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Convection-permitting modeling with regional climate models: Latest developments and next steps

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Abstract

Approximately 10 years ago, convection-permitting regional climate models (CPRCMs) emerged as a promising computationally affordable tool to produce fine resolution (1–4 km) decadal-long climate simulations with explicitly resolved deep convection. This explicit representation is expected to reduce climate projection uncertainty related to deep convection parameterizations found in most climate models. A recent surge in CPRCM decadal simulations over larger domains, sometimes covering continents, has led to important insights into CPRCM advantages and limitations. Furthermore, new observational gridded datasets with fine spatial and temporal (∼1 km; ∼1 h) resolutions have leveraged additional knowledge through evaluations of the added value of CPRCMs. With an improved coordination in the frame of ongoing international initiatives, the production of ensembles of CPRCM simulations is expected to provide more robust climate projections and a better identification of their associated uncertainties. This review paper presents an overview of the methodology to produce CPRCM simulations and the latest research on the related added value in current and future climates. Impact studies that are already taking advantage of these new CPRCM simulations are highlighted. This review paper ends by proposing next steps that could be accomplished to continue exploiting the full potential of CPRCMs.

This article is categorized under:
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KEYWORDS

added value, climate change impacts, climate simulations, convection-permitting regional climate models, explicit deep convection, high resolution, observations, precipitation, uncertainty

1 | INTRODUCTION

About 10 years ago, regional climate models (RCMs) reached spatial resolutions comparable to the scale of deep convective processes ($\Delta x < 4$ km), at which point parameterizations of deep convection—a well known source of modeling uncertainty (Ban et al., 2014; Foley, 2010; Fosser et al., 2015; Kendon et al., 2012)—can be removed from the models. Thus, so-called CPRCMs (convection-permitting RCMs) emerged as a promising tool to improve regional and local-scale climate change information (Hohenegger et al., 2008; Kendon et al., 2012). Furthermore, CPRCMs describe surface heterogeneities in greater detail due to their higher spatial resolution, which makes them better capable of representing local-scale climate conditions (Gutowski et al., 2020). Thus, related regional meteorological phenomena are simulated more realistically (Feser et al., 2011; Lucas-Picher et al., 2017; Rummukainen, 2016).

Performing decadal-long CPRCM climate change projections is computationally demanding and also requires huge data storage capabilities (Schär et al., 2020). Even though some climate centers have embarked on convection-permitting global climate models (GCMs) for short periods (Fuhrer et al., 2018; Satoh et al., 2019; Stevens et al., 2019), it is expected that it will take at least a decade, and probably longer, before multi-decadal convection-permitting GCM climate projections become feasible and widely performed (Gutowski et al., 2020; Schär et al., 2020). For those reasons, CPRCMs using limited area domains become an interesting alternative to perform convection-permitting climate change projections at a lower computational cost. They are especially appealing for many research climate centers and universities that only have access to limited computing facilities and storage capacities (Giorgi, 2019). Moreover, in contrast to GCMs, CPRCM simulations can efficiently target regions where CPRCM added value is expected or where very high resolution climate forcings are required for impact models (e.g., flash floods and urban climate).

In order to explore and demonstrate their promising capabilities, CPRCMs were initially used for performing case studies and multi-seasonal simulations over small domains (Hohenegger et al., 2008; Knote et al., 2010; Rasmussen et al., 2011). Then, less than 10 years ago, CPRCMs were used for decade-long and even longer climate simulations, still over small domains (Argüeso et al., 2014; Ban et al., 2014; Fosser et al., 2015; Kendon et al., 2012). The review of Prein et al. (2015) provided an overview of the initial studies using CPRCMs. Since then, CPRCMs have been used widely over many regions of the globe over longer periods and larger domains, reaching even continents (Europe: Leutwyler et al., 2016; North America: Liu et al., 2017; Africa: Stratton et al., 2018). A recent special issue of 31 papers highlighted the strong research activities using CPRCM simulations that cover many regions of the world and addressed a wide variety of scientific questions (Prein, Rasmussen, et al., 2020).

The benefits, often referred to as the added value, of these CPRCM simulations are now more easily quantifiable through evaluation studies that take advantage of improved gridded observations (Ban et al., 2014; Ban et al., 2021). Indeed, gridded observational datasets at fine temporal (down to 5 min) and spatial (down to 1 km) scales became recently available (Lin & Mitchell, 2005; Tabary et al., 2012; Winterrath et al., 2018; Wüest et al., 2010). Additionally, several scientific projects (Coppola et al., 2020; Hewitt & Lowe, 2018) were recently launched to better coordinate CPRCM research activities and increase the amount of CPRCM simulations with similar experimental configurations to explore uncertainties and robustness in CPRCM climate change projections.

This review paper first outlines the methodology and the principles behind CPRCMs. Then, an overview of the latest research activities is provided, focusing on studies investigating added value using hindcast CPRCM simulations that are evaluated with observations. Thereafter, studies investigating climate change CPRCM projections are highlighted, with a particular focus on climate change signals emerging from the finer scales simulated by CPRCMs. Afterwards, an overview of impact studies that benefit from CPRCM simulations such as hydrological, glacier, and urban modeling is presented. Finally, suggestions are made for the next steps to realize and maximize the potential of CPRCMs. This review paper describes the recent advances in the field of CPRCM, and is a natural follow-up of the reviews by Rummukainen (2010) on regional climate models and Prein et al. (2015) on the initial convection-permitting climate modeling research activities.

2 | METHODOLOGY AND PRINCIPLES BEHIND CPRCMS

2.1 | What is a CPRCM?

RCMs were designed ∼30 years ago (Dickinson et al., 1989) as a convenient way to produce high-resolution climate information that is computationally affordable and suitable for vulnerability, impacts, adaptation and climate services (VIACS) applications that require fine-scale climate information (Giorgi, 2019). The concept behind RCMs, commonly referred to as dynamical downscaling, is to run a climate model at high spatial resolution over a limited area using coarse-resolution 3D climate information to provide initial and lateral boundary conditions. This allows RCMs to simulate fine-scale meteorological processes and better describe surface forcings that are poorly represented in coarse-resolution GCMs, such as complex topography, land-sea contrast and land cover heterogeneities (von Storch et al., 2017). Thus, RCMs should be capable of producing fine-scale climate features that are missing in coarse-resolution GCMs. For further details, interested readers are referred to Laprise et al. (2008), where the main tenets of dynamical downscaling are discussed.

CPRCMs essentially extend the RCM concept to scales where deep convection can be explicitly simulated (Prein et al., 2015). Analyzing simulations at various resolutions, Weisman et al. (1997) showed that a 4-km simulation sufficiently reproduced the mesoscale structure and evolution of squall-line convective systems that were simulated at 1 km. In fact, 4 km is generally accepted as the coarsest resolution for which deep convection can be explicitly resolved and for which the deep convection parameterization (DCP) is no longer required (Prein et al., 2015; Weisman et al., 1997). Thus, CPRCMs are using a range of resolutions between 1 and 4 km where the explicit simulation of deep convection provides a huge gain compared to conventional deep convection parameterized RCMs. However, Vergara-Temprado et al. (2020) suggested that an explicit representation of convection may be beneficial to represent some aspects of climate at coarser resolutions than previously thought (>4 km). Higher resolution simulations (<1 km) with large-eddy simulation (LES) models can provide additional gains by resolving most of the energy-containing eddies (see the review of Chow et al. (2019) for more details).

Most CPRCMs, such as CRCM5 (Zadra et al., 2008), WRF (Skamarock et al., 2019), COSMO-CLM (Rockel et al., 2008), Met Office Unified Model (Clark et al., 2016), and AROME (Belušić et al., 2020; Seity et al., 2011), originate from convection-permitting numerical weather prediction (NWP) models, operating at kilometer scales for more than two decades (Mass et al., 2002). This follows an approach known as "seamless Earth system prediction" for which short-term NWP prediction scales up to climate change projections and where a common modeling system is adopted (Ruti et al., 2020). The scientific challenge of such an approach is to reduce systematic biases, and to preserve energy and water balance in long-term climate integration, using numerical codes initially designed for NWP. Additionally, to become a CPRCM, a NWP model should be modified to take into account varying greenhouse gas (GHG) and aerosol concentrations. Few other CPRCMs stem from "conventional" RCMs, operating at horizontal resolutions coarser than 10 km, for which the dynamical core has to be replaced with one that does not take into account the hydrostatic assumptions (Coppola, Stocchi, et al., 2021) as these are no longer valid (Prein et al., 2015). Moving toward higher resolutions, additional modifications may be implemented to improve the representation of processes related to convection (e.g., microphysics and radiation scheme). In this case, the CPRCM takes advantage of the many Earth system components (Giorgi & Gao, 2018) already implemented in the RCM such as a sophisticated lake, glacier and dynamic vegetation schemes. RegCM4-NH (Coppola, Stocchi, et al., 2021) and REMO (Jacob & Podzun, 1997) are amongst the RCMs that were recently modified to become capable of operating at CPRCM scales.

2.2 | General rules to perform CPRCM simulations

Because CPRCMs are an extension of RCMs, the same rules apply regarding nesting techniques (Giorgi, 2019; Rummukainen, 2010). However, the higher resolution requires a higher updating frequency of the lateral boundary conditions (LBC) (1 h for CPRCMs compared to 6 h for RCMs) (Fosser, Kendon, Chan, et al., 2020; Leutwyler et al., 2016; Tang et al., 2013). Generally, the maximum step in resolution of 12 between the nests identified for the RCMs (Antic et al., 2006; Beck et al., 2004; Denis et al., 2003) remains valid for CPRCMs (Berthou et al., 2020; Chawla et al., 2018). Larger resolution steps are possible, but at the expense of a large spatial spin-up zone required to develop small-scale transient eddies (Berthou et al., 2020).

To adhere to the maximum resolution step of a factor 12, multi-nest approaches (also known as telescopic nesting) with intermediate RCMs have been adopted to reach kilometer-scale CPRCMs from coarse-resolution (>100 km) GCMs (see Figure 1). Indeed, Matte et al. (2016) recommended a two-step approach because it provides similar quality small-scale details as the one-step approach and reduces the domain size needed for an adequate spin-up of the fine-scale features, allowing to save important computational costs. Lauwaet et al. (2013) and Brisson, Demuzere, and van Lipzig (2016) concluded that a two-nest approach (75–25–2.8 km) is sufficient to reach convection-permitting scales. A large majority (28 out of 30) of climate research centers participating in the FPS-Convection CORDEX project (Coppola et al., 2020) adopted a two-step nesting strategy using an intermediate domain RCM simulation in order to reach CPRCM resolutions. In a sensitivity study using different experimental configurations, Fosser, Kendon, Chan, et al. (2020) found that a 2.2-km simulation nested into an intermediary 12 km simulation provided the most reliable setup. However, using the latest 31-km resolution ERA5 reanalysis to force their CPRCM, Raffa et al. (2021) demonstrated that the one-step approach outperformed the two-step approach.

Nowadays, the CPRCM limited area domain size is largely constrained by the available computing power. The CPRCM domain size should be sufficiently large considering the spatial spin-up (Leduc & Laprise, 2009; Matte et al., 2017) of approximately 150 km required to fully generate small-scale details (Brisson, Demuzere, & van Lipzig, 2016). In addition, Chow et al. (2019) raised that deep convective cells have a lifetime of 3–6 h that corresponds to a typical travel distance of 50–100 km before reaching maturity. Therefore, to achieve a target area of 100 km in which convective cells are fully developed, a limited area domain of at least 300 × 300 km should be selected. Due to computational limitations, CPRCMs tend to use small domains compared to RCMs. This, in turn, implies that spectral nudging is only rarely required to further constrain the CPRCM large-scale atmospheric state toward the LBC (von Storch et al., 2000). Indeed, Schaaf et al. (2017) concluded that spectral nudging is not necessary for small CPRCM domain sizes of only several hundred kilometers in diameter. However, finding a closer match with the observations when nudging was used, Collier and Mölg (2020) decided to take advantage of nudging to produce a high-resolution climate dataset over Bavaria. In the rare cases when CPRCM domains are large such as over North America, the application of spectral nudging reduced 2-m temperature biases, improved precipitation patterns, but suppressed precipitation intensity over the western U.S. Mountains (Liu et al., 2017). When CPRCMs are used to reproduce a specific meteorological event, often referred to as a case study, the use of spectral nudging in the intermediate RCM simulation is welcome to maintain the large-scale atmospheric states of the driving reanalysis (Li, Pontoppidan, et al., 2020; Wootten et al., 2016).

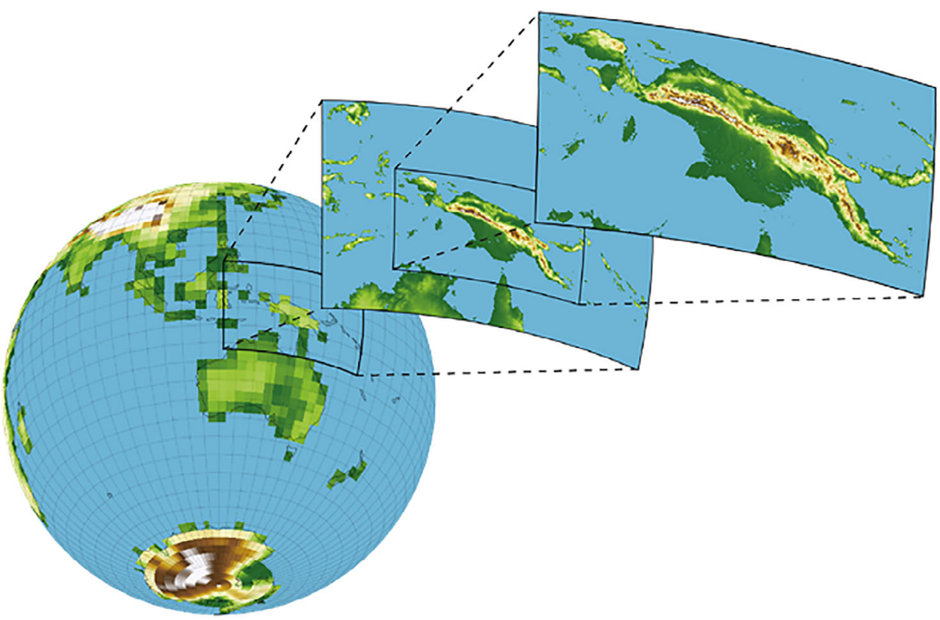

FIGURE 1 Visualization of multi-nested limited area domains (also known as telescopic nesting) allowing to zoom over a region up to a ~2-km grid spacing CPRCM. To respect the resolution step limit of 12 from one domain to another, an intermediate RCM simulation (grid spacing of 10–25 km) is in most cases needed, assuming the driving GCM or reanalysis have grid spacings close or above 100 km

2.3 | Sensitivity studies and calibration of subgrid parameterizations

Even though the removal of DCP in CPRCMs leads to significant improvements in the physical performance of the models, other sub-grid parameterizations (e.g., microphysics, shallow convection or turbulence parameterizations) may also need to remain active or, in some cases, to be adapted. Some processes are fully unresolved in CPRCMs, leading to a consensus in their parameterizations (e.g., microphysics or radiative processes). However, some studies underlined that kilometer-scale resolutions only allows to partially resolve convective clouds (Chow et al., 2019) and convective updrafts (Kendon et al., 2021), which may require to keep some convective parameterization active (e.g., shallow convection). Finally, some of the hypotheses at the basis of some parameterizations do not hold anymore at the kilometer-scale, which result in a need to adapt the parameterizations in the finest-resolution CPRCMs (e.g., Chow et al. (2019) explain how kilometer-scale modeling needs to transition from the classic 1D turbulence parameterizations used in RCMs to 3D turbulence parameterizations).

An essential step toward CPRCM production runs is to calibrate and to test different parameterization schemes to optimize the model setup and to verify that it produces reasonable values (Huang, Winter, et al., 2020; Maussion et al., 2011). While this step may be achieved using short simulations investigating extreme events (Chawla et al., 2018; Li, Szeto, et al., 2017; Luo et al., 2018; Zhu & Xue, 2016; Zittis et al., 2017), a common practice is to use longer simulation periods (one season to multi-years) to encompass a wider range of atmospheric phenomena and identify systematic biases (Guo et al., 2019; Huang, Winter, et al., 2020; Hughes et al., 2020). Considering the high computational cost of CPRCM simulations, the objective calibration of tunable parameters becomes increasingly appealing (Bellprat et al., 2016).

Sensitivity studies using CPRCMs mostly focus on processes that are somehow connected to convective processes (microphysics, cloud, radiation, and planetary boundary layer [PBL]). When turning the DCP off, microphysics schemes (MS) that resolve processes of water vapor, cloud and precipitation, and their mixed-phases have to be calibrated for an explicit simulation of convective processes. Moreover, this may require an update of the hydrometeors representations that notably account for hydrometeor size or falling speed (Yáñez-Morroni et al., 2018). Adding dense hydrometeors such as graupel and including multi-moment MS allow the model to simulate more intense precipitation (Brisson, Demuzere, & van Lipzig, 2016; Li, Szeto, et al., 2017; Luo et al., 2018), but appears to be computationally demanding (Brisson, Demuzere, & van Lipzig, 2016; Van Weverberg et al., 2014). While adding complexity to MS may be appealing, the literature is ambiguous that this always leads to improvements. For example, using a second-moment MS may provide an added value in areas with steep orography (Guo et al., 2019; Hughes et al., 2020; Liu et al., 2011; Luo et al., 2018; Orr et al., 2017; Yáñez-Morroni et al., 2018), but does not always improve the representation of precipitation in other regions (Cassola et al., 2015; Van Weverberg et al., 2014). Even for extreme precipitation events, added value that may appear for clouds (Keller et al., 2016) and hydrometeor distributions can be offset by microphysics processes such as collisional drop breakup, evaporation, or collection, involved in precipitation formation (Van Weverberg et al., 2014).

