A review on convection permitting climate modeling: demonstrations, prospects, and challenges

Based on the equally named article by:
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1 Introduction

Explicitly resolving deep convection with atmospheric climate models demands for horizontal grid spacing less than 4 km. The advantages of this approach are that convection permitting climate simulations (**CPCSs**) can:

- avoid the use of error prone deep convection parameterization schemes
- better resolve surface heterogeneities like orography, land water contrast, or land use changes

The drawback of this approach is the high computational cost.

2 Added Value of CPCSs

CPCSs have proven to add value compared to large scale climate simulations by improving:

- the representation of **extreme precipitation** in complex terrain (Fig. 2) and on hourly time scales (Fig. 3)
- the timing (onset and peak) of the **diurnal cycle** of summertime convective precipitation (Fig. 4)
- **spatial patterns** of precipitation and size and shape of precipitation objects [Prein et al. 2013]
- build-up and melting of **snowpack**
- **2 meter temperature** values due to the better resolved orography
- **center pressure** of tropical cyclones (Fig. 5)
- direct coupling of CPCSs to **impact models** (e.g., glacier, urban, or hydrologic models) because they operate on similar scales

3 Differences in climate projections

Climate projections of CPCSs show important differences compared to large scale climate simulations:

- **increase of short duration extreme precipitation** during summer [Kendon et al. 2014; Mahoney et al. 2013] (Fig. 6)
- **hail storms** produce more hail in clouds in a warmer climate, while the amount of hail reaching the surface reduce almost to zero [Mahoney et al. 2012] (Fig. 7)
- distinct **vegetation-atmosphere feedback** affecting 2 m temperature, humidity, surface fluxes, and cloud cover [Tölle et al. 2014]
- tropical cyclone mean **central pressure minimum decreases** by 23 % and maximum 10 m wind speed increases by 10 % (central pressure minimum decreases only by 5 % in the GCM driving data [Kanada et al. 2013])

