations, even at high resolution, still have the issue of underestimating instability processes outside of cloud coulums. In this contest the new generation of climate simulations at the convection permitting scale represent one suitable mean for the application of proxy methods, for their ability in representing explicitely mesoscale initiation of convective processes.

We will present the results of a convection-permitting multi models ensemble belonging to the CORDEX-FPS convection, analyzing some proxy variables correlated to potential initiation of convection to assess the ensemble ability to represent the present climatology of severe wet hazards over central Europe and Mediterranean.

The study of present trends provides a baseline for the interpretation of results carried out in the perspective of a future climate scenario (RCP8.5), providing a picture of the change of severe events over the Mediterranean regions.

Keywords: convection permitting modeling,climate change, precipitation hazards

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-11

Simulated precipitation in convection permitting scales using REMO-NH

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Moving towards convection permitting simulations up to few kilometers scale are emerging solutions to the challenge and complexities in simulating different convective phenomena especially over mountainous regions. This study is motivated to identify the regions where convection permitting model at 3 km have a higher skill in simulating precipitation compared to its coarser driving model of about 12 km. Under the framework of the Horizon2020 European Climate Prediction (EUCP)Project, convection permitting simulations using the non-hydrostatic regional model REMO-NH have been performed for several European regions in the ERA-Interim period 2000-2009. The REMO-NH model has a horizontal resolution of 0.0275 degree and 49 vertical levels and was driven by the REMO model from the EURO-CORDEX Ensemble. During the conference, we will show results of three domains covering the northern, central, and Alpine regions of Europe. We made a first evaluation of the precipitation for the Central European domain that covers Germany and the Alps. The fine resolution of REMO-NH shows much more details in the precipitation field in comparison to the corresponding EURO-CORDEX REMO run at 0.11 degree resolution. This result was especially true in the Alps and the German mid-range mountains where higher precipitation arises. A comparison with the REGNIE dataset of the German Weather Service revealed that the EURO-CORDEX simulation has some biases in the mountainous regions and underestimates the precipitation in the Black Forest throughout the whole year. The convection permitting REMO-NH simulation reduced these biases to some degree. However, a wet bias appears in eastern part of Germany during the DJF and MAM seasons. The Brier Skill Score has been used to evaluate the time series of daily precipitation totals of simulations compared to the observational datasets. It was found that REMO-NH has added value in many regions during the DJF and JJA season and in the upper Rhine Valley throughout the whole year. The absence of added value in most regions during the MAM and SON seasons can likely be explained by the wet bias and the higher noise in simulations without convective parameterization.

Keywords: precipitation, convection permitting model, REMO

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-12

Evaluation of WRF regional climate model at a convection-permitting resolution over eastern China

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Convection-permitting (CP) simulation using the Weather Research and Forecasting (WRF) model at 4-km resolution are analyzed to understand the diurnal characteristics of rainfall over eastern China. The model produces accurate representations of the observed mean rainfall and the upper-troposphere circulations. The low-tropospheric wind and the surface cyclone convergence contribute more to the seasonal precipitation. Compared to the CN05.1, the wet day intensity of summer precipitation in CMORPH dataset is much stronger, however, the model results are more in line with the later. The CP simulation produces a single diurnal peak of annual precipitation amount over land at around 1700LST, which is 1 h ahead than CMORPH and tends to overestimate the peak value. As for the summer diurnal variation features, CMORPH shows the higher frequency over the intense precipitation areas. The model can simulate the land-sea diurnal phase contrast well but overestimates the diurnal variations of precipitation amount, precipitation frequency and precipitation intensity. In generally, the modelled diurnal precipitation shows good agreement with CMORPH, albeit with a little timing and some intensity differences. The maximum of precipitation amount and precipitation frequency in model evidently occur earlier 1-2h than CMORPH but the modeled diurnal phase of precipitation intensity is less coherent. Though the CP simulation cannot catch the secondary morning peak of PI and midnight peak of PF, the eastward propagating convection is well captured.

Keywords: Convection-Permitting resolution, diurnal variation

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A2: Convection permitting modelling

A3-P-13

Gray-zone simulations of rainfall over the UAE and Arabian Peninsula

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A cloud permitting simulations are tested using Weather Research and Forecasting (WRF) model over United Arab Emirates (UAE) and Arabian Peninsula at the so-called gray-zone resolution, about at 9-km for multiple years. Such resolution is both too coarse to accurately simulate convective updrafts, and too fine to rely on the underlying averaging approximation that are inherent to most cumulus parameterization for deep convection. Yet, many studies have demonstrated that cloud permitting model at the gray-zone resolution can capture many regional precipitation patterns, including the Madden Julian Oscillation and the Indian Summer Monsoon.

In this study, a regional configuration of the WRF model is shown to capture the spatial distribution of precipitation over the Arabian Peninsula as well as the timing of occurrences of precipitation with respect to TRMM3B42 and GPM observations. Circulation features are also realistic in WRF. Wintertime precipitation events are credibly captured by the WRF, but systematic dry biases occur during summer precipitation. Wintertime precipitation events are for the most part initiated by extratropical intrusions. Mid tropospheric potential vorticity anomalies induce southerly wind over the Arabian Peninsula, which trigger a moisture transport from the Arabian and Red Seas. This inflow of moisture feeds precipitation over the frontal region. In contrast, Summer time precipitation over the UAE is strongly tied to the local land-sea contrast and its interaction with regional topography. While the 9-km configuration is unable to reproduce the Summer time rainfall, it does capture the variability in precipitable water and other cloud properties. This suggests that the coarse resolution is insufficient to capture the convective initiation of summertime precipitation events. A 10-years long simulations with the WRF model is used to investigate the variability of the precipitation over the Arabian peninsula and also its sensitivity to the change in large scale atmospheric patterns.