Adjustments of the microphysics parameterization and timestep have far-reaching consequences (Barrett et al., 2019) and may affect the representation of radiative processes in CPRCMs. This relation is bi-directional as radiative fluxes also impact the development of clouds. Including a radiative scheme that is properly coupled to the MS is an important step for consistent CPRCM simulations (Matsui et al., 2020). The redistribution of radiative fluxes reaching the surface may also significantly affect precipitation (Minder et al., 2020). In addition, the recycling of water highlights the importance of the surface scheme in simulating extreme events (Li, Szeto, et al., 2017). The distribution of surface heat fluxes can directly interact with the PBL schemes, which gain relevance in CPRCMs (Chawla et al., 2018; Kouadio et al., 2020; Minder et al., 2020). Some studies found that differences in PBL scheme may result in large precipitation sensitivity (Chawla et al., 2018; Huang, Winter, et al., 2020; Kouadio et al., 2020). Increasing the vertical resolution may also improve the representation of the PBL and the hydrometeor mixing (Mantsis et al., 2020; Yáñez-Morroni et al., 2018). Adding a representation of subgrid-scale features such as turbulent orographic draft (Wang et al., 2020), subgrid-scale orography (Lee et al., 2015), and sub-grid cloud fraction (Yun et al., 2020) could also lead to a significant improvement of precipitation.

2.4 | Types of CPRCM simulations

2.4.1 | CPRCM driven by a reanalysis (Hindcast simulation)

Compared to GCMs, CPRCMs (and RCMs) have a strong advantage because they can be evaluated in a “perfect framework” when they are forced at their lateral boundaries by reanalyses that are the best representation of the past atmospheric states due to the assimilation of observations. In this case, the CPRCM generates a hindcast for which not only the statistics of the climate are being reproduced, but also the sequence of the past events is retrospectively simulated. Moreover, based on the downscaling paradigm, a CPRCM that is driven by a reanalysis can complement the large-scale state of a reanalysis with regional details (Lucas-Picher et al., 2013, 2015; Maussion et al., 2011; von Storch et al., 2017). In this concept, often referred to as a "poorman's regional reanalysis", the high quality relatively homogenous large-scale state of the atmosphere from a reanalysis is downscaled using a CPRCM to create new regional-scale atmospheric data, without data assimilation. Such data can serve to better understand mesoscale features of a case study (Kumar et al., 2014; Norris et al., 2015), or to feed a hydrological or glacier model with new small-scale atmospheric forcing (Bonekamp et al., 2018; Collier et al., 2013; Mölg & Kaser, 2011), especially in regions where few weather stations are available such as near the poles and in complex terrain. During the evaluation of such a simulation, systematic biases of the CPRCM can be identified (Ban et al., 2021).

2.4.2 | CPRCM driven by a GCM and time slices

Once a CPRCM is evaluated when forced using "perfect LBC" from reanalyses, a CPRCM can then be driven by a GCM forced by historical GHG concentration where only climate statistics are evaluated (Giorgi et al., 2009). Due to their high computational costs, CPRCMs are currently not integrated continuously in time over centuries, but they are rather integrated in a "time slice" mode. In this case, to assess future changes, a CPRCM climate simulation performed over a certain historical period (typically 10 years) is compared to another simulation of the same length, but in the future, where GHG concentrations of the GCM LBC and CPRCM are modified according to different scenarios. This time slice approach using 10-year simulations has several limitations because the simulations are not long enough to compute robust climate statistics that usually require 30 years. Moreover, 10-year simulations are not sufficient to adequately sample long-term modes of variability such as the North Atlantic and the El Nino southern oscillations and are, hence, potentially subject to large uncertainties arising from natural climate variability. Because of the computational burden to run CPRCM simulations and the sensitivity of the CPRCMs to their driving GCMs, the latter should be carefully selected according to their performance on the region of interest (McSweeney et al., 2015; Parding et al., 2020). Finally, when short climate samples are simulated, the evaluation of extremes is also limited because only small return periods of extremes can be empirically assessed. To get around the sampling issues, some studies proposed the use of generalized extreme value theory (Ban et al., 2020) or stochastic storm transposition to resample synthetically short datasets (Yu, Wright, & Li, 2020).

2.4.3 | Pseudo global warming

In order to avoid the problems associated with the GCM biases and natural climate variability, a method called "pseudo global warming" (PGW) is gaining interest in the CPRCM community. According to this method, a CPRCM is driven at its lateral boundaries by a reanalysis that is perturbed by future changes of the 3D atmospheric conditions, often taken from an ensemble of GCMs (Prein, Rasmussen, Ikeda, et al., 2017; Schär et al., 1996). In this approach, the sequence of events and the atmospheric circulation are preserved in the climate change projection, which can be considered both a limitation and an advantage from case to case. This method can serve to isolate the thermodynamics aspect of climate change projections. It also reduces the number of simulations required to conduct climate change analysis because no historical climate simulation is needed. The climate change delta is computed between the evaluation and scenario simulations. Dai, Rasmussen, Ikeda, and Liu (2020) suggested an alternative approach that combines the transient weather signal from one GCM simulation with the monthly mean climate states from the multi-model ensemble mean for the present and future periods. Interested readers are referred to Adachi and Tomita (2020), which offers a review of the different approaches used to constrain RCMs at their lateral boundaries.

2.5 | Assessment of uncertainties

Dynamical downscaling has the main purpose to better describe local impacts of climate change at scales suitable for the VIACS community (Fowler et al., 2007; Maraun et al., 2010; Xu, 1999). The use of CPRCMs adds a new layer of uncertainty in addition to that related to GCMs and RCMs, and that associated with the GHG scenarios (Hawkins & Sutton, 2011). This concept known as the cascade of uncertainty (Wilby & Dessai, 2010) consists of an increase in the range of uncertainty at each step of the process. However, the uncertainty from each step of the chain is not necessarily additive. Sørland et al. (2018) and Coppola, Nogherotto, et al. (2021) found that RCMs systematically reduced biases and modified climate change signals of their driving GCMs, indicating limitations of the concept of cascading uncertainties.

2.5.1 | Increased coordination to better sample uncertainties

In order to provide a good spectrum of high-resolution climate change scenarios to the VIACS community, a large ensemble of climate simulations needs to be performed (Giorgi et al., 2008), requiring coordination of research centers through large collaborations (NARCCAP; Mearns et al., 2013, ENSEMBLES; Déqué et al., 2012, CORDEX; Giorgi et al., 2009). In this context, a matrix of GCMs, RCMs and CPRCMs is designed and climate simulations are performed by different climate centers to cover as many as possible the different sources of regional climate projection uncertainty (Déqué et al., 2012; Mearns et al., 2013). The recent EUCP European project that gathers many European research centers and six different CPRCMs aims at developing an ensemble climate prediction system based on CPRCMs over Europe (Hewitt & Lowe, 2018).

2.5.2 | CORDEX flagship pilot studies (CORDEX-FPS): An example of successful coordination

In order to encourage smaller community initiatives on key scientific questions targeting specific regional climate processes on sub-continental regions, CORDEX (Giorgi et al., 2009; Giorgi & Gutowski Jr, 2015) launched a call for flagship pilot studies (FPS) (Gutowski et al., 2016) where several build on CPRCM contributions. FPS Convection (Coppola et al., 2020) investigates present and future convective processes and related extremes over Europe and the Mediterranean, where 30 climate research centers are performing CPRCM simulations over a domain centered over the Alps in a coordinated effort. So far, the effort has shown positive evaluation on the added value of heavy precipitation at daily and hourly scales (Ban et al., 2021), as well as larger climate changes in extreme precipitation events compared to coarser-resolution RCMs (Pichelli et al., 2021). FPS Convection-Permitting Third Pole (CPTP) explores the water cycle over the Himalayas, with an initial focus on assessing model skill in the simulation of convection and precipitation (Zhou et al., 2021). The FPS Climate extremes in the Lake Victoria basin (ELVIC) aims to unravel the complex regional climate near Lake Victoria in East Africa with CPRCMs (van Lipzig et al., 2020). Finally, the more recent FPS southeastern South America (SESA) investigates multi-scale aspects, processes and interactions that result in extreme precipitation events using a suite of models including CPRCMs over South America (Bettolli et al., 2021; Lavin-Gullon, Feijoo, et al., 2021).

2.5.3 | Storyline approach

An alternative to large ensembles of CPRCM simulations is the "storyline approach" based on physically self-consistent plausible pathways (Shepherd, 2019; Zappa & Shepherd, 2017). This approach emphasized qualitative understanding rather than quantitive precision (Shepherd et al., 2018). Indeed, instead of the common approach that quantifies the probability for a specific event to occur, storylines focus on telling the plausibility of an event by understanding the driving factors of this event and their likelihood in future pathways. As there is no probabilistic quantification involved, storylines do not necessarily require building large ensembles. Instead, a single CPRCM experiment that allows a deep understanding of processes involved in the occurrence of an event is sufficient. In addition, uncertainties in related driving factors may usually be retrieved from robust ensembles of coarser models (GCMs). Therefore, this approach has a relatively low computational cost compared to ensembles, partly explaining its rapid gain of interest in the CPRCM community (Hegdahl et al., 2020; Kawase, Imada, et al., 2020; Schaller et al., 2020; Takayabu, Hibino, et al., 2015). Another reason for this gain in interest is the great potential of this approach to raise climate change risk awareness, particularly when addressing decision-makers, as understanding a story is sometimes easier than juggling with complex probabilistic uncertainties.

2.6 | Evaluation of CPRCMs

2.6.1 | Need of high-resolution gridded observations

As the resolution of climate models increases, the evaluation of climate simulations becomes a challenge due to the lack of high-quality high-resolution observational gridded datasets (Piazza et al., 2019; Prein & Gobiet, 2017). Indeed, many studies found large discrepancies between different observed gridded datasets despite that they are all based on weather stations (Prein & Gobiet, 2017; Zittis et al., 2017). This is especially true in low-density populated polar (Revokatova et al., 2021) and mountainous regions where weather stations are sparsely distributed. In addition, weather stations are affected by precipitation undercatch (Gao, Chen, & Jiang, 2020; Neff, 1977; Pollock et al., 2018), which is even more severe for snow measurements in winter (Fortin et al., 2008; Gao, Chen, & Jiang, 2020; Hughes et al., 2020; Rasmussen et al., 2012). Moreover, when it comes to assessing CPRCM added-value, the interest goes toward sub-daily data that is available only from a subset of weather stations (Lewis et al., 2019). Precipitation extremes are especially susceptible to be underestimated in the gridded observations due to the often localized nature of these events and the spatial interpolation that tends to smooth the spatial distribution (Piazza et al., 2019). Prein and Gobiet (2017) provided guidelines including recommendations when gridded precipitation observations are used.

An alternative method consisting of evaluating climate simulations using weather stations is sometimes performed (Chawla et al., 2018; Karki et al., 2017). Even though CPRCMs feature a higher spatial resolution than RCMs, they still fall short of the very local-scale of the data collected by weather stations and direct comparisons are impaired by scale effects (Rummukainen, 2010). Fortunately, such drawbacks were recently reduced with high spatio-temporal resolution radar data that are adjusted with gauges from weather stations over France (Tabary et al., 2012), Germany (Winterrath et al., 2018), the UK (Yu, Li, et al., 2020), the United States (Lin & Mitchell, 2005), Netherlands (Overeem et al., 2009), Sweden (Berg et al., 2016), and Switzerland (Wüest et al., 2010). This merging technique allows producing reliable sub-daily kilometer-scale gridded precipitation datasets. However, radar-based datasets rely on rather recent radars that are inhomogeneously distributed in space and time. Moreover, radar efficiency is distance-dependent and is affected by fixed-object echoes and mountain ranges, which limits their range.

With the improved realism of CPRCMs (Clark et al., 2016), the study of specific meteorological processes that sometimes require the use of less conventional measurements is of greater interest. Amongst others, remote sensing products allow to investigate more deeply deep convection processes likely improved with CPRCMs. Doppler polarimetric radars provide the opportunity to evaluate cloud properties such as hydrometeor mixing ratios and falling speeds (Carlin, 2015; Glushko & Yanovsky, 2010). However, these datasets are often 3D spatial datasets with high spatio-temporal resolution and are difficult to integrate on climate timescales (Glushko & Yanovsky, 2010). Other remote sensing-based applications have been used for CPRCM cloud evaluation (Brisson, Van Weverberg, et al., 2016; Hentgen et al., 2019; Keller et al., 2016). The merging of multiple generations of satellites allows the retrieval of consistent cloud parameters over long-time periods on high spatio-temporal scales. For example, the CMSAF provides 2D cloud parameters (CLAAS-2 products—Benas et al., 2017) or 2D radiation products (SARAH-2 products—Müller et al., 2015; Kothe et al., 2017) on decadal time scales with a spatial resolution up to 3 km and a temporal resolution up to 15 min that enables a deeper understanding of cloud representation in CPRCMs.

2.6.2 | Bias correction

To provide accurate climate change information for impact assessment studies that could be sensitive to climate model biases, different bias correction techniques are usually applied to RCM simulations (Berg et al., 2012; Christensen et al., 2008; Gutjahr & Heinemann, 2013). However, it is now being recognized that the skill in simulating rain and snow, at least in the mountains, can exceed the skill of observational networks in measuring precipitation (Lundquist et al., 2019). Thus, bias correcting a CPRCM climate simulation that is likely superior in many aspects to gridded observations could become an issue. Berg et al. (2015) discussed the problematic deterioration of fine scale information from the RCM when bias corrected to poor "actual resolution" gridded data sets, and suggested constructing a merged pseudo-observational data set including fine scale information from the RCM. In Argüeso et al. (2013), gridded observations were found to be inadequate to bias correct CPRCMs because they were subjected to too frequent low intensity precipitation due to the spatial averaging of weather station data. Novel bias correction methods that directly use weather station data are now being developed to alleviate the problems associated with coarse-resolution or the lack of observational gridded datasets (Argüeso et al., 2013; Haerter et al., 2015). Applying a nonlinear bias-correction to CPRCM simulated precipitation, Bannister et al. (2019) obtained a precipitation dataset that is superior to precipitation estimates from reanalysis and two gridded datasets in the Himalayas. In addition, CPRCM simulations are often too short to apply bias correction. Bias correction approaches typically require simulations and observations spanning at least 30 years to account for the effects of natural climate variability in their calibration (Berg et al., 2012; Gutjahr & Heinemann, 2013).

2.6.3 | Alternative strategies to optimize CPRCM evaluation

One of the major bottlenecks for CPRCM evaluation is the extensive storage size of both model and observational outputs, as the main added value is in fine spatial scales and sub-daily variability. Schär et al. (2020) suggested performing most of the analysis online (e.g., during the model simulation) to avoid needlessly producing and storing terabytes of data. Another approach to deal with large amounts of data in CPRCM evaluation is to follow an object-oriented approach that has been already applied several times for convective precipitation (Structure Amplitude Location verification measure (Brisson, Demuzere, & van Lipzig, 2016; Prein, Liu, Ikeda, et al., 2017) and tracking (Brisson et al., 2018; Caillaud et al., 2021; Crook et al., 2019; Li, Li, & Li, 2020; Prein, Liu, Ikeda, et al., 2017; Purr et al., 2019, 2021; Yang et al., 2017)). This approach consists in characterizing precipitation fields into a list of objects (usually a convective cell or a cluster of convective cells) that are associated with key parameters. This way, the size of the data to handle reduces dramatically from 3D fields (horizontal spatial dimension and time) to a few parameters of interest, without the loss of relevant information. As an interesting application of the tracking approach, Rüdisühli et al. (2020) analyzed the climatological distribution of precipitation in Europe in relation to cyclones and fronts in a 9-year European CPRCM simulation. Finally, a classification algorithm has been proposed to identify days with an elevated potential for extreme precipitation, or other variables for which added value is expected, in order to perform CPRCM simulations only when they are deemed the most useful, reducing the computational load (Beaulant et al., 2011; Meredith et al., 2018).

3 | EVIDENCE OF ADDED VALUE IN CPRCM HINDCAST SIMULATIONS

3.1 | Precipitation

Precipitation is the outcome of a long and complex chain of processes in which convection plays an essential role. With finer resolutions, that lead to a more detailed representation of the Earth's topography, and an explicit representation of deep convection with CPRCMs, precipitation characteristics such as the diurnal cycle, frequency, intensity, spatial and temporal distributions, and extremes should be improved.

3.1.1 | Diurnal cycle of precipitation

Over Europe in summer, the observed late afternoon diurnal peak of precipitation is associated with the strong solar radiative heating of the Earth surface during the day, generating vertical atmospheric instability and increasing convective build-up to a maximum in the afternoon (Vergara-Temprado et al., 2020). Focusing on the diurnal cycle of summer convection over the Alps, Keller et al. (2016) showed improvements of CPRCMs in simulated cloud cover and associated consequences on radiation compared to a RCM. Moreover, due to the formulation of their DCPs, RCMs have a tendency to prematurely release convective instabilities and adjust vertical stability of the atmosphere (Leutwyler et al., 2016, 2017). For most DCPs, there is no memory of the atmospheric instabilities from one time step to the next (Kendon et al., 2012), explaining why precipitation with RCMs tends to peak in association with the maximum solar radiation near noon. On the contrary, due to the explicit simulation of deep convection, atmospheric instabilities in CPRCMs build up during the day and are more realistically released in the form of precipitation at the end of the afternoon (Leutwyler et al., 2016). The diurnal cycle of precipitation simulated by CPRCMs was studied over the Alps (Ban et al., 2014, 2021; Keller et al., 2016; Leutwyler et al., 2017; Prein, Gobiet, et al., 2013; Vergara-Temprado et al., 2020), Austria (Piazza et al., 2019), Germany (Fosser et al., 2015; Knist et al., 2020a; Meredith et al., 2021), Belgium (Brisson, Van Weverberg, et al., 2016), UK (Chan, Kahana, et al., 2018; Fosser, Kendon, Chan, et al., 2020; Kendon et al., 2012), and Scandinavia (Lind et al., 2020). The shift of the peak and the increase in amplitude of the diurnal cycle over Europe by two RCMs and two CPRCMs are well illustrated in Berthou et al. (2020). In an intercomparison of many CPRCMs over Switzerland, France, and Italy, Ban et al. (2021) showed that the ensemble mean diurnal cycle timing and amplitude are generally improved with CPRCMs, but noted that the inter-model spread was quite large.

Over Asia, similar improvements in the precipitation diurnal cycle were also revealed with CPRCMs in summer with a later peak that matches the observations over China (Guo et al., 2019, 2020; Li, Furtado, et al., 2020; Yun et al., 2020), the Himalayas (Ahrens et al., 2020; Karki et al., 2017; Norris et al., 2017), India (Konduru & Takahashi, 2020; Willetts et al., 2017), and the maritime continents (Argüeso et al., 2016, 2020; Birch et al., 2016; Hassim et al., 2016). Birch et al. (2016) and Argüeso et al. (2020) emphasized that convection and precipitation sustained in the late afternoon are also due to sea breeze convergence and complex topography over the maritime continent that are better represented in CPRCMs. An interesting small-scale feature, that is only captured with the CPRCMs, is the nocturnal peak of precipitation in the Himalayan foothills (Ahrens et al., 2020; Karki et al., 2017; Norris et al., 2017).