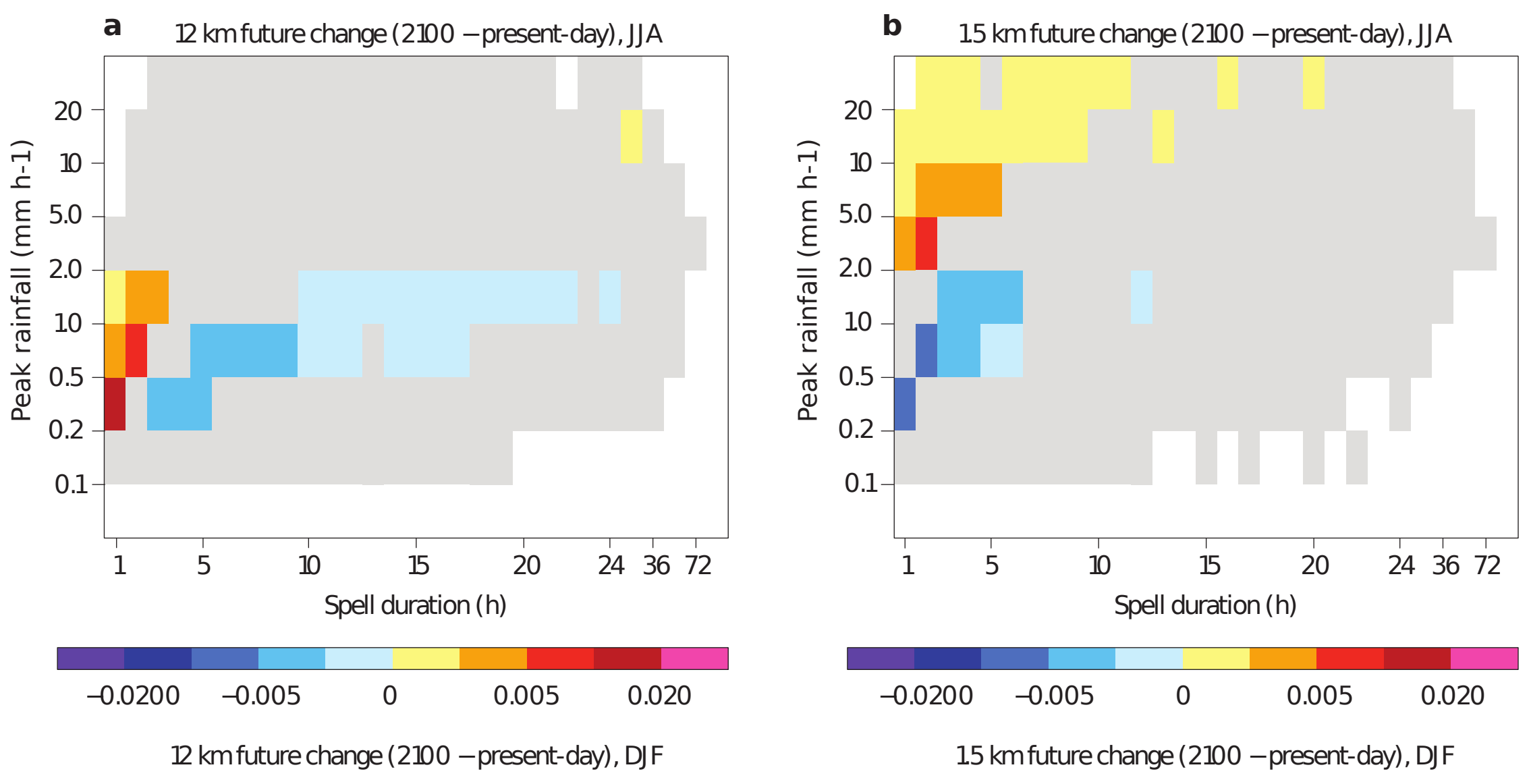

Fig. 6 **The CPCS predicts a significant intensification of short-duration extreme precipitation which is not seen in the large scale simulation.** Simulated climatological difference in the joint distribution of wet spell duration and peak precipitation intensity for the southern UK and for JJA from (a) a 12 km and (b) a 1.5 km model. The difference is computed between periods 1996–2009 and 2087–2099. Gray shaded areas show no significant differences at the 1 % level [Kendon et al., 2014].

