On the role of atmospheric simulations horizontal grid spacing for flood modeling

Felipe Quintero¹,²,⁵ · Gabriele Villarini¹,² · Andreas F. Prein³ · Witold F. Krajewski¹,² · Wei Zhang⁴

1 Introduction

Precipitation is the main driver used by hydrologic models to simulate the response of the river basins during flood events. Without an adequate representation of precipitation it is expected that the hydrologic response is biased, leading to an overestimation or underestimation of discharge (Fang and Pomeroy 2016; Bennett et al. 2018; Berghuijs et al. 2019; Grimley et al. 2020). Although these biases can be caused by other components of the hydrologic modeling, precipitation has a very important role (e.g. Quintero et al. 2012; Ayalew et al. 2014). It is also intuitive that the hydrologic models are sensitive to the level of detail used by atmospheric models to describe the physics of precipitation: it is expected that the higher the spatial and temporal resolution of precipitation, the better the representation of this phenomenon, resulting in higher expected accuracy of the hydrologic models.

The role of precipitation horizontal grid spacing from numerical models in hydrologic predictions has been explored in the literature (e.g. Graham et al. 2007; Dankers et al. 2007; van Roosmalen et al. 2010; Rasmussen et al. 2011; Prein et al. 2013; Olsson et al. 2015; Mendoza et al. 2016) showing mixed conclusions. There is agreement that the use of kilometer-scale horizontal grids or finer allows for better simulation of heavy summer events, compared to using coarser (36 to 50-km) resolutions. Rasmussen et al. (2014) reported that the use of 12- and 36-km resolutions results in the underestimation of basin-averaged annual precipitation totals with respect to 4-km precipitation simulations. Mendoza et al. (2016) analyzed horizontal grid spacing at 4-, 12- and 36-km at three basins between 700 km² and 1800 km² and found that precipitation horizontal grid spacing has a tremendous effect on the basin water balance at the annual scale (i.e., variations in mean annual runoff and evapotranspiration), regardless of the hydrologic model structure selected. Maina et al. (2020)
used WRF meteorological forcings from 0.5 to 40.5 km as input of a hydrologic model to simulate discharge in a 7,000 km² basin, and characterized river height differences with respect to the highest spatial resolution forcing across all the river network, finding that differences are larger when forcing coarser inputs and at smaller basin sizes.

Simulating precipitation with high spatial and temporal resolution has received extensive attention in the literature, with its realism that has been increasing due to the increased computational resources and the better representation of the processes at play. In particular, the advent of convection-permitting (i.e., kilometer-scale) modeling capabilities that allow to turn off error-prone deep convection parameterizations and largely improve land atmosphere interactions (e.g., orographic precipitation processes) has led to a step improvement in simulating heavy precipitation events in weather (e.g., Clark et al. 2016) and climate (Prein et al. 2015, 2021; Fowler et al. 2021) applications. However, kilometer-scale models are unable to resolve turbulent atmospheric motions properly and largely underestimate entrainment of mid-level air into convective storms resulting in an overestimation of vertical wind speeds and peak precipitation rates (Bryan and Morrison 2012; Prein et al. 2015; Wang et al. 2020; Kendon et al. 2021). Large-eddy simulations (LES) with grid spacings of equal or less than 250 m are necessary to improve the simulation of turbulent mixing of deep convective clouds (Lebo and Morrison 2015). The consequences of these deficiencies in kilometer-scale models on hydrologic applications are largely unknown so far.

Having a high-resolution input is important as long as we have a hydrologic model that is able to take advantage of it, making the use of distributed hydrologic models critical. Differently from lumped models, distributed models decompose the landscape into small units, and route the flow across the river network to estimate discharge. A more detailed description of the river network allows providing insights at the smaller basin scales, where it is very important to understand the expected hydrologic response. A finer decomposition of the river network allows also making better use of the detailed precipitation input, mitigating errors related to the aggregation of forcing across large-basin scales.

While we would like to simulate precipitation at turbulence-resolving (i.e., LES) scales and with the most realistic physics, this is currently not possible because of the prohibitive computational costs. However, it is unclear how large the differences from using kilometer-scale atmospheric model outputs are in terms of event flood peaks and volumes. Here, we take advantage of a unique dataset (Prein et al. 2021) that allows us to explore the sensitivity of hydrologic simulations to different rainfall resolutions and the associated physical processes across different catchment sizes.