The diurnal cycle of precipitation over Africa is characterized by a peak in the afternoon that is often simulated too early by parameterized-convection RCMs and GCMs (Stratton et al., 2018), similar to European summer. The diurnal cycle of moist convection, and thus precipitation, are better simulated in CPRCMs, and keep improving with finer grid spacings of only few km over West Africa (Birch, Parker, et al., 2014; Marsham et al., 2013; Pearson et al., 2014). Still, smaller systems such as convective plumes and small showers remain unresolved in CPRCMs (Stratton et al., 2018). Over West Africa, Zhang, Cook, and Vizy (2016) found that a CPRCM is capable of capturing afternoon rainfall peaks associated with elevated topography and nocturnal peaks downstream the mountains. Berthou, Rowell, et al. (2019) showed that the diurnal cycle of precipitation is improved with a CPRCM, affecting the diurnal cycle of monsoon winds and increasing the moisture convergence in the Sahel. Over East Africa, the explicit representation of convection with CPRCMs leads to significant improvements in the intensities and diurnal cycle of rainfall when compared with a parameterized-convection simulation, especially over the Lake Victoria and its vicinity (Finney et al., 2019; Van de Walle et al., 2020; Woodhams et al., 2018). In contrast to the above studies, Pohl et al. (2014) found that the use of a CPRCM did not clearly reduce the diurnal cycle biases simulated over Southern Africa.

The North American diurnal precipitation cycle is characterized by late afternoon convective precipitation over a large part of its territory, with similar improvements by CPRCMs as for the other regions mentioned above (Gao et al., 2017; Rasmussen et al., 2020). An exception to this diurnal cycle is evident for the Great Plains in central North America, where mesoscale convective systems (MCS) occur during the night and early morning (Prein, Liu, et al., 2020). Sun et al. (2016) showed that a 4-km CPRCM better simulates the low-level jet that transports moisture from the Gulf of Mexico toward the Great Plains, where precipitation extremes and diurnal cycle are consequently improved. In a study tracking MCS precipitation, Feng et al. (2018) showed that CPRCMs were capable of correctly simulating the eastward time shift of the diurnal cycle of the MCS precipitation fraction. Scaff et al. (2020) highlighted that a CPRCM is able to realistically simulate the magnitude and the timing of the diurnal cycle with the notable transition from the afternoon peak eastward of the Rockies to night peaks in central U.S. associated to propagating MCS.

3.1.2 | Intensity, frequency and duration of precipitation

With an improved realism of deep convection in CPRCMs, other important precipitation characteristics are also improved such as the precipitation frequency, intensity and duration. Using a probability distribution of rain spell duration for rainfall exceeding various percentile thresholds, Kendon et al. (2012) showed that precipitation in a 12-km RCM is too persistent, too widespread, and with heavy rain events that are underestimated over the UK. Conversely, with a 1.5-km CPRCM, Kendon et al. (2012) obtained heavy rain events that are too intense, but with a representation of rain duration and spatial extent that are in much better agreement with radar observations. Similar results were obtained over the Alps with better precipitation frequency and intensity with a CPRCM than an RCM, where improvements are more obvious at the hourly scale (Adinolfi et al., 2021; Ban et al., 2014; Lind et al., 2016). In an intercomparison of RCMs and CPRCMs covering most of Europe, Berthou et al. (2020) confirmed that precipitation that tends to be too frequent and too light with RCMs is largely corrected with CPRCMs over the UK, Switzerland and Germany. In a study comparing 23 CPRCM simulations, though individual CPRCMs gave contrasting results, the CPRCM ensemble means of the precipitation frequency and intensity are in much better agreement with different gridded datasets over France, Switzerland and Italy than those from the RCM ensemble (Ban et al., 2021). Reder et al. (2020) found better agreement in the number of consecutive dry and wet days from a CPRCM than an RCM with observations over Switzerland, especially at higher elevations. Improvements in the precipitation frequency and intensity with CPRCMs were also found over China (Gao, Chen, & Jiang, 2020; Guo et al., 2019, 2020; Li, Furtado, et al., 2020; Yun et al., 2020), Africa (Berthou, Rowell, et al., 2019; Stratton et al., 2018) and the United States (Chang et al., 2020; Dai, Rasmussen, Liu, et al., 2020).

3.1.3 | Precipitation extremes

Other important benefits in the use of CPRCMs to bridge the gap between GCMs and end-users (Maraun et al., 2010) come from their capacity to simulate sub-daily and shorter duration precipitation, including extremes (Barbero et al., 2019; Fowler et al., 2021a,b,c; Gutjahr et al., 2016; Tölle et al., 2018; Vergara-Temprado et al., 2021; Westra et al., 2014). CPRCMs are capable of more realistically simulating fine-scale meteorological phenomena that produce large amounts of rainfall, such as MCS (Feng et al., 2018; Prein et al., 2021; Prein, Liu, et al., 2020; Prein, Liu, Ikeda, et al., 2017), stronger tropical cyclones with lower central minimum pressure (Gutmann et al., 2018; Kanada et al., 2013), orographic precipitation (Jing et al., 2018; Prein, Holland, et al., 2013; Reder et al., 2020), drylines (Scaff et al., 2021), and squall lines (Purr et al., 2019). Figure 2 shows another example where CPRCMs add value in their better performance over RCMs in simulating Mediterranean Heavy Precipitation Events that occur in fall in southeastern France with >100 mm in a few hours (Caillaud et al., 2021; Fumière et al., 2020; Luu et al., 2021).

The signs of improved precipitation extremes in long-term (>5 years) CPRMs are prevalent in literature, with different percentile based metrics: Using percentile maps of daily and hourly precipitation over Europe (Ban et al., 2014, 2021; Berthou et al., 2020; Leutwyler et al., 2017; Lind et al., 2016), Africa (Berthou, Rowell, et al., 2019), northern (Diro & Sushama, 2019) and western (Li, Li, et al., 2019) Canada, and southern U.S. (Sun et al., 2016), using probability density functions or cumulative distributions of daily and hourly precipitation intensities (Ban et al., 2014; Brisson, Van Weverberg, et al., 2016; Diro & Sushama, 2019; Fosser et al., 2015; Kendon et al., 2012; Knist et al., 2020a; Kouadio et al., 2020; Leutwyler et al., 2017; Li, Li, et al., 2019; Lind et al., 2016; Murata, Sasaki, Kawase, & Nosaka, 2017; Piazza et al., 2019; Pieri et al., 2015; Reder et al., 2020; Sun et al., 2016; Vergara-Temprado et al., 2020; Wang et al., 2018), using the contribution of each precipitation bin to the total precipitation (Berthou et al., 2020; Berthou, Rowell, et al., 2019; Dai, Rasmussen, Liu, et al., 2020; Finney et al., 2019; Lind et al., 2020; Stratton et al., 2018; Vergara-Temprado et al., 2020) or quantile–quantile plots (Gutjahr et al., 2016; Karki et al., 2017; Wang et al., 2018). The use of percentiles differs between studies, in that there is no standard practice on whether all time steps or only wet intervals above some lower limit are included. This can strongly affect how extreme, that is, how rare, the events really are (Schär et al., 2016). A bias in the number of dry intervals in the historical period or a shift of these intervals in future periods can therefore affect the results. Extreme value theory focusing on the very largest events has also been applied to CPRCMs (Ban et al., 2020; Chan, Kendon, Fowler, Blenkinshop, & Ferro, 2014; Gutjahr et al., 2016; Knote et al., 2010). Analyzing a long 67-year CPRCM simulation over northern Germany and Denmark, Schaaf et al. (2019) found large decadal variability and a significant positive trend in extreme precipitation. Some studies also suggest that improvements of extremes are even seen in shorter duration events such as sub-hourly precipitation where CPRCMs outperform RCMs (Chan, Kendon, Roberts, Fowler, & Blenkinsop, 2016; Meredith et al., 2020; Vergara-Temprado et al., 2021), supporting the use of CPRCM precipitation for flash flood studies. Validation of daily and sub daily precipitation statistics derived from intensity-duration-frequency (IDF) curves, showed a better match of the two CPRCMs with the observations compared to the driving GCMs and reanalyses (Tabari et al., 2016).

Short CPRCM simulations have also been performed to reproduce specific extreme events (Beaulant et al., 2011; Cassola et al., 2015; Chawla et al., 2018; Coppola et al., 2020; Khodayar et al., 2016; Kumar et al., 2014; Li, Guo, et al., 2019; Li, Szeto, et al., 2017; Mahoney et al., 2013; Meredith, Semenov, et al., 2015; Olsson et al., 2017; Pontoppidan et al., 2017; Warrach-Sagi et al., 2013). In this case, the evaluation is based on the ability of the model to reproduce a specific or few extreme events rather than the extreme statistics from a long climate sample. In such evaluations, a CPRCM is driven at the LBC by a reanalysis (or an intermediate RCM driven by a reanalysis) or from a GCM in which extreme events are selected (Beaulant et al., 2011; Mahoney et al., 2013). Simulating only few days, the case study approach can be useful to reach higher resolutions in order to focus on smaller scale meteorological processes (Wang et al., 2013) or to perform many simulations in which some parameters are perturbed (Meredith, Semenov, et al., 2015) or parameterization schemes are modified (Chawla et al., 2018). In Coppola et al. (2020), while most CPRCMs were able

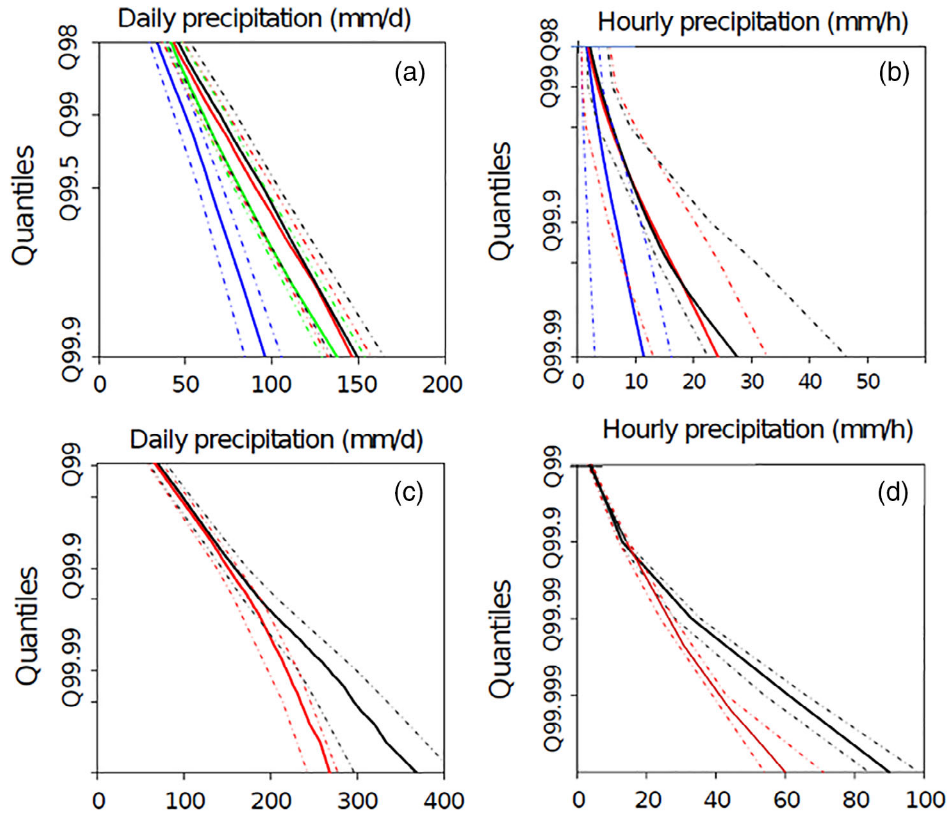

FIGURE 2 Tail of the cumulative density functions (1-cdf) of daily rainfall (a, c) in mm/day and of hourly rainfall (b, d) in mm/h from dry and wet days over all the grid points of a southeastern France region in fall (SOND) between 1997 and 2006. The CNRM-ALADIN 12-km RCM (blue) and CNRM-AROME 2.5-km CPRCM (red) are compared to two gridded precipitation observations (COMEPHORE [black] and SAFRAN [green]). Dot-dashed lines correspond to the 90% confidence interval according to a bootstrapping method. Figures (a) and (b) represent the datasets at a resolution of 12.5 km (CNRM-ALADIN grid) while figures (c) and (d) represent COMEPHORE and CNRM-AROME datasets at a resolution of 2.5 km (CNRM-AROME grid). (Reprinted with permission from Fumière et al. (2020). Copyright 2020 springer nature)

to capture the selected extreme events, some CPRCMs completely missed them, either because of the poor performance of the CPRCMs or of the deviation of the intermediate RCM synoptic circulation from the driving field, a consequence of RCM internal variability (Alexandru et al., 2007; Lucas-Picher et al., 2008; Lavin-Gullon, Fernandez, et al., 2021).

3.2 | Temperature

While 2-m temperature (2mt) is rarely the main focus of CPRCM evaluation and added value over RCMs, many studies have found improvements in simulating 2mt with a CPRCM over the Alps (Ban et al., 2014; Hohenegger et al., 2008; Keller et al., 2016; Prein, Gobiet, et al., 2013), Germany (Hackenbruch et al., 2016; Tölle et al., 2018), Scandinavia (Belušić et al., 2020; Lind et al., 2020), Europe (Leutwyler et al., 2017), Africa (Stratton et al., 2018), the United States (Liu et al., 2017), Alaska (Monaghan et al., 2018), western (Li, Li, et al., 2019) and northern (Diro & Sushama, 2019) Canada, and Himalayas (Karki et al., 2017; Norris et al., 2017). Many reasons are proposed to explain why the representation of 2mt would be improved in CPRCMs.

First, at higher resolutions, mountain and valley elevations in CPRCMs are closer to reality. Thus, following the general cooling of the atmosphere with higher elevations by approximately 6.5°C/km (Karki et al., 2017; Li, Li, et al., 2019; Lind et al., 2020; Prein, Gobiet, et al., 2013), the simulated 2mt should be improved with a CPRCM purely by the more accurate topography. Indeed, Karki et al. (2020) used a CPRCM to improve the estimate of the lapse rate seasonal variability over the Himalayas. Consequently, when exploring CPRCM added value, the elevation dependency is often removed by adjusting 2mt using a lapse rate correction (Ban et al., 2014; Belušić et al., 2020; Hohenegger et al., 2008; Keller et al., 2016; Lind et al., 2020; Prein, Gobiet, et al., 2013). Second, with a better representation of clouds and radiative budget due to the explicit simulation of convection with CPRCMs, the diurnal cycle of temperature and the diurnal temperature range, are usually improved with a CPRCM, especially in summer (Ban et al., 2014; Hohenegger et al., 2008; Keller et al., 2016; Leutwyler et al., 2017; Lind et al., 2020; Stratton et al., 2018). Leutwyler et al. (2017) and Hentgen et al. (2019) highlighted the difference of the simulated cloud cover between RCMs and CPRCMs. They explained that the explicit representation of deep convective clouds leads to more frequent clear-sky conditions, inducing an increase in surface solar radiation, ultimately affecting 2mt. Third, because 2mt biases are often related to precipitation biases (too wet too cold, too dry too warm), improved temporal and spatial patterns of precipitation can improve the simulation of 2mt (Liu et al., 2017). The simulated 2mt is also closely linked to the degree of sophistication of schemes related to the representation of snow cover (Li, Li, et al., 2019; Liu et al., 2017), soil moisture feedback (Hohenegger et al., 2009; Leutwyler et al., 2017; Taylor et al., 2013; Zhang, Li, et al., 2020), and land-atmosphere coupling strength (Chen et al., 2019), which are usually more advanced in CPRCMs. Fourth, the improved simulation of local meteorological processes such as foehn (Bannister & King, 2015; Temme et al., 2020), wind channeling (Norris et al., 2017), sea breezes (Zhu et al., 2017), and orographic precipitation (Li, Li, et al., 2019) could lead to locally improved mean seasonal and diurnal 2mt. Finally, with higher resolution, a better spatial distribution of land use and land cover can locally improve the spatial distribution of 2mt (Argüeso et al., 2014; Bonekamp et al., 2018; Jänicke et al., 2017; Tölle et al., 2014; Vanden Broucke & Van Lipzig, 2017). Prescribing land-use and land-cover changes in CPRCMs can be useful to investigate the effects of mitigation strategies such as greening of the Arctic and afforestation (Mooney et al., 2020). When decomposing 2mt changes associated with land-use change, Vanden Broucke and Van Lipzig (2017) found that a CPRCM reduced biases in daytime shortwave radiation, daytime sensible heat flux, and nighttime incoming longwave radiation compared to an RCM. Qian et al. (2020) found that including irrigation in a CPRCM increased evapotranspiration, increased MCS, and reduced summer precipitation deficits, alleviating warm 2mt biases over central U.S.

3.3 | Non orographically induced mesoscale meteorological phenomena

3.3.1 | Tropical and extratropical cyclones

High-resolution (10–50 km) GCMs and RCMs with parameterized convection are able to produce tropical cyclones (TCs), but the low-pressure center intensities remain high compared to those observed (Caron et al., 2011). In a sensitivity study of the TC structure to horizontal resolutions, Gentry and Lackmann (2010) noted that as the resolution is increased (8–1 km), minimum central pressure decreases significantly, approaching that observed. Other studies based on the simulation of a single or few TCs with a CPRCM found improvements in the intensification, track, and the realism of TCs (Braun, 2002; Davis & Bosart, 2002; Kanada et al., 2012; Taraphdar et al., 2014). Analyzing a 13-year 4-km CPRCM simulation over North America, Gutmann et al. (2018) showed that cyclone tracks, storm radii, and translation speeds in the western Atlantic Ocean and Gulf of Mexico were generally well simulated, but the maximum wind speeds were underestimated, while the minimum central pressures were too high.