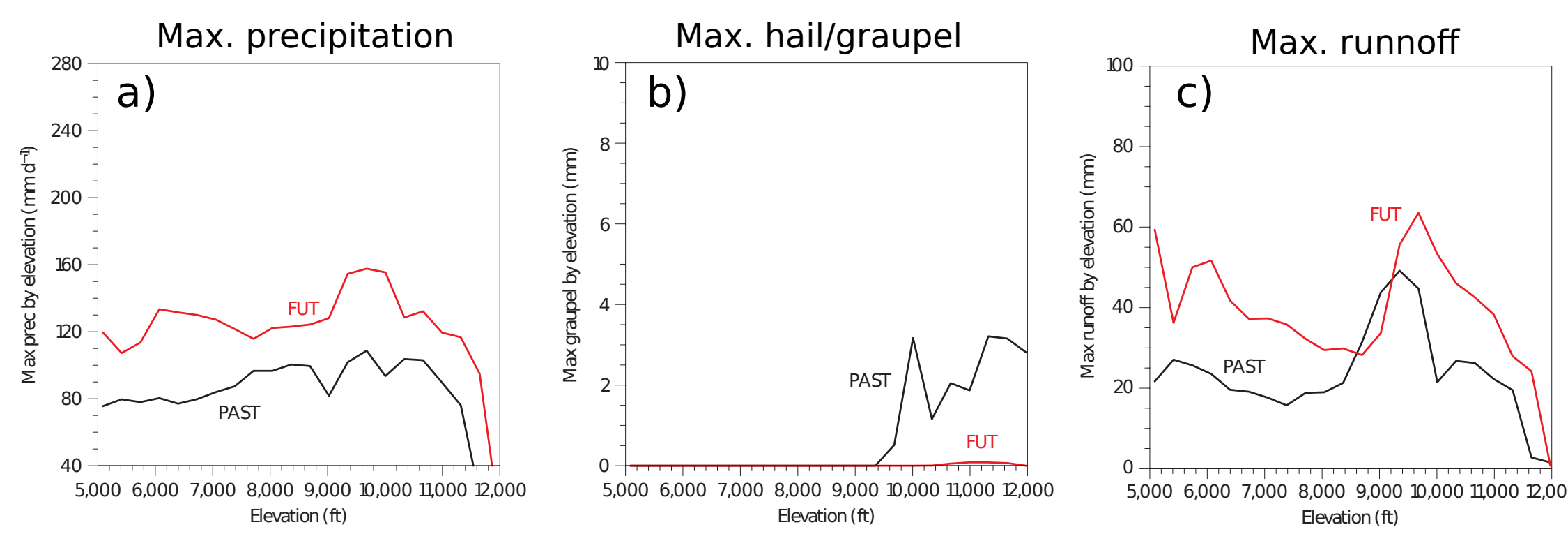

Fig. 7 **While the future maximum precipitation and runoff increases at all elevations the hail/graupel reaching the surface almost vanishes.** A comparison of precipitation, hail/graupel and surface runoff relative to elevation. a) maximum grid point event-total precipitation (mm d−1) versus elevation. b) maximum ratio of graupel/total precipitation versus elevation. c, Maximum surface runoff (mm) versus elevation. For all plots PAST is shown in black and FUT in red [Mahoney et al. 2012].

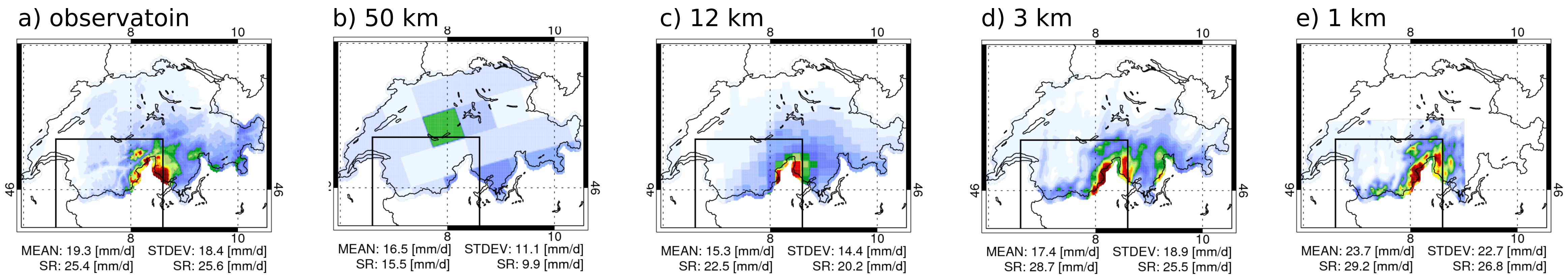

Fig. 2 **CPCSs improve the intensiy, location, and spatial patterns of extreme precipitation.** Simulation of the extreme precipitation event of September 19-21 1999 with the COSMO-CLM model using 50 km, 12 km, 3 km, and 1 km grid spacing (panel b-e respectively).