Keywords: Grey zone resolution, winter precipitation, moisture transport

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-14

Sensitivity of monsoon precipitation to physical parameterizations in a cloud permitting regional model

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Simulations with a high-resolution cloud permitting atmospheric model have been shown to accurately capture many features of the Indian Summer Monsoon (ISM) including the timing of the onset and the intra-seasonal variability. Such simulations are however highly sensitive to the physical configurations of the models. In particular, we investigate here how changes in the parameterization used for cloud microphysics (MP) and planetary boundary layer (PBL) can severely affect the precipitation patterns over India.

In this study, the ISM is simulated with the Weather Research and Forecast (WRF) model at a horizontal resolution of 9km over the south-east Asian monsoon region (39 E – 111 E & EQ – 38 N) for three different years, i.e. 2007, 2008 and 2015, which are representative of an early, normal and delayed monsoon onset respectively. Two different PBL (ACM2 and MYNN) and MP (Thompson and WDM6) schemes are tested over the 3 years. It is shown that the choice for the PBL scheme has a dramatic impact on the ISM. Indeed, while simulations performed with ACM2 captures most of the circulations and precipitations patterns over India, simulations using MYNN, lead to a very substantial reduction in rainfall and an overall weakening of the atmospheric circulation. In contrast, the impacts of the microphysical schemes are much less pronounced. Simulations with the Thompson scheme being better able to capture the rainfall over the Western Ghat regions and Arabian Sea, while the WDM6 schemes produced excess rainfall over Norther India and the Himalayan Foothills.

To assess how changes in physical parameterization affects the over rainfall over South Asia, we analyze both the energy and water budgets of the subcontinent. It is shown here that the changes in precipitation are not directly driven by local changes in evaporation. Rather, changes the regional distribution of the energy sources and sinks modify the atmospheric circulation, which in turns affects the distribution of rainfall. It is argued here that systematic study of the energy and water budget can provide important guidelines for understanding the sensitivity of precipitation patterns in regional climate models.

Keywords: cloud permitting model, evaporation, energy and water budget

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A2: Convection permitting modelling

A2-P-15

Model validation methodology of short-duration precipitation extremes

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The estimation of the impact of climate change on short-duration rainfall extremes is especially relevant in an urban context. Indeed, due to surface impermeability, cities are highly susceptible to intense precipitation events and can cause flash floods with high socio-economic impact.

However, to estimate the climate-change impact, one requires the availability of long time series of sub-hourly data from convective-permitting model runs. Moreover for model validations corresponding observations are required. All such data is scarce such that the estimation of extreme rainfall is associated with large uncertainties. Within the URCLIM project that aims to provide climate services, different uncertainties related to extreme precipitation and their projections are quantified. To achieve this goal, different qualitative features of extreme precipitation are addressed. These are tested on both observational datasets across Western and North Europe, and on climate model ensembles (CORDEX/CORDEX.be).

More specifically we focus on Intensity-Duration-Frequency (IDF) curves with multi-scaling characteristics and the Clausius-Clapeyron (CC) scaling between extreme rainfall and temperature. The uncertainties associated with the statistical modeling are quantified. The statistical modelling and uncertainty estimation of (i) the IDF-characteristics is done in a Bayesian framework (Van de Vyver, 2015, 2018), and (ii) the scaling properties is done with quantile regression and associated information criteria. The latter allows to study the deviations from the CC scaling that have recently been found for hourly extreme precipitation.

Keywords: extreme rainfall, precipitation,model validation, IDF,Clausius-Clapeyron

Parallel Session A: Advances in regional downscaling

A2: Convection permitting modelling

A2-P-16

Synergistic effect of high resolution and orographic drag parameterization to reduce WRF simulated precipitation bias in central Himalaya

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Current climate models usually have significant wet biases in the Tibetan Plateau and have particular difficulties in representing the role of the Central Himalaya (CH), where the topography is very steep and terrain is very complex. In order to quantify precipitation bias and improve climate modeling in this region, a network consisting of 14 rain gauges was set up at elevations > 2800 m a.s.l. along a CH valley. Numerical experiments with Weather Research and Forecasting model (WRF) were designed to investigate the effect of mesoscale and microscale terrain on water vapor transport and precipitation. The control case uses a high resolution (0.03o) to explicitly resolve the mesoscale terrain and switches on a Turbulent Orographic Form Drag (TOFD) scheme to represent sub-grid microscale terrain effect. As a result, this case has the lowest bias in the simulated precipitation. The roles of the resolution and the TOFD scheme were then analyzed through comparison with sensitivity cases that either use a lower resolution (0.09o) or switch off the TOFD scheme. It is found that the simulations with the high resolution can not only increase the spatial consistency (correlation coefficient: 0.84-0.92) between the observed and simulated precipitation, but also considerably reduce the wet bias by more than 200%. Therefore, resolving mesoscale terrain plays a leading role in precipitation modeling for this terrain-complex region. The TOFD scheme also reduces the precipitation bias at almost all stations in the CH; it functions to reduce precipitation intensity and reduces more heavy precipitation (>10 mm hr-1). Both high resolution and TOFD enhance the orographic drag to slow down wind; as a result, less water vapor is transported from lowland to the high altitudes of CH, causing more precipitation at lowland south to the CH and less at high altitudes of CH. Therefore, for this highly terrain-complex region, it is crucial to use a high resolution to depict mesoscale complex terrain and a TOFD scheme to parameterize the drag effect due to microscale complex terrain.

Keywords: WRF, precipitation in central Himalaya, orographic drag parameterization, high resolution