Extratropical cyclones (ETC) often originate from TCs that weaken as they migrate toward the poles. While ETC are synoptic-scale systems that are generally well simulated with coarse-resolution GCMs and RCMs, some mesoscale features of ETC such as wind speed (Schaaf & Feser, 2018), wind gusts (Eisenstein et al., 2020; Pantillon et al., 2018; Schaaf & Feser, 2018), core mean sea level pressure (Leutwyler et al., 2016; Schaaf & Feser, 2018), small-scale precipitation along the cold front (Leutwyler et al., 2016), and cloud cover (Schaaf & Feser, 2018) are better simulated using CPRCMs. Many studies highlighted CPRCM added-value in their ability to simulate sting jets that are air streams that descend from cloud head into the frontal-fracture region, which can produce extreme surface gusts in some intense ETCs, especially over the UK and central Europe (Eisenstein et al., 2020; Pantillon et al., 2018). Only high-resolution simulations of few km grid spacing with convective parameterization turned off can well represent the mesoscale instability release and embedded convection in sting jets (Eisenstein et al., 2020; Martínez-Alvarado et al., 2018; Pantillon et al., 2018).

3.3.2 | Hail and lightning

Kendon et al. (2017) pointed to hail and lightning as weather hazards for which CPRCM benefits were likely, but not yet proven. By accurately modeling hazardous convective weather, Gensini and Mote (2014) already suggested that such processes are likely to be well reproduced in CPRCMs. Early studies definitely assess that advanced parameterizations, particularly adapted for CPRCMs (that rely on updraft speed or/and graupel estimations), provide improved representations of lightning compared to more common parameterizations (Cloud top height, CAPExPREC) used in GCMs and RCMs (Brisson et al., 2021; Finney, Marsham, Wilkinson, et al., 2020; Lagasio et al., 2017). Hail applications using CPRCMs are rather limited due to the difficulty in both modeling and retrieving robust observations. Initial studies in NWP indicated good potential in simulating storms capable of producing hail using convection-permitting resolutions (García-Ortega et al., 2017; Luo et al., 2018, 2020) and exploiting double-moment MS treating graupel and hail separately, that could serve wind turbine erosion applications (Letson et al., 2020a, 2020b). Two methods are paving the way: the use of an online hail growth model, which gives promising results in convection-permitting models over short periods (Adams-Selin & Ziegler, 2016) and statistical approaches fed by CPRCM outputs.

3.3.3 | Monsoon

GCMs show large biases in the Indian summer monsoon with a wet bias over the Indian Ocean and a dry bias over India due to a too weak low-level flow into India and a poor representation of moist convection (Willetts et al., 2017). The representation of the Indian monsoon characteristics is improved with the higher resolution of RCMs, but many biases remain (Lucas-Picher et al., 2011). Willetts et al. (2017) showed that a CPRCM simulated more intense rainfalls over India, a later peak in the diurnal cycle of convective rainfall over land, and a reduced positive rainfall bias over the Indian Ocean. The timing and amplitude of the rainfall, and the vertical distribution of hydrometeors in short CPRCM simulations were generally in agreement with observations (Jayakumar et al., 2017, 2020). Finally, in a series of CPRCM simulations over India, Konduru and Takahashi (2020) revealed that rainfall characteristics of the Indian summer monsoon such as the diurnal cycle, diurnal peak, and the intensity and frequency of precipitation are well captured when the cumulus parameterization is turned off.

Issues with parameterized convection in GCMs give biases also in context of the West African Monsoon (WAM) (Dirmeyer et al., 2012). Marsham et al. (2013) showed that improving the representation of convection with a CPRCM produced greater latent and radiative heating farther north, which brought more realistic rainfall over the Sahel. In addition, Birch, Parker, et al. (2014) found that the water cycle is improved over West Africa with a better diurnal cycle and location of convection when convection is explicitly simulated, while Birch, Marsham, et al. (2014) showed that a CPRCM improved the initiation and the magnitude of convection during the WAM season. Stein et al. (2015) demonstrated that the representation of clouds and precipitation of the WAM improved dramatically when convection parameterization is switched off due to a reduction in daytime convection. Using a tracking algorithm of MCSs, Maurer et al. (2017) confirmed the importance of local convection initiation downstream of spatial land-surface anomalies in the Sahel. Berthou, Rowell, et al. (2019) showed that many aspects of the WAM such as the distribution of precipitation rates, wet and dry spells, and the diurnal cycle of rainfall are improved in a CPRCM simulation. From sensitivities studies, Matsui et al. (2020) highlighted that lowering the radiation update frequency increased precipitation and cloudiness over the WAM region, while Mantsis et al. (2020) revealed that the simulation of Saharan mid-level clouds improved when the vertical resolution becomes high enough to allow layers of supercooled water and ice to exist separately.

The East Asian summer monsoon (EASM) is characterized by a northward summer migration of rain bands across China that is not well simulated in GCMs, partly due to the representation of convection with parameterizations (Chen et al., 2010). The simulated precipitation over China is improved using a high resolution RCM, but dry bias remains in northern China (Zou et al., 2016). EASM features such as the northward progression and southward retreat of the main rain band, the diurnal variations of precipitation, and propagation of precipitation through embedded MCS are more realistically simulated with CPRCMs (Yun et al., 2020; Zhu et al., 2018). In a comparison of simulations with different resolutions, Li, Furtado, et al. (2020) showed that a CPRCM improved the spatial distribution of precipitation intensity and diurnal cycle, but overestimated the intensity and produced too much rainfall over central eastern China.

Warm season convection in the North American monsoon (NAM) region is handicapped by the inability of atmospheric models using conventional RCMs to simulate MCSs (Luong et al., 2018). Moker Jr. et al. (2018) and Risanto et al. (2019) highlighted the advantages of using CPRCMs to resolve atmospheric features that are useful to improve forecasting skills of the NAM. Luong et al. (2017) showed that a CPRCM is able to represent the diurnal cycle of convective precipitation and extreme precipitation in southwestern U.S. compared to coarser resolution simulations. In a sensitivity study of summer precipitation at different resolutions, Gao et al. (2017) found that summer rainfall and its diurnal cycle are notably improved at 4 km with the cumulus parameterization turned off. Finally, mean and extreme precipitation biases were reduced and the representation of the eastward MCS propagation, largely accounting for extreme summer rainfall during the NAM, was improved employing a 3-km CPRCM over southwestern U.S. (Pal et al., 2019).

3.3.4 | Lake effect

Natural and artificial lakes can have large impacts on the climate of their surroundings (Eichenlaub, 1987; Scott & Huff, 1996). Due to the different heat capacities of land and water, thermal contrasts occur and different regional meteorological phenomena such as lake breezes and lake effects are initiated. With finer resolutions and explicit convection from CPRCMs, lakes can be better delineated and their impacts on the atmospheric circulation and dynamics can be better simulated. Indeed, conducting monthly CPRCM simulations including or not the Lake Nam Co over the Tibetan Plateau, Dai et al. (2018) found that the presence of the lake can increase precipitation up to 60% over and downwind the lake. However, CPRCM simulated lake effects are closely linked to the ability of the lake model to represent lake temperatures, dynamics, and initial conditions (Wu et al., 2020; Xu et al., 2017).

Comparing control and no-lake CPRCM simulations, Van de Walle et al. (2020) found that the presence of Lake Victoria in East Africa intensified over-lake rainfall, improved the timing and location of precipitation, but slightly increased regional precipitation. The timing of the peak precipitation diurnal cycle was found to be better simulated with CPRCMs due to more realistic land and lake breezes over and around Lake Victoria (Belušić et al., 2020; Finney et al., 2019; Van de Walle et al., 2020). With the use of convection-permitting NWP models, wind speeds and rainfall rates are more realistic over Lake Victoria and its vicinity, leading to improved weather and storm forecasts (Chamberlain et al., 2014; Woodhams et al., 2018).

Meredith, Semenov, et al. (2015) and Meredith, Maraun, et al. (2015) explored CPRCM added value comparing the response of a coastal precipitation extreme to a wide range of sea surface temperature (SST) of the Black Sea forcing an ensemble of RCM and CPRCM simulations. They found that increased local intensities of vertical motion and precipitation simulated only in the CPRCM simulations were essential in shaping a nonlinear extreme precipitation response to SST increase. In their CPRCM simulations, the SST increase caused precipitation intensity to increase until a threshold was reached compared to a much more linear response in parameterized convection simulations.

Lake effect snow is a mesoscale convective phenomenon that occurs in northern hemisphere fall and winter when a cold air mass flows over a warm ice-free water surface, triggering convection and producing heavy snowfall over downwind regions. Due to the high sensitivity to sharp temperature gradients and localized convection processes, parameterized convection RCMs with resolutions coarser than 10 km showed mixed results in simulating lake effect snow events (Lucas-Picher et al., 2017; Notaro et al., 2015). McMillen and Steenburgh (2015) showed that a CPRCM realistically simulated lake effect snow events around the Great Salt Lake and produced skilled forecasts, but struggled with precipitation amount and location. Simulating two major lake-effect snowstorms with a CPRCM over the Great Lakes, Minder et al. (2020) found that most CPRCM configurations simulated credible lake-effect snow, but with a large sensitivity to different parameterizations of turbulent surface layer and PBL. Finally, events over Finland that were generated over the Baltic Sea were captured well in a CPRCM with good timing and location of the most intense snowstorms (Olsson et al., 2017). Olsson et al. (2020) refined a set of criteria to detect lake-effect snowfall over the Finnish coast simulating four case studies with a CPRCM to gain information on atmospheric conditions favoring coastal snow band formation.

3.3.5 | Sea breeze

Sea breeze is a daily recurring thermally driven mesoscale meteorological phenomenon that consists of a wind blowing from a large body of water toward a landmass (Crosman & Horel, 2010). This phenomenon can produce precipitation along the sea breeze front and when sea breezes converge over islands (Argüeso et al., 2020; Birch et al., 2016). While 12-km RCMs can partially simulate this phenomenon (Lucas-Picher et al., 2017), higher resolution is needed for a detailed simulation (Crosman & Horel, 2010; Love et al., 2011). Some CPRCM studies analyzed sea breezes over the maritime continent (Argüeso et al., 2016, 2020; Birch et al., 2015, 2016; Love et al., 2011; Wei et al., 2020), Lake Victoria (Brousse et al., 2020; Finney et al., 2019; Van de Walle et al., 2020), Southeastern China (Yeung et al., 2020), southern UK (Wang et al., 2013), West Africa (Coulibaly et al., 2021), and the Netherlands (Arrillaga et al., 2020). Sensitivity studies have shown that both explicit convection and higher resolutions contribute to the improved sea breeze with

CPRCMs, that ultimately lead also to an improved diurnal cycle of precipitation (Argüeso et al., 2016, 2020; Birch et al., 2016; Finney et al., 2019). Using hodographs and wind roses, Coulibaly et al. (2021) demonstrated that their CPRCM is capable of simulating the sea breeze and its rotation along the Guinean coast.

3.3.6 | Representation of clouds and radiation

With the need to use parameterizations for representing clouds and radiative processes that occur on spatial scales much finer than the grid scale of climate models, the simulation of clouds and radiation with RCMs suffers from persistent biases (Kothe et al., 2011; Tjernström et al., 2008). With the explicit representation of convection in CPRCMs, an improved description of hydrometeors is expected to result in improved cloud and radiation modeling. Most studies with a focus on cloud properties showed an improved description of the diurnal cycle of cloudiness, as well as an improved description of total cloudiness and high clouds all along the day with CPRCMs (Brisson, Van Weverberg, et al., 2016; Hart et al., 2018; Hentgen et al., 2019; Keller et al., 2016; Mantsis et al., 2020; Schaaf & Feser, 2018; Stein et al., 2015). However, modeling clouds remains a challenge even with CPRCMs that still require several parameterizations (shallow convection, microphysics and clouds) that need to be adapted for finer resolutions (Kendon et al., 2021). While the explicit representation of the vertical mixing provides more reliable input to the cloud dynamics and the microphysics parameterizations, large uncertainties remaining in these model components still limit the potential of CPRCMs.

3.4 | Orographically induced meteorological phenomena

3.4.1 | Orographic precipitation

Orographic precipitation is produced when moist air is lifted as it moves over a mountain range, with resulting cooling, and eventually condensation and precipitation formation (Piazza et al., 2019; Roe, 2005). The simulation of orographic precipitation is expected to be improved in CPRCMs due the more realistic representation of the Earth's topography at high resolutions.

The lack of reliable weather stations in regions with complex topography leads to little knowledge on how orographic precipitation shapes the local precipitation. Consequently, this fact challenges the evaluation of climate simulations (Maussion et al., 2011; Norris et al., 2017) and the application of bias corrections (Bannister et al., 2019). Many RCM simulations over the Himalayas have a wet bias at high elevations and a dry bias in the foothills because of the underestimation of orographic precipitation (Ghimire et al., 2018; Lin et al., 2018). CPRCMs show more realistic orographic precipitation over the Himalayas with improvements of the spatial distribution of precipitation and extremes compared to coarser RCMs (Ahrens et al., 2020; Karki et al., 2017; Li, Gochis, et al., 2017; Lin et al., 2018; Maussion et al., 2011; Norris et al., 2015, 2017). The wet bias over the Tibetan Plateau in RCM simulations is corrected by the reduction of water vapor transport toward the Tibetan Plateau due to the steeper terrain of CPRCMs that slow down winds speeds and increase orographic precipitation at the Himalayan foothills (Li et al., 2021; Lin et al., 2018).

Using climate simulations at different resolutions over the Alps, Grell et al. (2000) found evidence of added value by increasing resolution of the terrain. They also found that with the different treatment of convection, parameterized convection in RCMs tends to be locked to the mountains, while convection moves with the upper level flow producing precipitation maxima away from mountain tops when it is explicitly simulated. Langhans et al. (2013) showed that Alpine-scale flow convergence weakens when a convection scheme is applied, due to too early cloud cover formation, which shields incoming shortwave radiation. The reduced grid spacing and the explicit representation of convection with CPRCMs generally improves the simulation of orographic precipitation over the Alps (Adinolfi et al., 2021; Ban et al., 2014; Giorgi et al., 2016; Grell et al., 2000; Hohenegger et al., 2008; Keller et al., 2016; Langhans et al., 2013; Leutwyler et al., 2017; Lind et al., 2016; Lüthi et al., 2019; Piazza et al., 2019; Prein, Gobiet, et al., 2013; Reder et al., 2020). Over the Alps, more precipitation is produced at higher elevations with an improved agreement with observation using CPRCMs compared to RCMs (Ban et al., 2014; Lind et al., 2016; Lüthi et al., 2019; Reder et al., 2020). Comparing CPRCM simulations with other simulations using a smoothed orography, Prein, Gobiet, et al. (2013) and Piazza et al. (2019) determined that the added value of precipitation with CPRCMs is largely due to the explicit treatment of convective processes and that the more detailed orography at higher resolutions plays a minor role. However, in a sensitivity study of CPRCM simulations to land surface inhomogeneity, Knist et al. (2020b) found that a coarser-resolved orography significantly alters the flow over and around the mountains ridges of the Alps, affecting local precipitation pattern and intensity. Fosser et al. (2015) emphasized the importance of the more detailed representation of the orographic features with a CPRCM, which produces areas of atmospheric convergence that trigger convection.

Orographic precipitation is an important source of water in the interior western United States, a region that would otherwise be arid (Jing et al., 2018; Rasmussen et al., 2014; Roe, 2005). Jing et al. (2017) revealed that a 4-km CPRCM simulation captured wintertime orographic precipitation distribution and intensity well over western United States and that some of the biases were partly due to error in the snowfall measurements. In a following study, Jing et al. (2018) determined that the dominant factor controlling orographic precipitation is the low-level wind speed perpendicular to the mountain. In a CPRCM evaluation study over western Canada, Li, Li, et al. (2019) explained that higher peaks and lower valleys over the Canadian Rockies introduced orographic precipitation differences between their CPRCM and coarse-resolution observed gridded datasets, making a thorough evaluation difficult. Over the central Andes, an increase of CPRCM resolution led to smaller precipitation biases, with an improved performance as elevation increased (Schumacher et al., 2020) that was also associated with a better structure of cloud systems (Moya-Álvarez et al., 2019). Performing a sensitivity study with a CPRCM using terrain height modifications, Rasmussen and Houze (2016) underlined the importance of the orographic control of the Andes on the initiation of convection and its upscale growth into MCSs in South America.

The use of a CPRCM was found to be useful to improve the simulation of orographic precipitation in many other regions. Indeed, Mölg et al. (2020) linked observed glacier meteorological elevation gradients to a CPRCM dataset that revealed the importance of mesoscale atmospheric circulation on the evolution of the Kersten Glacier near the Kilimanjaro Summit. El-Samra et al. (2018) showed that a CPRCM improved the simulation of mean and extreme precipitation over the orographically complex terrain of Lebanon. Jing et al. (2020) found that seasonal precipitation distributions, mean monthly precipitation, and precipitation variability were well simulated using a CPRCM mainly due to the better resolved complex terrain at high resolution over the United Arab Emirates. In a comparison of the orographic precipitation simulated at different resolutions over a southern Norway island, Barstad and Caroletti (2013) found that 1-km resolution is necessary for capturing the most intense precipitation events satisfactorily. Simulating an intense precipitation event in western Norway Mountains using different resolutions, Pontoppidan et al. (2017) found the largest improvements decreasing the model grid from 9 km (parameterized convection) to 3 km (explicit convection). Finally, Poujol, Sobolowski, et al. (2020) presented a physically based algorithm allowing to separate precipitation in three types (convective, stratiform, orographically enhanced) that may become useful to investigate precipitation characteristics and related processes.

3.4.2 | Snowfall and snow cover in mountainous regions

Related to an improved simulation of mesoscale dynamics and orographic precipitation in CPRCMs is their ability to better represent snowfall and surface snow cover in orographically structured terrain. Both snow parameters highly depend on the prevailing temperature conditions in the free atmosphere and close to the ground. The interactive simulation of surface snow cover as part of the land surface schemes of climate models is essential to represent interactions with the overlying atmosphere. This especially relates to the snow-albedo feedback (SAF) mechanism (Fletcher et al., 2015; Hall, 2004; Thackeray et al., 2019) and the influence of snow cover on the energy flux partitioning at the ground surface (Cohen & Rind, 1991). At local and regional scale, a diminishing snow cover can for instance amplify simulated temperature increases along a retreating snowline (Kotlarski et al., 2012, 2015; Letcher & Minder, 2015; Minder et al., 2016; Salathé et al., 2008; Winter et al., 2017). In mountainous regions, the higher spatial resolution of CPRCMs offers the attractive possibility to explicitly represent snow cover at high to very high elevations and to better account for increasing snow mass with elevation and associated feedbacks.