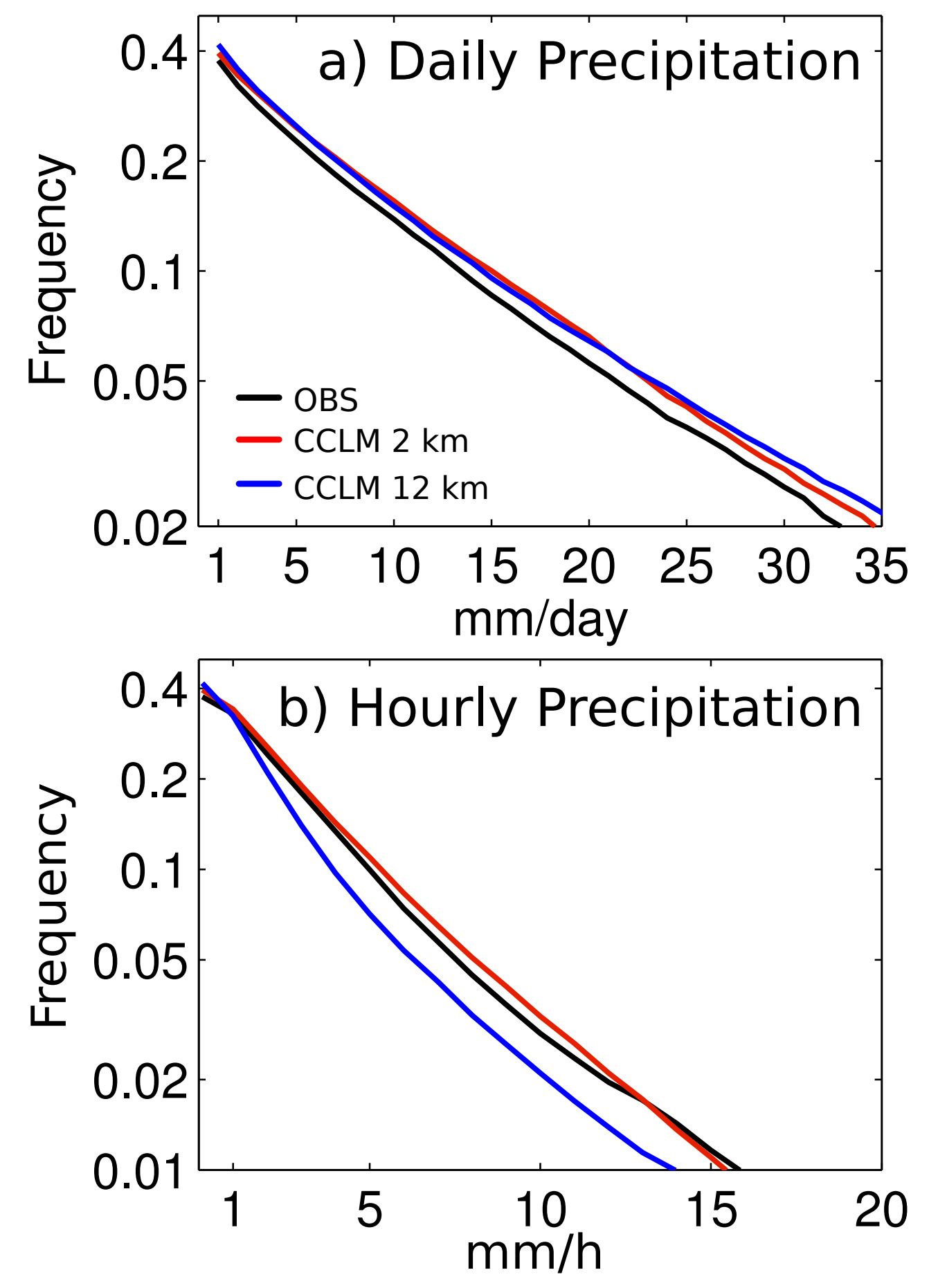

Fig. 3 **The CPCS CRM2 reproduces the observations very well, while the large scale simulation CPM12 underestimates the frequency of daily maximum 1 h precipitation.** Cumulative distributions of a) daily precipitation and b) daily maximum 1 h precipitation as a function of threshold relative to the data at 24 stations in Switzerland. The distributions have been calculated for JJA in the period 1998-2007 [Ban et al., 2014].