2 Materials and methods

We use a ten-member ensemble of idealized Mesoscale Convective System (MCS) simulations performed with the Weather Research and Forecasting (WRF) model v. 3.9.1.1 (Skamarock and Klemp 2008; Powers et al. 2017) presented in Prein et al. (2021). The simulations are idealized since they only use a single atmospheric sounding for initialization and do occur over flat surface without any surface fluxes and radiation impacts. This method is standard in process oriented atmospheric modeling (see e.g., Bryan and Morrison 2012) and allows us to isolate the impacts of model grid spacing on extreme precipitating mesoscale convective systems (MCSs). The atmospheric soundings for initializing the simulations where derived from MCS inflow environments as simulated by a 13-year-long reanalysis driven 4 km WRF simulation (Liu et al. 2017). The environments were taken from most intense precipitating MCSs in the Central U.S. in this 13-year simulation and represent the tail of extreme precipitation events in this region. Each event is run for seven hours over a 600 km × 600 km domain, and the model output is saved every five minutes. A unique aspect of this ensemble is that each event is simulated at various grid spacings including 12-km, 4-km, 2-km, 1-km, 500-m, and 250-m while the other model settings stayed largely unchanged (except for the model time step and the use of a deep-convection scheme in the 12-km simulations). This allows a systematic assessment of the impact of atmospheric model grid spacing on event flood peaks and volumes. For more information on these simulations, see Prein et al. (2021).

We overlaid the precipitation domain on top of the area containing the river network of the state of Iowa. The location of the precipitation cells and their movement is different from event to event, and falls over different areas of the river network. To maximize the number of basins that receive precipitation, we also rotated the precipitation fields by 90, 180 and 270 degrees. This results in expanding our dataset from 10 to 40 synthetic events.

For the hydrologic simulations we used the Hillslope Link Model (HLM) (Quintero et al. 2020), a continuous distributed hydrologic model that uses hillslopes and channel links as the primary units for landscape decomposition where the hydrologic processes are modeled. We used a simplified version of the model where the transformation of precipitation into runoff is controlled by a runoff coefficient equal to one; that is, all the precipitation is converted into surface runoff and eventually into discharge in the channel.
Routing is modeled using a non-linear representation of water velocity that considers the geomorphologic characteristics of the channels (Mantilla 2005; Ghimire 2018). Hillslopes and channels are obtained from a 90-meter DEM; the average area of the hillslopes is 0.1 km$^2$ and the average channel length is 600 m (Quintero and Krajewski 2018). This partitioning allows the characterization of the streamflow predictions at a wide range of spatial scales, ranging from tenths to thousands of square kilometers.

We created lookup tables that relate the rainfall grids and the polygons describing the hillslopes. The lookup table allows obtaining the rainfall rate at each hillslope, as a weighted sum of the cells intersecting the hillslope that considers the intersection area. The hydrologic model was forced with a total of $10 \times 4 \times 6 = 240$ inputs, that result from the original 10 rainfall events, rotated in 4 directions, and at 6 different spatial resolutions. The seven hours of rainfall were forced into the model, and then the water routed for 15 days to allow all the runoff to leave the domain.

![Figure 1](image.png)

**Fig. 1** Total rainfall accumulation of one rainfall event used in the experiment, after modeling precipitation at six horizontal grid spacings varying from 250 m (top-left map) to 12 km (bottom-right map). The large polygon shows the boundaries of the state of Iowa, and the small polygon the catchment delineation of the Des Moines River basin near Tracy.