Indeed, previous works have revealed the encouraging potential of CPRCMs to improve on conventional RCMs in the representation of both snowfall and snow cover (Ikeda et al., 2021; Lind et al., 2020; Lüthi et al., 2019). Regarding the former, Lind et al. (2020) reported a more realistic simulation of the snowfall fraction over Scandinavia in their 3-km CPRCM simulation compared to an accompanying 12-km RCM simulation. In addition, some studies yielded an improved representation of snowfall amounts in the Colorado Headwaters regions at grid spacings of 6 km or finer (Ikeda et al., 2010; Rasmussen et al., 2011), but with a high sensitivity to the cloud microphysics, land surface, radiative transfer, and PBL schemes (Liu et al., 2011). In terms of the spatial snowfall distribution, CPRCMs can even improve on gridded observation-based products (Hughes et al., 2020). Regarding the simulated snow cover characteristics, Lüthi et al. (2019)

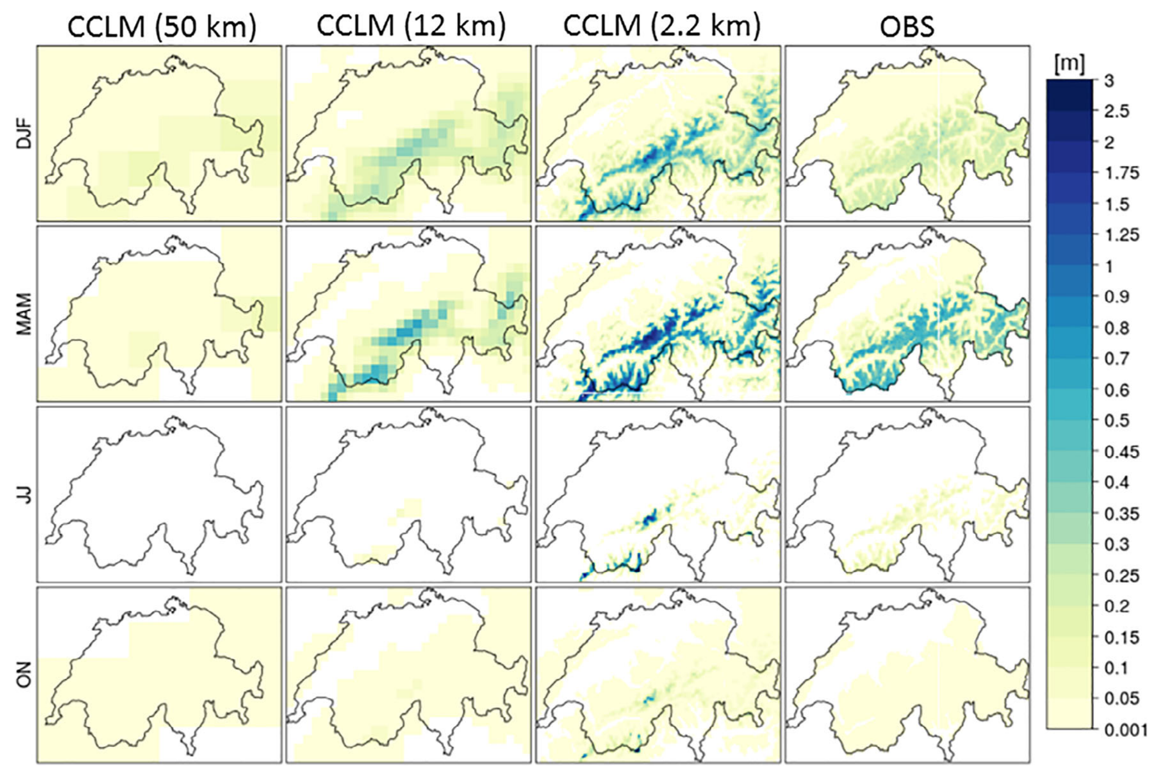

FIGURE 3 Seasonal mean snow water equivalent (meters) over Switzerland during the evaluation period 1998–2007. Results are shown for the three COSMO-CLM (CCLM) simulations (driven by ERA-interim lateral boundary conditions) with grid spacings of 50 km (left column), 12 km (center-left), and 2.2 km (center-right) and observations (OBS) interpolated to the 2.2 km grid (right column). (Reprinted with permission from Lüthi et al. (2019). Copyright 2019 MDPI)

found a much better representation of Alpine snow water equivalent (SWE) in a 2.2-km CPRCM compared to its coarser resolution counterparts (see Figure 3). Similar results were obtained over the Rocky Mountains (Liu et al., 2017; Rasmussen et al., 2011; Silverman et al., 2013) and Alaska (Monaghan et al., 2018). Over the interior western United States, CPRCMs yielded a satisfying performance in terms of several snow parameters and mountain snowpack (Scalzitti et al., 2016; Wang et al., 2018). As for the Japanese Alps, CPRCMs have been shown to realistically represent spatial and temporal snowpack characteristics (Kawase et al., 2018). In addition to the CPRCM added value of the online-simulated snowpack, there are also strong indications for advantages of CPRCMs in offline applications where simulated atmospheric drivers are used to force offline snow cover models (Gao, Chen, & Jiang, 2020; He et al., 2019).

However, Minder et al. (2016) highlighted substantial biases in the simulated CPRCM snow characteristics over the Rocky Mountains, which are in parts related to an inaccurate treatment of vegetation canopy and snow albedo. Wrzesien et al. (2015) underlined the challenges in the simulation of snow cover fraction (SCF) and SWE at finer scales with a CPRCM due to the difficulties in producing temporal variations in grid-scale SCF and too rapid snow depletion. Such inaccuracies of snow cover parameterizations can to some extent be amplified when the spatial resolution is increased. For instance, accumulation issues have been reported, that is, constantly increasing snow mass, at high-elevation grid cells in the European Alps with RCMs (Frei et al., 2018; Hakala et al., 2018; Jacob et al., 2020; Kotlarski et al., 2014) with adverse feedbacks on the simulated 2mt. Such elevations might indeed experience a positive long-term snow mass balance in reality as they are partly exceeding regional-scale glacier equilibrium line altitudes. The problem of simulated "snow towers" might indeed be enhanced in CPRCMs due to their higher-reaching topography and could be accounted for by dedicated snow redistribution or online glacier parameterization schemes (Kotlarski et al., 2010).

3.4.3 | Wind channeling, foehn and diurnal mountain winds

Simulated spatial and temporal variability of wind over land is largely conditioned by the representation of fine-scale orography in climate models (Herrmann et al., 2011; Menendez et al., 2014). The orography can channel local winds and affect wind speeds when a valley is narrowing or widening (Lucas-Picher et al., 2017). Cholette et al. (2015) showed that only CPRCMs (1- and 3-km) are capable of realistically simulating wind channeling (wind direction and speed) occurring in the Saint-Lawrence River Valley in Quebec, Canada (see Figure 4). Hackenbruch et al. (2016) showed that a 2.8-km CPRCM simulated nighttime local wind systems channeling in the Neckar Valley of Germany yielded better agreements with observations than a 7-km RCM. Studying different local winds (Bora, Etesian, and Sirocco) over the Adriatic region, Belušić et al. (2018) found that a CPRCM led to better performance and disclosed that grid spacing of a few km is needed to capture small-scale wind systems. Focusing on the impacts of model resolution on the simulation of Bora wind features, Josipovic et al. (2018) determined that a 2.8-km CPRCM can simulate gap wind and wave breaking features. Wang et al. (2013) demonstrated the added value of CPRCM simulations in modeling local mesoscale climate patterns including southwesterly flows and wind channeling over southern UK. Finally, Lin et al. (2018) found improvements in CPRM simulations regarding the barrier effect of high mountains and the channeling effect of valleys

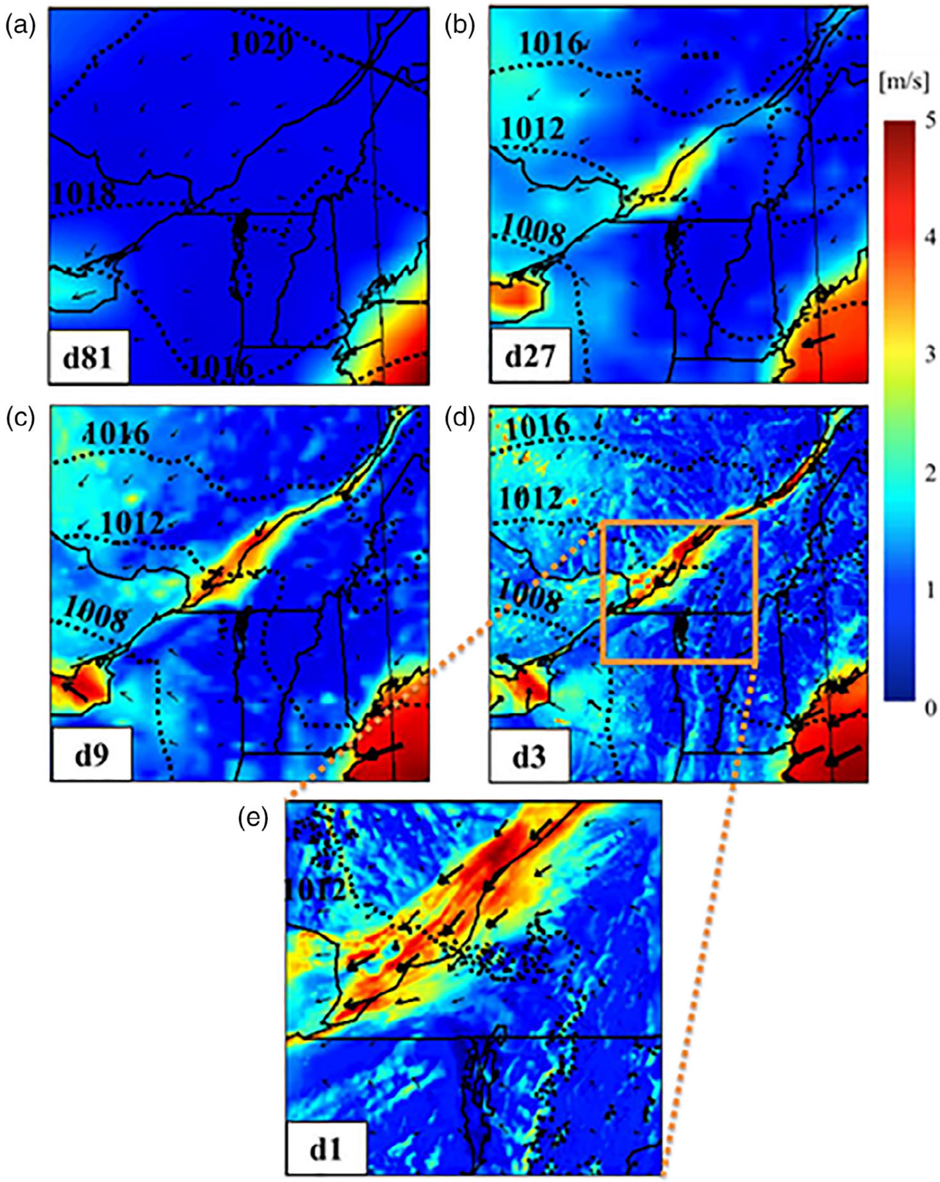

FIGURE 4 Typical situation for northeast winter wind channeling in the Saint Lawrence River valley. Wind speed (background colors in m/s), wind directions (black arrows) of the low-level wind, and mean sea level pressure (black dashed lines) for (a) 81-km, (b) 27-km, (c) 9-km, (d) 3-km, and (e) 1-km simulations at 1200 UTC 26 February 2002. (Reprinted with permission from Cholette et al. (2015). Copyright 2015 MDPI)

that regulates the spatial pattern of water vapor content, which in return reduces precipitation biases over the Tibetan Plateau.

Another local mountainous wind, the foehn is a dry and warm wind, caused by the release of latent heat, going downslope on the lee side of a mountain range. Foehn has been shown to be more realistically simulated with CPRCMs in many regions around the world, for example, southern Patagonia (Temme et al., 2020), South Georgia Island (Bannister & King, 2015), Germany (Knist et al., 2020b), and Larsen C Ice Shelf (Elvidge et al., 2015, 2016, 2020; Turton et al., 2017) and McMurdo dry valleys (Speirs et al., 2010; Steinhoff et al., 2013, 2014) over the Antarctic ice sheet. Bannister and King (2015) found that a CPRCM is capable of reproducing the main characteristics of foehn that contributed to the asymmetry of South Georgia Island's unique regional climate. Carvalho et al. (2020) evaluated a CPRCM that captured well the mesoscale characteristics of sundowner winds, which are downslope gusty winds observed in coastal Santa Barbara that exacerbate wildfires and constitute a major hazard for aviation.

Diurnal mountain winds are thermally generated diurnal circulations that develop along topography gradients and are important to determine local climate conditions in mountainous regions. As example, katabatic winds were simulated realistically in a case study that tried to better understand a warm air event over northeastern Greenland (Turton et al., 2019) and the evaluation of a preliminary CPRCM over southwestern Greenland designed for glacier modeling studies (Mottram et al., 2017). Letcher and Minder (2017) evaluated the ability of two CPRCM simulations to represent the SAF, which modulates the strength and the character of diurnal mountain winds. In a following study, Letcher and Minder (2018) found with a CPRCM that the loss of snow cover could cause an increase in the strength of the Front Range mountain-plain circulation.

4 | CLIMATE CHANGE PROJECTIONS USING CPRCMS

4.1 | Europe

Europe, and more especially the Alps and the UK, is a region for which many studies using CPRCMs are used to project the impacts of climate change, largely because of the large coordination of climate research centers in the FPS-Convection and EUCP projects, and the scientific interests related to the high orography of the Alps.

4.1.1 | Alps and surroundings

Over central and southern Europe, decrease of summer mean precipitation associated with frequency reductions of small and intermediate precipitation events were projected by a CPRCM (Ban et al., 2015), and then by an ensemble of CPRCMs (Pichelli et al., 2021), results being consistent with RCMs. However, daily and hourly heavy precipitation events are projected to become more frequent and intense, with larger changes with CPRCMs (Ban et al., 2015; Pichelli et al., 2021). Assessing rare events through the computation of return period values, Ban et al. (2020) found weaker changes in a 2.2-km CPRCM compared to a 12-km RCM in extreme hourly precipitation, with narrower uncertainty estimates with the CPRCM. Using a suite of climate models, Giorgi et al. (2016) showed that in contrast to the reduction of summer precipitation found by GCMs, RCMs and CPRCMs projected an increase of summer precipitation over the high Alpine elevations due to increased convective rainfalls simulated at higher elevations. In another study, Lüthi et al. (2019) projected that the reduction of SWE increases at higher elevation with a CPRCM, a result that is in contrast to that from an RCM where the relative decrease becomes gradually smaller with elevation. Keller et al. (2018) showed a strong sensitivity of the climate change signal according to the horizontal resolution where a 2-km CPRCM exhibited stronger negative feedback in the top of the atmosphere energy budget compared to a 12-km RCM.

4.1.2 | Germany

In climate change studies over Germany and its surroundings, Fosser et al. (2017) and Knist et al. (2020a) found a decrease in mean summer precipitation and an increase in hourly extreme precipitation, the increase being larger with CPRCMs than with RCMs. On the contrary, Knote et al. (2010) found almost no change in precipitation extreme over western Germany, a possible consequence of the small domain and little change expected in early-century projections.

Studying scale dependency of current and future climate extremes in Germany, Tölle et al. (2018) projected smaller future warming and more spatial variability of precipitation with more severe extremes of precipitation in summer with a CPRCM compared to an RCM. Using 2.2-km over western Germany and the Benelux regions, Meredith et al. (2019) revealed that the future intensification of extreme precipitation varies according to the diurnal cycle and that the maximum probability for the occurrence of extreme precipitation may shift from late afternoon to the overnight/morning period.

Including the increasing impact of bioenergy production, irrigation effects, and agricultural practices in a 1.3-km CPRCM climate change study over Germany, Tölle et al. (2014) revealed increased accuracy of climate projections at the local scale associated with the better representation of surface heterogeneities with a CPRCM. Comparing health-related indices from a multi-model RCM ensemble and one CPRCM, Junk et al. (2014) found that the CPRCM anomalies of summer days above 25°C are higher than the RCM ensemble mean, but within the RCM ensemble spread. In studies analyzing thunderstorm indices with a CPRCM over central Europe, Schefczyk and Heinemann (2017) projected a decrease of thunderstorm frequencies, except over the Alps where an increase of thunderstorm occurrences and intensity was found. Brisson et al. (2021) computed the climate change signals in future flash rates, highlighting the contrasted lightning projections between different diagnostics and model resolutions over central Germany.

4.1.3 | United Kingdom

Over southern UK, Chan, Kendon, Fowler, Blenkinshop, and Roberts (2014) and Kendon et al. (2014) showed that RCM projections of summer hourly precipitation extremes and intensities are resolution dependent. While a 1.5-km CPRCM projected a 10% uniform increase of hourly summer precipitation intensities for different return periods, in contrast, a 12-km RCM projected decreases in short return period (≤5 years) events, but strong increases in long return period events (≥20 years) (Chan, Kendon, Fowler, Blenkinshop, & Roberts, 2014). On the contrary, in winter, both RCM and CPRCM showed larger return period increases that are consistent with previous work based on coarser resolution models (Chan, Kendon, Fowler, Blenkinshop, & Roberts, 2014; Kendon et al., 2014). Chan, Kendon, Fowler, Blenkinshop, and Roberts (2014) showed signs of increased risk of flash flooding due to more intense precipitation extremes in CPRCM simulations, and longer meteorological droughts due to longer dry spells projected by both CPRCM and RCM. In a study focusing on the scaling of future hourly extreme precipitation intensities with temperature with a CPRCM, Chan, Kendon, Roberts, Fowler, and Blenkishop (2016) found a scaling following the Clausius–Clapeyron rate (6–7%/°C), in agreement with the present-day scaling seen in the observations. At the sub-hourly scale, Chan, Kendon, Roberts, Fowler, and Blenkinsop (2016) also found clear intensification of summer sub-hourly rainfall, but did not find a decrease in rainfall duration that is seen in present-day observations. Over northern UK, Chan, Kahana, et al. (2018) revealed greater summertime increase of return levels and extreme precipitation intensity in both RCM and CPRCM, but with larger intensification with the CPRCM. Examining large-scale predictors of extreme hourly precipitation, Chan, Kendon, et al. (2018) found a similar regression relationship in the future for their RCM and CPRCM, likely due to changes of the large-scale circulation patterns. Benefiting from the more realistic 1.5-km CPRCM at different temporal scales over southern UK, Kendon et al. (2018) indicated that changes in 10-min and hourly precipitation emerge before changes in daily extremes. Taking advantage of the first ensemble of CPRCM projections over the UK, Fosser, Kendon, Stephenson, and Tucker (2020) found significantly stronger intensification of summer hourly precipitation using CPRCMs compared to using RCMs. The climate change signals of the different CPRCM simulations seem to converge, likely a consequence of the more realistic representation of local storm dynamics, providing a sign of increased accuracy of future changes of extreme summer precipitation. In a study covering the entire UK using a CPRCM ensemble, Chen et al. (2021) projected that summer heavy rainfall will be more intense, with a faster translation speed, and a wider spatial coverage.