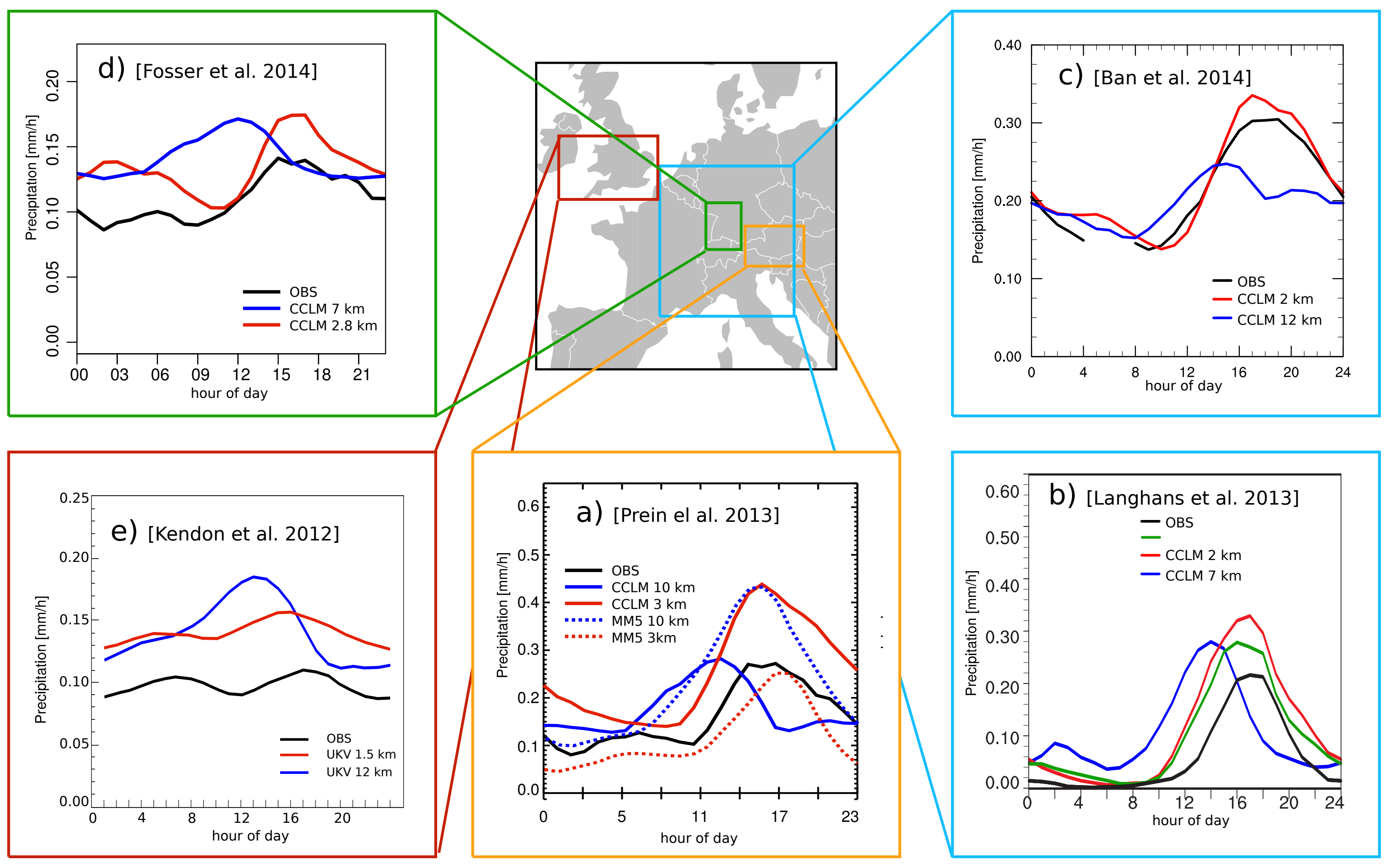

Fig. 4 **All CPCSs show improvements in the shape (onset and peak) of the precipitation diurnal cycle compared to their corresponding large scale simulations.** Diurnal cycle of precipitation in different regions of Europe (shown are the simulation domains): (a) (d) JJA in eastern part of the Alps [Prein et al., 2013a], (b) (c) July 2006 in Switzerland [Langhans et al., 2013], (c) JJA in Switzerland [Ban et al., 2014,], (d) JJA in Baden-Württemberg, Germany [Fosseruet al., 2014], and (e) annually in Southern UK [Kendon et al., 2012].