For every model simulation we obtained the peak flow and total volume at every channel link of the river network where Horton-Strahler order is equal or larger than 4, resulting in 50,000 channels, representing basins between 10 and 100,000 km$^2$. We used the simulations that were forced with inputs at 250 m grid-cell size as reference since turbulent atmospheric motions, which are important in convective storms, are much better resolved at this grid spacing compared to kilometer-scale model simulations. Better resolving turbulent atmospheric motions generally leads to improved simulations of convective precipitation (e.g., Bryan and Morrison 2012). We calculated the relative differences (in percentage) of peak flows and volumes at every river network channel using the equation:

$$e_{i,j} = \left( \frac{x_{i,j} - x_{i,250}}{x_{i,250}} \right) \times 100$$

(1)
where $i$ is the channel link, $j$ is the resolution of the precipitation modeling and ranges from 500 m to 12 km, and $x$ is the analyzed variable, either simulated peak flow ($m^3s^{-1}$) or total volume ($m^3$). The characterization of the relative differences allowed us to analyze the effect of decreased precipitation resolution in peak flows and volumes, as a function of basin size.

3 Results

In Fig. 1 we illustrate the methodology by selecting randomly one precipitation event out of the ten available, and one random basin with enough concentration time that allows to visualize the development of the hydrologic response. The upper panel in Fig. 1 shows the total precipitation for one of the events for the six horizontal resolutions. Not only do the precipitation values change across resolutions, but also the location of the highest precipitation values (e.g., compare the 12-km resolution with the other ones). This is because we are not simply coarsening the highest resolution, but because of the limited predictability and chaotic behavior of convection and the accuracy of the explicitly simulated physical processes in those simulations (e.g., turbulent motions), leading to different simulated rainfall (Prein et al. 2021). When we force the hydrologic model with the various inputs, we obtain different hydrologic responses (Fig. 2, bottom panel). The simulation driven by the highest-resolution input shows a first peak during Day 2, followed by a second and smaller peak during Day 3. As we consider coarser resolutions, this pattern is generally captured by the simulations at 500 m and 1 km. At the 2-km scale, the hydrograph is smoother and the first and second peaks are of comparable magnitude; the 4-km simulation, on the other hand, has a single peak that is about 25% larger than the reference simulation; finally, the 12-km results show a response in which the second peak is much larger than the first one. The upper panel in Fig. 2 shows the mean areal rainfall of the different precipitation inputs for the precipitation event used as an example. The differences in the precipitation volume and the temporal distribution of the basin precipitation during the event are the main factor causing the differences of the hydrologic simulations. Those differences are more visible for the simulations with larger grid spacing. The results in Figs. 1 and 2 are representative of one event and one basin. In Fig. 3, we expand the analyses across the entire domain, all the storms and their rotations, and by stratifying the results by catchment size (i.e., from basins smaller than 100 km$^2$ to basins larger than 10,000 km$^2$).

Each boxplot in Fig. 3 shows the distribution of the differences in terms of runoff, when forcing the model with inputs from coarser horizontal grid spacing simulations (500 m to 12 km), compared to the corresponding simulation using 250 m inputs. The behavior of the differences is similar for the peak flows and the volumes: as the horizontal grid spacing of precipitation increases, the range of variability of the errors increases as well. If we use the median as point estimate, we see that the differences for grid spacing between 500 m and 2 km are close to zero, with an underestimation of the peaks and volumes for larger grid spacing. This behavior is particularly evident for the smaller basins, while the dependence on the input grid spacing tends to decrease at increasing basin sizes for peak flows, and to increase for...
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Again the linear dependence between the grid spacing and the differences; the largest differences in the distribution are obtained with the 12-km grid spacing output, across all the basin sizes. Our model configuration guarantees that all the precipitation becomes runoff and does not get stored in the soil; therefore, the results are not affected by water loss in the runoff generation process. The results can be explained by the differences in the position of the storm cells with respect to the river network, differences in the spatial pattern of precipitation, and differences in the input precipitation intensity. Using coarser grid spacing input can result in overlaying precipitation on top of basins that, according to the benchmark input, should not have receive any precipitation. If the displacement of precipitation is small, the water eventually drains out at the larger scale basin outlets, which explains why volume differences in large basin sizes are