4.1.4 | Belgium

Numerous studies focused on resolution dependency of the climate change signals over Belgium. Saeed et al. (2017) revealed an amplification of future summer daily precipitation extremes with a CPRCM compared to an RCM, both in frequency and intensity. Despite a general summer drying caused by changes in large-scale circulation, Vanden Broucke et al. (2019) projected a significant increase in the frequency of daily and hourly extreme precipitation events, that is consistent between a CPRCM and an RCM in the mountainous areas, but significantly less in the RCM in the lowlands for hourly extremes. Helsen et al. (2020) found that two different CPRCMs show consistent scale-dependency of the future increase in daytime summer hourly extreme precipitation, with larger differences in the climate change signals over flatlands than over mountainous regions. Using a CPRCM, Ramon et al. (2020) were able to identify local temperature differences at the regional level and obtained better precision for the degree-days computation using hourly values.

4.1.5 | Whole Europe and comparison of different regions

To get a more comprehensive overview of CPRCM benefits, studies over different regions have been compared. Comparing results over southern UK and the Alps, Kendon et al. (2017) found that changes in rainfall occurrence are consistent between CPRCMs and RCMs in summer and winter. However, changes in rainfall intensity are robust across model resolutions in winter, but they show significant differences in summer. Over most of Europe, Gadian et al. (2018) projected longer dry periods, and shorter wet events with an increase in average precipitation for each event with a CPRCM. In another study comparing Europe-wide CPRCM (2.2 km) and GCM (25 km) precipitation projections, Chan et al. (2020) found similar future changes between both models, except for the robust enhanced intensification of precipitation extremes in summer and autumn simulated only by the CPRCM. Studying the response of hourly precipitation extremes using PGW with a CPRCM, Lenderink et al. (2019) obtained 12–16% increase per degree Celsius over the Mediterannean Sea, which is in contrast to the 6–7% increase over dryer regions of Spain. Hentgen et al. (2019) projected a reduction of low- and mid-level cloud cover fractions, and an increase in cloud top height over most of Europe. These projections were consistent between an RCM and a CPRCM, despite a more realistic and reduced biases in cloudiness and radiation with their CPRCM. In a study using a CPRCM over four regions across Europe, Hodnebrog et al. (2019) found for three regions further intensification of sub-daily extremes compared to daily extremes in summer. Finally, Poujol et al. (2021) recently showed robust shifts to higher intensity convective precipitation over Norway that are quite consistent with those reported for other regions of Europe.

4.2 | Africa and Arabian Gulf

Few studies analyzed CPRCM climate change projections over Africa. Kendon et al. (2019) found greater future increases in extreme 3-hourly precipitation intensity with their CPRCM compared to a convection-parameterized 25-km RCM (see Figure 5). Their models also projected future increases in dry spell length during the wet season over western and central Africa, which is weaker or not apparent at coarser resolution. In another study using the same simulations, but focusing on the WAM, Berthou, Kendon, et al. (2019) found changes in mean rainfall and wet-day frequency that are linearly related between a CPRCM and an RCM. However, changes of rainfall intensity between both models become independent where the intensification of rainfall is larger in the CPRCM. Focusing on the western African Sahel, Fitzpatrick et al. (2020) projected a 28% increase of the extreme rain rates of MCS with a CPRCM that is primarily explained by the projected increase of the total column water. Focusing on Eastern Africa, Finney, Marsham, Rowell, et al. (2020) projected a widespread increase in mean and extreme rain rates with a CPRCM, which differed from that projected with a parameterized RCM. Using a CPRCM, Finney, Marsham, Wilkinson, et al. (2020) projected a weak increase in lightning that is associated with an increase of graupel and updraft velocities in the future.

Analyzing CPRCM projections over the Arabian Gulf region driven by bias-corrected GCM data, Jing et al. (2020) projected a warming of around 3°C with precipitation increases over the Arabian Gulf and precipitation decreases over most of the continental area. They explained that future changes in precipitation are mainly determined by the thermodynamic impact, controlled by the warming and moistening of the atmosphere, resulting in more precipitation over the ocean, but not over the land.

4.3 | North America

Climate change studies using CPRCMs over North America are numerous and cover different climate characteristics and variables. Using the PGW approach, Liu et al. (2017) projected enhanced annual and winter–spring-fall precipitation over most of the contiguous U.S., but reduced summertime precipitation in the central U.S. From the same set of simulations, precipitation frequency is found to decrease in summer due to fewer light to moderate precipitation events, while heavy precipitation events are projected to increase (Dai, Rasmussen, Liu, et al., 2020). As a result, dry spells are

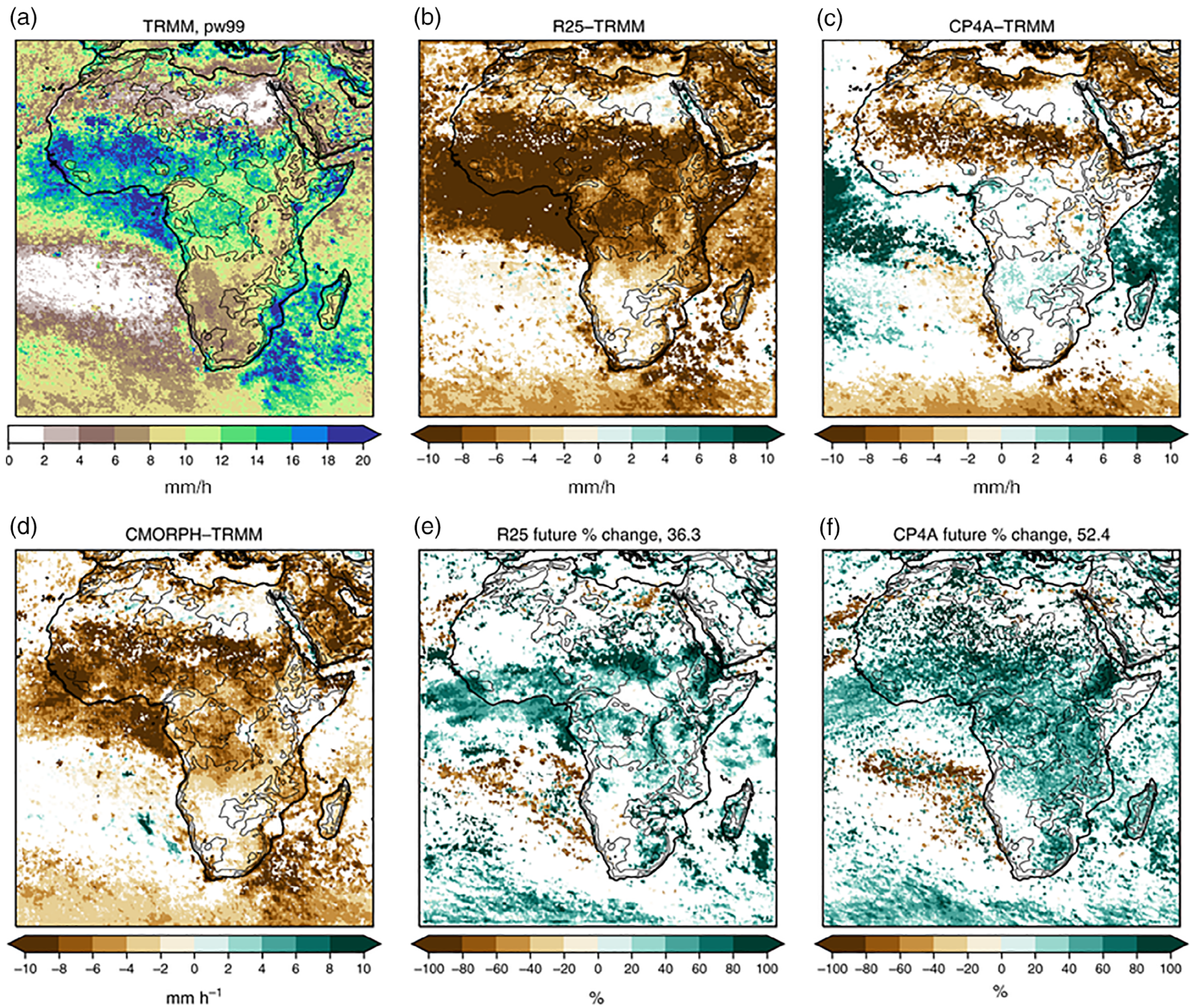

FIGURE 5 Wet season extreme precipitation intensity. (a) TRMM gridded observation, differences with respect to TRMM for (b) a 25-km RCM, (c) a 4.5-km CPRCM and (d) CMORPH another gridded observation. Percentage differences between 2100 and present day for (e) a 25-km RCM and (f) a 4.5-km CPRCM. Extreme precipitation intensity is defined as the 99th percentile of wet values (>0.1mmh − 1), for 3-hourly precipitation. The median of future percentage changes across Africa (land points only) is indicated next to the image titles in (e) and (f). Dataset differences and future changes are masked in white, where differences are not significant at the 5% level compared with year-to-year variability. The wet season is the 3-month period with the highest mean precipitation in TRMM, defined on a grid-point basis. The black lines indicate the 500, 1000, 2000, 3000, and 4000 m height contours. (Reprinted with permission from Kendon et al. (2019). Copyright 2019 Springer Nature)

expected to last longer and be more frequent with a reduction in temporal average relative humidity in the lower troposphere in summer (Dai, Rasmussen, Liu, et al., 2020). These changes are explained using a mechanism proposed by Dai, Rasmussen, Liu, et al. (2020) in which the size of intense storms is increasing, but where the number of storms is decreasing in the future. This mechanism is in agreement with the intensification of hourly extremes that has been observed and which is expected to further increase according to the Clausius–Clapeyron rate of 6–7%/°C over the United States (Prein, Rasmussen, Ikeda, et al., 2017). According to the study of Moustakis et al. (2021) using a 4-km PGW CPRCM simulation, hourly precipitation is expected to intensify under climate change and a 20-year rainfall may become a 7-year rainfall on average for a large part (~75%) of the U.S. Over a smaller CPRCM domain covering western Canada, Li, Li, et al. (2019) projected an increase of precipitation in spring and late autumn over most of the regions, while precipitation is anticipated to decrease (10–20%) in summer in the southern Canadian Prairies. In all seasons, Li, Li, et al. (2019) found shifts in the distribution of precipitation events toward more extreme intense events. Using the same set of simulations, Kurkute et al. (2020) projected an increase of precipitation and evapotranspiration leading to a decrease in runoff, and ultimately to a water resources deficit of two western Canadian basins in a warmer climate.

Still using PGW over a smaller domain covering southern U.S. (Texas), Chen et al. (2020) found that future increasing heavy rainfall and potential evapotranspiration are expected to lead to more frequent dry-wet abrupt alternating events due the increasing number of heavy rainfall and drought events projected under global warming. Dynamically downscaling with a CPRCM the top 10 extreme precipitation events from three RCM projections over central U.S., Mahoney et al. (2013) found that despite the large spread in projected changes, local maximums of the extreme events in the CPRCM simulations remain as strong or even increase. Focusing on changes in orographic precipitation in the interior western United States, Jing et al. (2019) projected a widespread increase in wintertime precipitation caused by higher precipitation rates during winter storms.

The precipitation diurnal cycle is expected to change in the future with earlier peak, larger maximum amount, reduced frequency, and increased intensity over most of the United States, indicating a clear intensification of the hydrologic cycle in summer (Rasmussen et al., 2020; Scaff et al., 2020). This intensification is stimulated by a decrease of weak to moderate convection and an increase in frequency of strong convection in a future climate over the United States (Rasmussen et al., 2020). The combined effect of the higher maximum precipitation rates (15–40%) and spreading of regions impacted by heavy precipitation in a warmer atmosphere, could lead to an increase of up to 80% in the total MCS precipitation volume within a 40-km radius around the storm center (Prein, Liu, Ikeda, et al., 2017). As a result, using a storm-tracking algorithm, Prein, Liu, Ikeda, et al. (2017) projected a tripling of intense summertime MCS frequency in North America. With the expected amplified arctic warming and moistening, the frequency and extent of intense organized convective systems are projected to triple under future climate conditions in northern Alaska (Poujol, Prein, & Newman, 2020). Additionally, the future increase of CAPE could lead logically to more hazardous convective weather such as tornadoes, damaging wind gusts, and large hail simulated using a proxy model forced by a CPRCM over eastern U.S. (Gensini & Mote, 2015). Studying long-term changes in NAM precipitation intensity from objectively identified severe weather events, Luong et al. (2017) noted that precipitation is becoming more intense and that the more favorable thermodynamic environment in southwestern U.S. facilitated stronger organized monsoon convection in the recent years.

Gutmann et al. (2018) projected in a PGW approach future TCs with faster maximum winds, slower storm translation speeds, lower central pressures, and higher precipitation rates in the southern U.S. While useful to compare TC individually, the PGW approach cannot assess changes in the frequency and trajectory of TCs that come with changes in the atmospheric circulation. In another study, Patricola and Wehner (2018) revealed increased rainfall and wind speed intensity in most of the TCs simulated with a CPRCM under future anthropogenic warming conditions. Finally, future increases in total accumulated precipitation and hourly precipitation intensity from selected extreme atmospheric river storms were found with a CPRCM (Huang, Swain, & Hall, 2020), with a consequence of projecting more intense floods in the future over California (Dougherty et al., 2020).

Additional studies using CPRCMs over North America are assessing future changes in snowfall, and the potential impacts on the SAF, affecting local atmospheric circulations. Using a series of CPRCM cold-season simulations with the PGW approach, Rasmussen et al. (2011) projected enhanced snowfall (10–25%) over the Colorado Headwaters and enhanced melting at the lower-elevation boundary of the snowpack. In a following study, Rasmussen et al. (2014) revealed an increase of precipitation in winter, but a decrease in summer resulting from low-level inhibition of convection over the Colorado Headwaters. Using a PGW CPRCM simulation over Alaska, Newman et al. (2021) projected large decreases of the snowpack season (50–100 days) in lower elevations, but increases of snowfall and snowpack (>20%) at the highest elevations. Still using a CPRCM PGW experiment, Ikeda et al. (2021) predicted that most snowpack in the Pacific Northwest U.S. could be gone by 2100 under a RCP8.5 scenario, despite annual precipitation increase by 10%. Analyzing snowmelt in CPRCM simulations, Musselman et al. (2017) estimated that the fraction of meltwater volume produced at high snowmelt rates is greatly reduced in a warmer climate due to a contraction of the snowmelt season. Additionally, Musselman et al. (2018) revealed that rain-on-snow events may become less frequent at lower elevations in the future due to snowpack decline, but more frequent at higher elevations where seasonal snow cover persists.

Letcher and Minder (2015) found that warming in the Colorado Headwaters is strongly enhanced in regions of snow loss due to the SAF, with substantial resolution dependent differences in SAF seasonality and spatial structure. Analyzing a pair of CPRCM simulations showing different magnitudes of SAF-enhanced warming, Minder et al. (2016) claimed that further work is needed to improve representation of snow cover and albedo to provide more confident CPRCM projections. Minder et al. (2018) found strong elevation-dependent warming primarily caused by the SAF that can reach up to 2°C in certain elevation bands using PGW CPRCM simulations. Analyzing a pair of CPRCM PGW experiments, Letcher and Minder (2017) found that in a warmer climate, the SAF may enhance the regional variability of warming, leading to enhanced upslope flow during the day and reduced downslope flow overnight in the Rocky Mountains. Letcher and Minder (2018) found a mean increase in the springtime Front Range mountain-plain circulation strength in the future driven primarily by the SAF with a CPRCM. Finally, using a set of CPRCM simulations, Wallace and Minder (2021) emphasized that future snow cover reductions over the Rockies may increase convective instability and boundary layer moisture, and decrease lifting condensation level over the high terrain.

With their improved ability to simulate extreme events, CPRCMs were also used to project changes in heat waves. Taking advantage of higher resolution topography and land use information, Gao et al. (2012) found more severe heatwaves simulated in a mid-century 4-km CPRCM simulation over eastern U.S. Analyzing a PGW simulation, Raghavendra et al. (2019) projected a tripling in frequency and sixfold increase in mean duration of heatwaves over Florida that are caused by a further increase of heat and moisture content. In another study presenting CPRCM projections intended to support regional sustainability studies over northeastern U.S., Komurcu et al. (2018) noticed smaller changes of maximum 2mt from their CPRCM compared to the driving GCM, a possible consequence of the interactive Great Lakes simulated at higher resolutions.

4.4 | Japan

Several climate projections using CPRCMs were performed over Japan, some of them using the PGW approach to investigate impacts of global warming on TCs and precipitation intensity. Dynamically downscaling a 20-km GCM simulation to 5 km with a CPRCM, Wakazuki et al. (2008) found that the top 3 annual precipitation events were projected to increase significantly over mountainous areas. Using a 2-km CPRCM, Murata, Sasaki, Kawase, Nosaka, Aoyagi, et al. (2017) projected a robust increase of 99th percentile of hourly temperature over all Japan, with the largest increase over northern Japan. In contrast, an increase of the 99th percentile of hourly precipitation was only found over northern and part of eastern Japan in regions where increased moisture flux convergence was found. Analyzing CPRCM projections in idealized 2 and 4 K warmer conditions, Kawase, Yamazaki, et al. (2020) projected enhanced snowfall above 2000 m for the years with heavy snow and a decrease of snowfall intensity below 500 m.