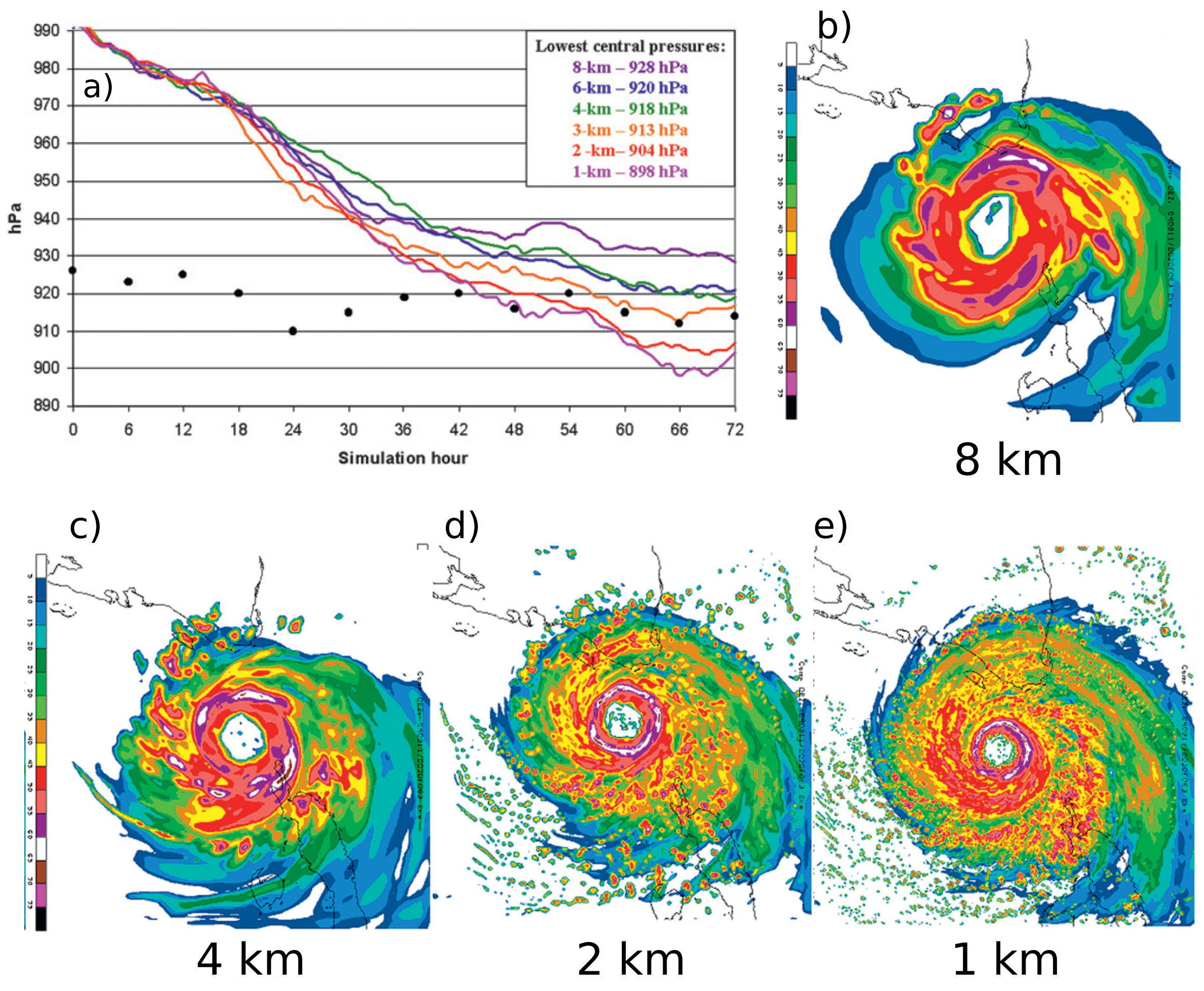

Fig. 5 **CPCSs can reproduce realistic the central pressuer and spatial details of tropical cyclones.** a) Minimum central pressure as a function of time for the 8- (purple), 6- (blue), 4- (green), 3- (orange), 2- (red), and 1-km (pink) simulations, plotted with best-track observations (black) from the NHC (Stewart 2008). Lowest central pressure for each run is shown in the inset box. At simulation time 63 h 20 min, composite model-simulated radar for the b) 8-, c) 4-, d) 2-, and e) 1-km runs.