Fig. 3 The upper (lower) row shows the distribution of peak flow (total volume) difference after forcing the model with precipitation inputs of different horizontal grid spacing, compared to the reference provided by the 250-m precipitation input. The analysis is conditioned by the size of the basin, A, in km², where the differences were obtained.
and their correspondent representation of precipitation can influence the outcomes of hydrologic simulations at event temporal scales. We took advantage of a unique precipitation dataset that allowed us to explore the impact of atmospheric model resolutions ranging from 250 m to 12 km. Compared to previous studies, our experiments use finer horizontal grid-spacing and a larger number of catchments, using about 50,000 basins across a continuous range from tens to tens of thousands square kilometers. We showed that coarser-resolution models lead to an overall underestimation in the distribution of peak flows and volumes. These differences are particularly evident for smaller basins and become smaller for larger catchments. Our results agree with findings of previous literature (e.g., Mendoza et al. 2016; Maina et al. 2020) and expand knowledge on the topic of hydrologic implications of horizontal grid-spacing.

4 Conclusions

We designed an experiment that provides insights about how the horizontal grid-spacing of atmospheric models smaller. The displacement of precipitation also attenuates the peak flows because, even if the same volume of water is routed along the river network, the aggregation of the flow occurs with a different velocity and timing compared to the benchmark. It is important to mention that the displacement of precipitation is mainly due to small-scale convective processes because the overall storm movements are very similar across grid-spacings (the storm tracks agree within ~10 km between 250-m and 4-km simulations) except for the 12-km simulations (see Fig. 3 in Prein et al. (2021)).

Fig. 4 The upper (lower) row shows the distribution of peak flow (total volume) values after forcing the model with precipitation inputs of different horizontal grid spacing. The analysis is conditioned by the size of the basin, A, in km$^2$, where the differences were obtained.
at a broad range of spatial scales. There is a loss of fidelity in reproducing rainfall processes as we coarsen the atmospheric model resolutions. However, it is currently not feasible to perform extensive simulations for long periods and across a large domain at a resolution of 250 m because computational costs are approximately ten-fold when doubling the model grid spacing.

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Authors’ contributions FQ, GV, and AP designed the experiments; FQ and AP performed the analyses. All authors interpreted the results and wrote the paper.

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Code Availability Custom codes that support the statistical modeling results are available from the corresponding author upon request.

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References

Ayalew TB, Krajewski WF, Mantilla R, Small SJ (2014) Exploring the effects of hillslope-channel link dynamics and excess rainfall properties on the scaling structure of peak-discharge. Adv Water Resour 64:9–20. https://doi.org/10.1016/j.advwatres.2013.11.010

Bennett B, Leonard M, Deng Y, Westra S (2018) An empirical investigation into the effect of antecedent precipitation on flood volume. J Hydrol 567:435–445. https://doi.org/10.1016/j.jhydrol.2018.10.025

Berghuis WR, Harrigan S, Molnar P et al (2019) The Relative Importance of Different Flood-Generating Mechanisms Across Europe. Wiley Online Libr 55:4582–4593. https://doi.org/10.1029/2019WR024841

Bryan GH, Morrison H (2012) Sensitivity of a simulated squall line to horizontal resolution and parameterization of microphysics. Mon Weather Rev 140:202–225. https://doi.org/10.1175/MWR-D-11-00046.1

Clark P, Roberts N, Lean H et al (2016) Convection-permitting models: A step-change in rainfall forecasting. Meteorol Appl 23:165–181

Dankers R, Christensen OB, Feyen L et al (2007) Evaluation of very high-resolution climate model data for simulating flood hazards in the Upper Danube Basin. J Hydrol 347:319–331. https://doi.org/10.1016/j.jhydrol.2007.09.055

Fang X, Pomeroy JW (2016) Impact of antecedent conditions on simulations of a flood in a mountain headwater basin. Wiley Online Libr 30:2754–2772. https://doi.org/10.1002/hyp.10910

Fowler HJ, Lenderink G, Prein AF et al (2021) Anthropogenic intensification of short-duration rainfall extremes. Nat Rev Earth Environ 2(2):107–122. https://doi.org/10.1038/s43017-020-00128-6

Graham LP, Andréassian V, Carlsson B (2007) Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods - A case study on the Lule River basin. Clim Change 81:293–307. https://doi.org/10.1007/s10584-006-9215-2

Grimley LE, Quintero F, Krajewski WF (2020) Streamflow predictions in a small urban-rural watershed: The effects of radar rainfall resolution and urban runoff models. Atmos (Basel) 11:774. https://doi.org/10.3390/ATMOS11080774