Kanada et al. (2013) projected an intensification of extremely intense TCs with structural changes such as an eyewall region becoming smaller and taller in the future. Comparing control and PGW simulations of a specific typhoon, Kanada, Tsuboki, et al. (2017) noticed an increased amount, intensity and duration of rainfall associated with a typhoon in a warmer climate. In a multimodel intercomparison of an intense typhoon in a warmer climate, all models projected an increase in the maximum intensity of the simulated typhoon in the future (Kanada, Takemi, et al., 2017). Kanada et al. (2019) projected an increased frequency of strong typhoon-related precipitation and Kanada et al. (2020) projected a decrease of TCs′ mean central pressure from an ensemble of CPRCM climate change simulations.

4.5 | Other regions

CPRCMs were used to perform climate change studies in a few additional regions. Using the PGW approach with a CPRCM over the Hawaiian Islands, Zhang, Wang, et al. (2016b) projected the greatest warming at highest elevations and a significant increase of extreme rainfall events. Analyzing 2-km CPRCM simulations over the greater Sydney region, Evans and Argüeso (2015) projected precipitation increases up to 40% with extreme precipitation (>95th percentile) contributing to a larger proportion of the future precipitation total. In a following study, Li, Johnson, et al. (2017) projected an increase in short duration rainfalls over the Greater Sydney region.

5 | CPRCM BENEFITS FOR IMPACT STUDIES

5.1 | Impacts on the water cycle and coupling with hydrological models

5.1.1 | Clausius–Clapeyron relation

The physical law of Clausius–Clapeyron dictates the maximum atmospheric water holding capacity of air at a given temperature. Per degree warming, atmospheric moisture may increase by around 6–7%, referred hereafter to as the

CC-rate. Increases of the global-mean precipitation is constrained by energy conservation to a few %/K, but extremes may deviate (Allen & Ingram, 2002; Pall et al., 2007). Observations of extreme rainfall at the daily scale show a globally fairly consistent picture of increases at close to the CC-rate (Fischer & Knutti, 2016; Guerreiro et al., 2018; Rajczak & Schär, 2017; Scherrer et al., 2016; Westra et al., 2014), with some modulation by changes in local atmospheric circulation (Westra et al., 2014). At sub-daily scales, observed precipitation extremes show signs of exceeding the CC-rate: in day-to-day scaling with surface (dew point) temperature (Berg et al., 2013; Lenderink et al., 2011, 2021; Lenderink & Van Meijgaard, 2008, 2010; Panthou et al., 2014; Park & Min, 2017), and between separate time periods over larger land areas (Guerreiro et al., 2018). Such super-CC scaling is possible through dynamical feedbacks to the convective processes, and several mechanisms have been proposed (Lenderink et al., 2017; Moseley et al., 2016; Nie et al., 2018). The convective processes behind the intensification of sub-daily precipitation events are at least partly resolved in CPRCMs (Fowler, Lenderink, et al., 2021b), thereby allowing classification of the precipitation formation process (Poujol, Sobolowski, et al., 2020).

The improved physical realism of CPRCMs has proven to affect the sub-daily extremes with a general intensification of hourly peak intensity (Ban et al., 2015; Fosser, Kendon, Stephenson, & Tucker, 2020; Fowler et al., 2021a,b, c; Hodnebrog et al., 2019; Huang, Swain, & Hall, 2020; Kendon et al., 2014, 2019; Knist et al., 2020a; Lenderink et al., 2019; Prein, Rasmussen, Ikeda, et al., 2017; Vergara-Temprado et al., 2021). At mid-latitudes, the improvement is most apparent in summertime extremes, where convection is playing a large role for the most intense events (Fosser, Kendon, Stephenson, & Tucker, 2020; Kendon et al., 2014). The increased realism in precipitation and near-surface temperature with CPRCMs also lead to more realistic day-to-day scaling rates of high percentile precipitation to near-surface (dew point) temperature (Cannon & Innocenti, 2019; Chan, Kendon, Roberts, Fowler, & Blenkishop, 2016; Diro & Sushama, 2019; Knist et al., 2020a; Moustakis et al., 2020). Furthermore, the increased spatial resolution in itself allows studies at shorter temporal scales (Eggert et al., 2015). More detailed studies of events and inter-event dynamics are then possible, for example, event tracking studies (Lochbihler et al., 2017; Moseley et al., 2013; Prein, Liu, Ikeda, et al., 2017), and cloud size, albeit yet with inconclusive trends (Feng et al., 2018; Li et al., 2018; Prein, Rasmussen, et al., 2017; Prein, Liu, Ikeda, et al., 2017), and the spatial footprint, that is, the total precipitation projected on the affected area, which is shown to increase with warming (Prein, Liu, Ikeda, et al., 2017).

The improvement in the CPRCM simulation of the day-to-day scaling of intense precipitation with near-surface (dew point) temperature is encouraging, and also precipitation extremes are better simulated. This kind of scaling is aggregating several processes such as synoptic situations, land-surface feedback, boundary layer stability, and linkages to climate change are disputed (Bao et al., 2017; Chan, Kendon, Roberts, Fowler, & Blenkishop, 2016). CPRCMs have also been used to explore the influence of aerosols on precipitation formation, where details of the microphysics come into play (Da Silva et al., 2020). The general pattern amongst different CPRCMs show near or above the CC-rate scaling in summertime precipitation (Ban et al., 2015, 2020; Kendon et al., 2014, 2019; Knist et al., 2020a; Prein, Rasmussen, Ikeda, et al., 2017; Vergara-Temprado et al., 2021). Amongst other things, differences in the scaling depend on the CPRCM (Helsen et al., 2020), the geographical location (Helsen et al., 2020; Knist et al., 2020a), and a complex interplay of processes including future higher freezing and melting levels, and elevated relative humidity (Lenderink et al., 2017; Poujol et al., 2021). Furthermore, the CPRCMs show generally larger future increases in extreme precipitation compared to lower resolution RCMs in regions ranging from Europe (Helsen et al., 2020; Kendon et al., 2014; Knist et al., 2020a; Saeed et al., 2017), the United States (Prein, Rasmussen, Ikeda, et al., 2017), Africa (Kendon et al., 2019), and Australia (Li et al., 2018).

5.1.2 | Hydrological studies using CPRCM simulations

It is recognized that hydrological climate change impact studies benefit from high-resolution RCMs forcing because of their more realistic simulation of regional meteorological phenomena and precipitation extremes (Fowler et al., 2007; François et al., 2019; Lee, Lu, et al., 2019; Maraun et al., 2010). Recent RCM simulations from the Euro-CORDEX initiative at a 12 km resolution allow the analysis of climate change impacts on smaller watersheds (Alfieri et al., 2015). However, in many applications, a 12-km resolution is not sufficient, especially for smaller basins affected by flash floods or urban hydrology where higher resolution is required. Linked to the spatial resolution, the daily time step is insufficient for these applications, requiring sub-daily variables in particular for precipitation. Various methods have been proposed to downscale the RCM outputs to higher spatio-temporal resolution, but most approaches lack a physical ground to preserve the interdependence between the variables (Maraun et al., 2017). Most downscaling methods also consider a constant bias or transfer function over time (Fu et al., 2018), that may not be representative of the changes in large/small scale atmospheric interactions (Van Uytven et al., 2020). In addition, recent studies suggest that a direct scaling between daily and hourly precipitation intensities may not be valid under climate change (Ganguli & Coulibaly, 2017; Innocenti et al., 2019; Martel et al., 2020), requiring more advanced methods able to represent sub-daily rainfall fields (Benoit et al., 2018).

In this context, CPRCM forcing provides a major improvement for hydrological applications by providing further dynamical downscaling of several variables that require a fine spatio-temporal resolution and in which the physical consistency between variables is preserved. Several studies have already used CPRCMs in hydrological applications to assess future flood risks in the United States (Dougherty & Rasmussen, 2020, 2021; Lackmann, 2013), Eastern Alps (Reszler et al., 2018), Texas (Wang & Wang, 2019; Zhang, Wang, & Wang, 2020), Colorado River basin (Mendoza et al., 2016), Ouagadougou (Senior et al., 2021), and in the UK (Kay et al., 2015; Rudd et al., 2020). CPRCMs have also been applied to estimate the water budget of East Africa (Finney et al., 2019), Himalayan basins (Li, Gochis, et al., 2017), California (Dougherty et al., 2020), but also for droughts and low flows analysis (Lee, Bae, & Im, 2019; Qing et al., 2020). Rudd and Kay (2016) did not find clear improvements for temperature and potential evapotranspiration estimation with CPRCMs at the basin scale. In contrast, most studies indicate better performance of CPRCMs to reproduce small-scale convective processes and the spatial heterogeneity of precipitation, which thereby improve the simulated river discharge with hydrologic models (Lee, Bae, & Im, 2019; Li, Gochis, et al., 2017; Mendoza et al., 2016; Qing et al., 2020). Indeed, the mean annual cycle of precipitation of a control experiment over three basins of the headwaters of the Colorado River basin (see Figure 6) showed a better agreement with observations using a 4-km CPRCM than 12- and 36-km RCMs (Mendoza et al., 2016). However, Kay et al. (2015) and Reszler et al. (2018) reported that CPRCMs did not provide improved flood simulations, despite their improvements on the representation of precipitation. Kay et al. (2015) attributed the lack of improvements on the simulated discharge to a wet bias in heavy precipitation over the UK, also reported in the Himalaya by Li, Gochis, et al. (2017). In a series of sensitivity analyses focusing on the simulation of a flood event forced by a CPRCM in the mountains of western Norway, Li, Pontoppidan, et al. (2020) simulated the correct peak flow volume and timing of the flood, which were sensitive to soil moisture and snow cover more than snow depth. In a study focusing on the water budget of two western Canada basins, Kurkute et al. (2020) found that their CPRCM outperformed three reanalyses in balancing the surface water budget. Using a stochastic method to resample CPRCM rainfall scenarios, Yu, Wright, and Li (2020) projected an intensification of extreme precipitation in the future where smaller watersheds exhibited the greatest flood magnitude increases. Finally, Martel et al. (2021) highlighted the strong potential of CPRCMs to provide more reliable future projections of sub-daily precipitation that would be useful to update IDF curves necessary to design more resilient infrastructures to climate change. These first hydrological studies using CPRCM simulations show the need for a better evaluation of this new generation of climate models, in various climatic regions, and for a range of basins with different attributes.

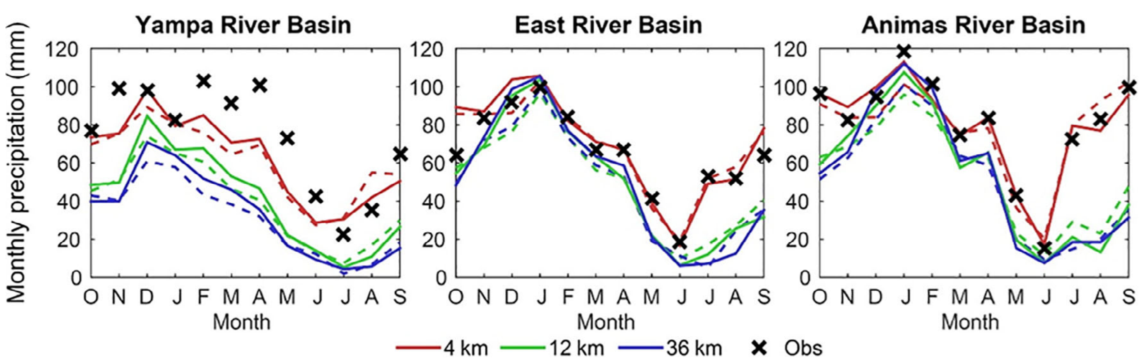

FIGURE 6 Basin-averaged observed (x symbols) and simulated (colored lines; red 4 km, green 12 km, blue 36 km) monthly precipitation values for current (CTRL, dashed lines) and future (PGW, solid lines) WRF outputs for the period October 2002 to September 2008 for three basins of the headwaters of the Colorado River basin. (Reprinted with permission from Mendoza et al. (2016). Copyright 2016 Elsevier)

5.2 | Urban climate and land use changes

CPRCMs are of major interest for urban studies in several ways. Their fine horizontal resolution allows for an improved description of land use variations related to the presence of cities (Gutowski et al., 2020), as well as increasing the relevance in activating specific urban canopy parameterizations (Trusilova et al., 2013, 2016; Argüeso et al., 2016; Hamdi et al., 2020; Li, Zhou, et al., 2019; Wouters et al., 2016). Coupled with urban models, CPRCMs can simulate the evolution of climatic conditions in the city, diagnosing environmental conditions within canyons (Lee et al., 2016), and thus address the issues of climate change impacts in cities. Nevertheless, CPRCMs can introduce substantial biases in temperature, humidity, incoming radiation, or precipitation (Argüeso et al., 2014; Arima et al., 2016; Fallmann et al., 2017; Ortiz et al., 2019). The online modeling configuration with "urbanized" CPRCMs allows to take into account feedback from urban areas on the atmosphere that could be crucial for urban heat island (UHI) and its evolution with climate change (Hamdi et al., 2014). Varentsov et al. (2019) described the benefits in conducting UHI studies using CPRCMs, notably highlighting their continuous high spatial and temporal resolutions, the accessibility to many variables at different levels, and the possibility to perform sensitivity studies. However, Li and Bou-Zeid (2014) underlined the main challenges in identifying an optimal CPRCM experimental setup to simulate the UHI effect, which is especially sensitive to the PBL scheme during nighttime and surface roughness length parameterization during daytime.

Several sensitivity studies comparing configurations with and without cities or with different levels of urban development with CPRCMs enable assessments of urban effects and their influence on the regional climate. As expected, urbanization results in an increase in daily average near-surface temperature (up to 2 K in Jakarta and Kuala Lumpur (Argüeso et al., 2016) and around 1 K in Brussels (Van Weverberg et al., 2008)). This warming is more marked at night than during the day due to the UHI effect over London (Grawe et al., 2013), Paris (Wouters et al., 2013), Moscow (Varentsov et al., 2018), and Sydney (Argüeso et al., 2014), and can be correlated with an urban dry island (Argüeso et al., 2015; Brousse et al., 2020). Li, Zhang, et al. (2019) and Gao, Santamouris, and Feng (2020) showed that urbanization may lead to a cooling of maximum air temperature due to the irrigation of green spaces. Another effect is a decrease in wind speed over the city due to surface roughness, with several studies agreeing that this decrease is more pronounced at night than during the day (Varentsov et al., 2018; Li, Zhang, et al., 2019; Yeung et al., 2020). For coastal cities, breeze circulations are found to be reinforced on the coastline by the intensification of the land/sea (or land/lake) thermal contrast generated by urbanization (Argüeso et al., 2016; Brousse et al., 2020; Yeung et al., 2020). Cities can also modify the intensity, triggering, and location of convective precipitation especially in summer (Liu & Niyogi, 2019). Kusaka et al. (2014) showed the influence of Tokyo's megacity on rainfall accumulation in summer due to an increase in surface sensible heat. Varentsov et al. (2018) showed an excess of precipitation by +25% over Moscow city center and its leeward side. Large UHIs can create a more unstable atmosphere, which increases vertical uplift and moisture convergence, and ultimately lead to a local intensification of extreme hourly precipitation (Rajeswari et al., 2021; Li, Fowler, et al., 2020; see Figure 7) and an increase of the frequency of extreme precipitation events (Marelle et al., 2020).

As a result of climate change, cities face an increase in average temperature and occurrences of extreme events (Zhang & Ayyub, 2020), which can increase urban vulnerabilities (Revi et al., 2014) and affect ozone concentrations (Lauwaet et al., 2014). Greater frequency of occurrence of heat waves favors situations of strong nocturnal UHIs (Wouters et al., 2017). Ortiz et al. (2019) found that the evolution of the number of heat wave days in the NYC area is strongly correlated to urban density. In both Paris and Brussels, Hamdi et al. (2015) showed an intensification of UHI at night in the middle of the century, while UHI decreases during the day due to a weakening of evapotranspiration resulting from soil drying. Lauwaet et al. (2016) projected a decrease in the magnitude of the UHI due to an increased incoming longwave radiation caused by higher air temperature and humidity. UHI was found to be related to the physical size of the city and can be amplified during heat waves (Ramamurthy & Bou-Zeid, 2017; Ramamurthy et al., 2017). Using a CPRCM centered over Washington DC, Zhang and Ayyub (2020) found that heat waves frequency and duration may double and that green roofs could reduce amplitude and duration of heat waves, contrary to reflective pavements.

Many studies with CPRCMs are looking at the consequences of climate change on the thermal comfort conditions of cities' inhabitants projecting a systematic increase in heat stress for urban populations during the summer period (Argüeso et al., 2015; Kikumoto et al., 2016; Wouters et al., 2017; Yeung et al., 2020). Nonetheless, for the Sydney region, Argüeso et al. (2015) showed that urbanization reinforces local warming, but conversely decreases the trend of increasing humidity. Ramon et al. (2020) revealed a 27% decline in heating degree-days over Belgium due to more pronounced regional warming in urban areas only captured by a CPRCM. Using CPRCM outputs to force a building

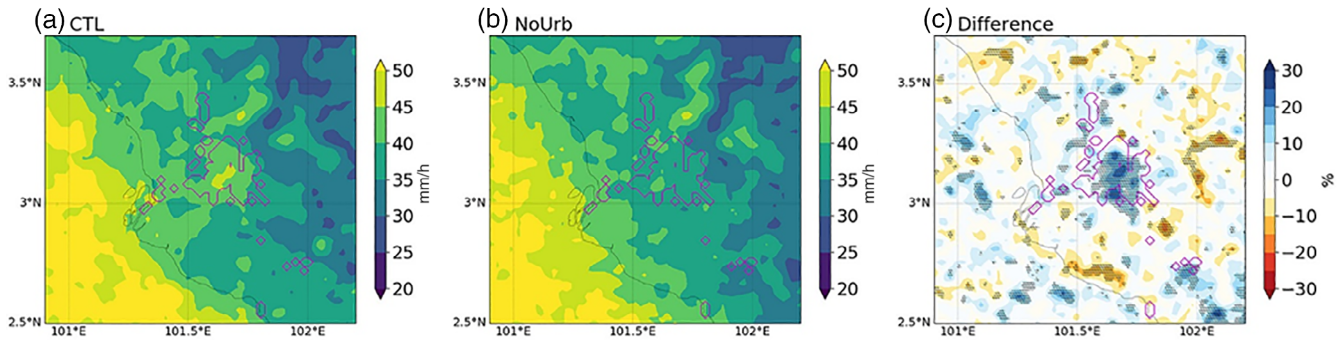

FIGURE 7 Mean hourly intensity of events above the 95th percentile for control (a) and no-city (b) CPRCM experiments, and percentage difference between these two experiments (c). Urban areas of Kuala Lumpur designated in the control run are shown with purple contours (c) while stippling indicates statistically significant differences using a two-sided Mann–Whitney *U* test at the 99% confidence level. (Reprinted with permission from Li, Fowler, et al. (2020). Copyright 2020 John Wiley and Sons)

energy model for Tokyo, Arima et al. (2016) showed a substantial increase in sensible and latent heat load in the next decade. Finally, some sensitivity analyses conducted with CPRCMs sought to quantify the main drivers of climate change in cities. Several studies agreed on the dominant role of regional climate change trends on daily maximum temperature in cities compared to the local urbanization effect (Argüeso et al., 2014, 2015; Wouters et al., 2017; Yeung et al., 2020). Furthermore, urbanization is accompanied by an increase in anthropogenic heat release (Doan & Kusaka, 2018; Doan et al., 2019), which combined with a lack of surface moisture in urban areas can intensify heat waves over cities more than over rural areas (Li & Bou-Zeid, 2013). Finally, idealized future land cover scenarios changing surface albedo have been employed in a CPRCM to show that afforestation can locally lead to additional warming of surface temperatures in winter and spring, and cooling in summer (Mooney et al., 2021).