4 Outlook and Chalanges

To exploit the full potential of CPCSs several challenges have to be tackled:

- develop **turbulent parameterizations** to represent the planetary boundary layer and deep convective systems for grid spacings between 3 km to 100 m.
- **cloud microphysics** have to be better understood and microphysics schemes have to be further developed
- **high accuracy and stability** of the numerical solver to avoid instabilities and numerical diffusion
- efficient simulations on **future high performance computing** architectures demands for restructuring or rewriting of model code
- challenging **data** input/output operations, handling and transfer, analysis as well as storage and archival of data volumes
- fine gridded **observational data sets** in high temporal resolution are needed since highest added value is expected at small temporal and spatial scales
- A **joint effort** to address both, **added value** and **climate change signals** in CPCSs in an organized and coordinated way would be highly beneficial to establish more robust results and support model development

Fig. 1 **Limited-area modelling with regional climate models** is the most frequently used method for generating CPCSs. This approach telescopically nests limited-area domains at decreasing horizontal grid spacings with boundary conditions provided by a GCM or reanalysis until convection-permitting scales are reached. Alternative approaches include the application of global CPCSs, superparameterizations, and stretched-grid models.

Ban, N., J. Schmidli, and C. Sch¨r (2014), Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations, Journal of Geophysical Research: Atmospheres, 119 (13), 7889–7907.

Fosser, G., S. Khodayar, and P. Berg (2014), Benefit of convection permitting climate model simulations in the representation of convective precipitation, Climate Dynamics, pp. 1–16.

Kanada, S., A. Wada, and M. Sugi (2013), Future changes in structures of extremely intense tropical cyclones using a 2-km mesh nonhydrostatic model, Journal of Climate, 26 (24), 9986–10,005.

Kendon, E. J., N. M. Roberts, C. A. Senior, and M. J. Roberts (2012), Realism of rainfall in a very high-resolution regional climate model, Journal of Climate, 25 (17), 5791–5806.

Kendon, E. J., N. M. Roberts, H. J. Fowler, M. J. Roberts, S. C. Chan, and C. A. Senior (2014), Heavier summer downpours with climate change revealed by weather forecast resolution model, Nature Climate Change.

Langhans, W., J. Schmidli, O. Fuhrer, S. Bieri, and C. Schär (2013), Long-term simulations of thermally driven flows and orographic convection at convection-parameterizing and cloud-resolving resolutions, Journal of Applied Meteorology and Climatology, 52 (6), 1490–1510.

Mahoney, K., M. A. Alexander, G. Thompson, J. J. Barsugli, and J. D. Scott (2012), Changes in hail and flood risk in high-resolution simulations over colorado’s mountains, Nature Climate Change, 2 (2), 125–131.

Mahoney, K., M. Alexander, J. D. Scott, and J. Barsugli (2013), High-resolution downscaled simulations of warm-season extreme precipitation events in the colorado front range under past and future climates, Journal of Climate, 26 (21), 8671–8689.

Prein, A., A. Gobiet, M. Suklitsch, H. Truhetz, N. Awan, K. Keuler, and G. Georgievski (2013a), Added value of convection permitting seasonal simulations, Climate Dynamics, 41 (9-10), 2655–2677.

Tölle, M. H., O. Gutjahr, G. Busch, and J. C. Thiele (2014), Increasing bioenergy production on arable land: Does the regional and local climate respond? germany as a case study, Journal of Geophysical Research: Atmospheres, 119 (6), 2711–2724.

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