Kendon EJ, Prein AF, Senior CA, Stirling A (2021) Challenges and outlook for convection-permitting climate modelling. Philos Trans R Soc A Math Phys Eng Sci 379(2195). https://doi.org/10.1098/rsta.2019.0547

Lebo ZJ, Morrison H (2015) Effects of horizontal and vertical grid spacing on mixing in simulated squall lines and implications for convective strength and structure. Mon Weather Rev 143:4355–4375. https://doi.org/10.1175/MWR-D-15-0154.1

Maina FZ, Siirila-Woodburn ER, Vahmani P (2020) Sensitivity of meteorological-forcing resolution on hydrologic variables. Hydrol Earth Syst Sci 24:3451–3474. https://doi.org/10.5194/hess-24-3451-2020

Mendoza PA, Mizukami N, Ikeda K et al (2016) Effects of different regional climate model resolution and forcing scales on projected hydrologic changes. J Hydrol 541:1003–1019. https://doi.org/10.1016/j.jhydrol.2016.08.010

Olsson J, Berg P, Kawamura A (2015) Impact of RCM spatial resolution on the reproduction of local, subdaily precipitation. J Hydrometeorol 16:534–547. https://doi.org/10.1175/JHM-D-14-0007.1

Powers JG, Klemp JB, Skamarock WC et al (2017) The weather research and forecasting model: Overview, system efforts, and future directions. Bull Am Meteorol Soc 98:1717–1737. https://doi.org/10.1175/BAMS-D-15-00308.1

Prein AF, Holland GJ, Rasmussen RM et al (2013) Importance of regional climate model grid spacing for the simulation of heavy precipitation in the Colorado headwaters. J Clim 26:4848–4857. https://doi.org/10.1175/JCLI-D-12-00027.1

Prein AF, Langhans W, Fosser G et al (2015) A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. Rev Geophys 53:323–361

Prein AF, Rasmussen RM, Wang D, Giangrande SE (2021) Sensitivity of organized convective storms to model grid spacing in current and future climates. Philos Trans R Soc A Math Phys Eng Sci 379(2195). https://doi.org/10.1098/rsta.2019.0546

Quintero F, Sempere-Torres D, Berenguer M, Baltas E (2012) A scenario-incorporating analysis of the propagation of uncertainty to
flash flood simulations. J Hydrol 460–461:90–102. https://doi.org/10.1016/j.jhydrol.2012.06.045
Quintero F, Krajewski WF (2018) Mapping Outlets of Iowa Flood Center and National Water Center River Networks for Hydrologic Model Comparison. J Am Water Resour Assoc 54:28–39. https://doi.org/10.1111/1752-1688.12554
Quintero F, Krajewski WF, Seo BC, Mantilla R (2020) Improvement and evaluation of the Iowa Flood Center Hillslope Link Model (HLM) by calibration-free approach. J Hydrol 584:124686. ISSN 0022-1694. https://doi.org/10.1016/j.jhydrol.2020.124686
Rasmussen R, Liu C, Ikeda K et al (2011) High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. J Clim 24:3015–3048. https://doi.org/10.1175/2010JCLI3985.1
Rasmussen R, Ikeda K, Liu C et al (2014) Climate change impacts on the water balance of the Colorado headwaters: High-resolution regional climate model simulations. J Hydrometeorol 15:1091–1116. https://doi.org/10.1175/JHM-D-13-0118.1
Skamarock WC, Klemp JB (2008) A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. J Comput Phys 227:3465–3485. https://doi.org/10.1016/j.jcp.2007.01.037
van Roosmalen L, Christensen JH, Butts MB et al (2010) An intercomparison of regional climate model data for hydrological impact studies in Denmark. J Hydrol 380:406–419. https://doi.org/10.1016/j.jhydrol.2009.11.014
Wang D, Giangrande SE, Feng Z et al (2020) Updraft and Downdraft Core Size and Intensity as Revealed by Radar Wind Profilers: MCS Observations and Idealized Model Comparisons. J Geophys Res Atmos 125:e2019JD031774. https://doi.org/10.1029/2019JD031774

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