5.3 | Meteorological processes simulated over islands

Islands are an ideal environment for realizing the potential of CPRCMs. Reasons for this are their well-defined extension (i.e., the benefit of placing lateral boundaries over the ocean), the sharp gradients of climatological characteristics (i.e., the presence of microclimates), and the key role of fine-scale processes such as orographically induced rainfall, gravity wave propagation, land/sea breezes, deep moist convection, and complex surface heterogeneities. In fact, the first numerical experiments at convection-permitting scales were aimed at studying deep convective storms over a tropical island (Golding, 1993). Spatial resolution at convection-permitting scales is often crucial to represent the islands themselves and their topography, which is a major factor in defining the spatial distribution of climate variables (Morel et al., 2014; Zhang, Wang, et al., 2016a). However, CPRCMs provide a new insight in island climates that is not solely explained by increased resolution, but also from a better representation of fine-scale processes such as the relationship between island rainfall enhancement and vertical motion (Ruppert Jr. & Chen, 2020), the role of gravity waves in defining rainfall features (Ruppert & Zhang, 2019; Ruppert Jr. et al., 2020; Vincent & Lane, 2016), the mechanisms driving offshore convective propagation (Barthlott et al., 2014; Coppin & Bellon, 2019a, 2019b), and land-sea breeze circulations (Zhu et al., 2017).

Modeling studies at convection-permitting scales that span climate-relevant periods (≥10 years) include the British Isles (Chan et al., 2013; Kendon et al., 2012, 2014, 2017; Fosser, Kendon, Chan, et al., 2020; Fosser Kendon, Stephenson, et al., 2020), Svalbard (Dobler, 2019; Dobler et al., 2020), Iceland (Nawri et al., 2014), Japanese Islands (Murata, Sasaki, Kawase, & Nosaka, 2017; Murata, Sasaki, Kawase, Nosaka, Aoyagi, et al., 2017), Hawaii (Zhang et al., 2012; Zhang, Wang, et al., 2016a, 2016b; Argüeso & Businger, 2018; Xue et al., 2020), Puerto Rico (Bhardwaj et al., 2018), Canary Islands (Expósito et al., 2015), Maritime Continent (Vincent & Lane, 2017, 2018), and New Caledonia (Dutheil et al., 2021). Other have focused on shorter periods, such as La Réunion (Morel et al., 2014), Cyprus (Zittis et al., 2017), Hainan (Zhu et al., 2017), Puerto Rico (Wootten et al., 2016), Fiji (Dayal et al., 2020, 2021), and Corsica (Barthlott et al., 2014). Overall, studies using CPRCMs have largely focused on the present climate to evaluate the model (Morel et al., 2014; Zhang et al., 2012; Zhang, Wang, et al., 2016a), determine the benefits of switching off convective schemes (Love et al., 2011; Kendon et al., 2014; Wootten et al., 2016; Murata, Sasaki, Kawase, & Nosaka, 2017; Zittis et al., 2017;

Fosser, Kendon, Chan, et al., 2020; Argüeso et al., 2020) or investigate atmospheric processes such as the Madden-Julian Oscillation (Birch et al., 2016; Vincent & Lane, 2016, 2018), gravity waves propagation (Ruppert Jr. et al., 2020), offshore convection propagation (Coppin & Bellon, 2019a, 2019b) and land-sea breezes (Wei et al., 2020). Some studies have used idealized configurations to investigate the role of islands and their topography on rainfall (Coppin & Bellon, 2019a, 2019b; Tan et al., 2020). Studies of future climate projections were limited to single realizations (Murata, Sasaki, Kawase, Nosaka, Aoyagi, et al., 2017; Bhardwaj et al., 2018; Chan, Kahana, et al., 2018; Dobler, 2019; Dobler et al., 2020; Fosser, Kendon, Stephenson, & Tucker, 2020) or have generally used a PGW approach to reduce computational costs (Expósito et al., 2015; Zhang, Wang, et al., 2016b; Dutheil et al., 2021; Xue et al., 2020).

The vast majority of studies using CPRCMs over islands have focused on rainfall (Love et al., 2011; Chan et al., 2013; Chan, Kahana, et al., 2018; Morel et al., 2014; Kendon et al., 2014; Fosser, Kendon, Stephenson, & Tucker, 2020; Dutheil et al., 2021) because it is directly affected by the way convection is represented in models. However, some experiments took advantage of convection-permitting resolutions to study other variables such as temperature (Expósito et al., 2015; Zhang, Wang, et al., 2016a, 2016b), and wind (Nawri et al., 2014; Argüeso & Businger, 2018; Dayal et al., 2020, 2021) that also require fine spatial detail. Most studies agree that precipitation extremes are more realistic in CPRCMs (Kendon et al., 2012; Zhang, Wang, et al., 2016a; Dutheil et al., 2021), despite the fact that they tend to overestimate rainfall amounts compared to observations (Murata, Sasaki, Kawase, & Nosaka, 2017). The overestimation is typically present with steep topography (Morel et al., 2014; Hassim et al., 2016; Vincent & Lane, 2016, 2017; Argüeso et al., 2020), indicating that the orographic forcing may be too strong in CPRCMs. Murata, Sasaki, Kawase, and Nosaka (2017) and Zhang, Wang, et al. (2016a) found that further increasing resolution was beneficial to reduce this bias. CPRCMs also tend to improve amplitude and phase of the diurnal cycle of precipitation over islands due to a combination of higher resolution and explicit convection (Birch et al., 2015; Argüeso et al., 2016, 2020; see Figure 8), although the amplitude is sometimes too large in CPRCMs (Vincent & Lane, 2016; Wei et al., 2020). CPRCMs are superior at correctly distributing rainfall over the islands by better representing the interaction between topography and low-level winds (Morel et al., 2014; Zhang, Wang, et al., 2016a). As a result of a finer resolution, temperature spatial distributions are also closer to reality, thanks to a finer topography and more realistic coastlines (Expósito et al., 2015; Zhang, Wang, et al., 2016a; Murata, Sasaki, Kawase, Nosaka, Aoyagi, et al., 2017).

5.4 | Atmospheric conditions over glaciers and coupling with glacier models

With their small sizes and their locations over complex terrains, glaciers require small-scale climate forcings that are better simulated with CPRCMs. Higher resolution climate forcing helps to assess the evolution of glaciers in greater detail through the computation of their surface mass balance. In a study focusing on the meteorological drivers of two glaciers in the Karakoram and Central Himalaya, Bonekamp et al. (2019) highlighted the strong contrast of the drivers from one glacier to another that could explain the strong variation in glacier mass balances in response to global warming. Until now, in most studies, glacier models are forced in an "offline mode" where the climate forcing is simulated first, and then used to force glacier models (Mölg & Kaser, 2011; Collier et al., 2013; Schaefer et al., 2013, 2015; Bonekamp et al., 2019). Some studies implemented a glacier model inside the CPRCMs to perform interactive climate simulations where a two-way feedback is computed (Collier et al., 2013; Collier & Immerzeel, 2015; Mottram et al., 2017).

Initial studies verified the potential of CPRCMs in simulating small-scale atmospheric forcing over glaciers using short hindcast simulations (few days to several months) driven by reanalyses over the Kilimanjaro (Mölg & Kaser, 2011; Collier et al., 2019), Himalayas (Collier & Immerzeel, 2015; Bonekamp et al., 2018), Karakoram (Collier et al., 2013), Patagonia (Temme et al., 2020), parts of Greenland (Mottram et al., 2017; Turton et al., 2019), and parts of Antarctica (Steinhoff et al., 2014; Turton et al., 2017; Elvidge et al., 2020). In their evaluation of simulations at different resolutions over the Himalayas, Bonekamp et al. (2018) highlighted that the highest resolution of 500 m provided the best match of precipitation, wind and 2-m temperature with the observations. CPRCM hindcast simulations of 1 year and above were analyzed over different glaciers such as the Kilimanjaro (Collier et al., 2018), Himalayas (Bonekamp et al., 2019), part of Greenland (Turton et al., 2020), Patagonia (Schaefer et al., 2013, 2015; Sauter, 2020), and South Georgia Island (Bannister & King, 2015). Amongst those studies, one focused on the impacts of TCs at high elevations of the Kilimanjaro (Collier et al., 2019) and another one took advantage of a long simulation to study the impacts of modes of climate variability on climate variables at different elevations (Collier et al., 2018). Performing CPRCM simulations using resolutions up to 810 m, Mölg et al. (2012) found limited impact of local land-cover change on the

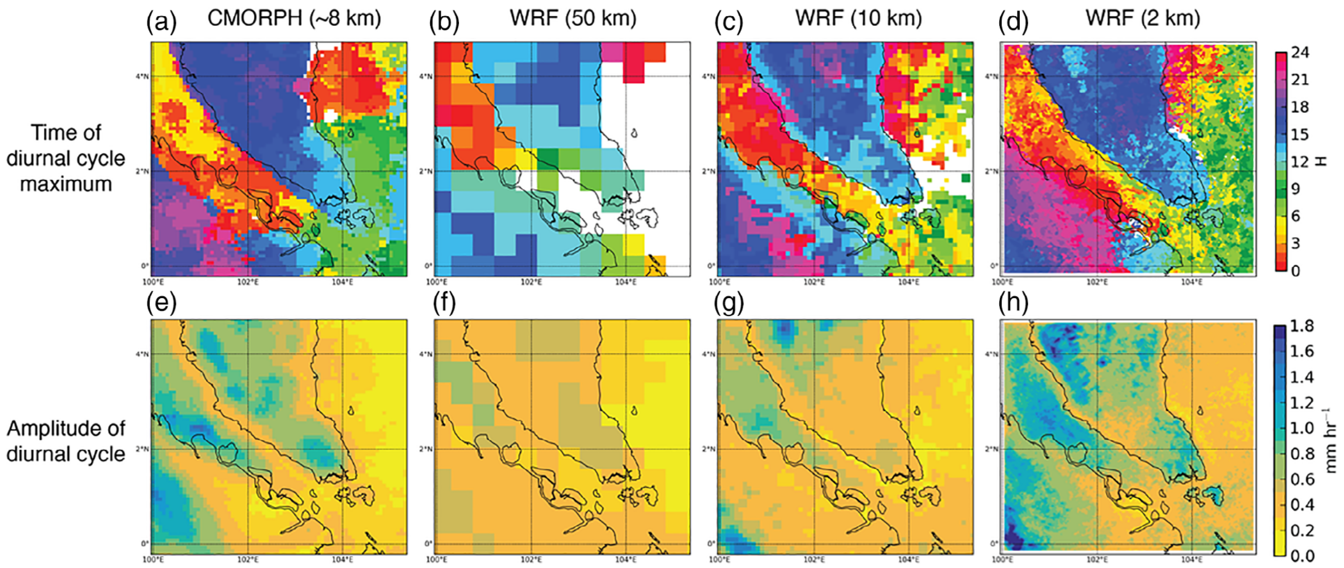

FIGURE 8 Time of the precipitation diurnal cycle maximum (in local solar hours) and amplitude of the precipitation diurnal cycle over southern Malay Peninsula from CMORPH gridded observations (∼8 km) (a,e), WRF RCM at 50 km (b,f), RCM at 10 km (c, g), and CPRCM at 2 km (d, h) spatial resolutions. White grid-boxes indicate areas where the ratio between the maximum and minimum of the diurnal cycle is <2. (Adapted with permission from Argüeso et al. (2016). Copyright 2016 Springer Nature)

Kilimanjaro's glaciers. To our knowledge, no CPRCM climate change projections were performed yet to assess the future evolution of glaciers.

In many studies, the main interest lies in the evaluation of the simulated precipitation (Mölg & Kaser, 2011; Collier et al., 2013, 2018, 2019; Collier & Immerzeel, 2015; Bonekamp et al., 2018, 2019; Schaefer et al., 2013) and precipitation extremes (Sauter, 2020) at high elevations, which contribute to the growth of glaciers. However, the atmospheric circulation (Bonekamp et al., 2018; Turton et al., 2019, 2020), and especially the recurrence of foehn events (Steinhoff et al., 2014; Bannister & King, 2015; Turton et al., 2017; Temme et al., 2020; Elvidge et al., 2020), are of large interest because such events directly affecting the melting of glaciers are improved at higher resolutions. Interestingly, Bannister and King (2015) were able to explain the recent asymmetrical retreat of South Georgia Island glaciers via enhanced leeside surface warming and drying. In another study, Turton et al. (2017) highlighted that only the highest resolution simulation (1.5 km) was able to simulate the propagation of the warm and dry air and foehn jets across the Larsen C ice shelf. Other variables of interest generally improved with CPRCMs for glacier modeling are the relative humidity and 2-m temperature (Mölg & Kaser, 2011; Collier et al., 2013; Bannister & King, 2015; Mottram et al., 2017; Turton et al., 2017; Collier et al., 2018; Bonekamp et al., 2019; Turton et al., 2019) and some variables of the radiative budget (Collier et al., 2018; Bonekamp et al., 2019).

5.5 | Evaluation of renewable energy resources and wind farm impacts on atmospheric conditions

A good knowledge of today's and tomorrow's wind and solar resources is very important to install solar panels and wind farms in relevant regions and establish strategies taking into account future changes (de la Vara et al., 2020). With their higher resolutions, CPRCMs are closing even more the gap between GCMs and end users, providing improved climate variables at finer temporal resolutions not only for precipitation, but also for radiation and atmospheric circulation. In a recent study on the current and future potential of solar and wind energy using 12-km CORDEX simulations, Sawadogo et al. (2020) expressed that CPRCM simulations would enable a more accurate estimate of the solar resource due to the better representation of mesoscale systems along with the diurnal cycle of convective clouds.

Recently, Jiménez, Hacker, et al. (2016) developed a new version of a CPRCM to meet the growing demand for specialized short- and long-term forecasts for solar power applications. This new CPRCM version improves the representation of the model physics to provide, in particular, a better simulation of the cloud-aerosol-radiation feedback. This

CPRCM largely improves the clear sky estimations of the radiation, and also that in all sky conditions, including the radiative effects of unresolved clouds (Jiménez, Alessandrini, et al., 2016). Thereafter, Pereira et al. (2019) proposed an offline procedure to improve further solar irradiance magnitude and variability that takes into account shadowing and slope effects from orographic features. CPRCMs were used in different studies to evaluate the solar energy resources and identify regions that have a greater photovoltaic potential over the contiguous U.S. (James et al., 2017), Kuwait (Gueymard & Jiménez, 2018), the Arabian Peninsula (Dasari et al., 2019), southeastern Australia (Prasad & Kay, 2020), and Lesotho (D'Isidoro et al., 2020). Moreover, CPRCM projections were performed to assess the impacts of climate change on the solar resources (Carreño et al., 2020) that would consequently affect power system operations (Craig et al., 2019) and high energy stress periods in a region (Texas) with high wind and solar penetrations (Craig et al., 2020). Finally, Chen et al. (2021) highlighted the conflicting surface solar radiation projections over the United States from GCMs, RCMs, and CPRCMs that are likely associated with the transient aerosol scenarios used in certain models.

For more than a decade, CPRCMs have been used to simulate regional surface wind over complex terrain (Jiménez et al., 2010), offshore (Jiménez et al., 2015), and during storms (Schaaf & Feser, 2018; Platonov & Kislov, 2020) and polar lows (Revokatova et al., 2021). CPRCMs were deemed quite useful to identify regions with high wind energy potential (Carvalho et al., 2012) and where observational coverage could be improved (Jiménez et al., 2010). Performance of CPRCMs in simulating wind speed and directions in complex regions was generally judged satisfactory (Jiménez et al., 2010; Jiménez & Dudhia, 2013). Errors in simulating wind direction were found dependent on wind speed: regions with larger wind speed showed smaller wind differences with respect to observations (Jiménez & Dudhia, 2013). Further studies identified that CPRCM wind errors can originate from problems in the lateral boundary conditions, misrepresentations at the synoptic scale, or the realism of topography (Jiménez, Dudhia, et al., 2013; Fernández-González et al., 2018). Over plains and valleys, wind speed overestimations were noticed and corrected by improving the representation of resolved and unresolved topographic effects (Jiménez & Dudhia, 2012; Lee et al., 2015). The analysis of a multi-decadal simulation (1960–2005) over northern Iberia allowed identifying different sources of wind variability and finding relationships with different large-scale atmospheric circulation modes (Jiménez, González-Rouco, et al., 2013). In another study, reduced wind speeds during heat waves and drought conditions were found, leading to potential implications for climate change studies (Jiménez et al., 2011). CPRCMs were used in different studies to evaluate wind energy potential over Iceland (Nawri et al., 2014), the United States (James et al., 2017), Hawaii (Argüeso & Businger, 2018), Fiji (Dayal et al., 2020, 2021), northeastern Spain (Fernández-González et al., 2018), northwestern Spain (Prósper et al., 2019), and Lesotho (D'isidoro et al., 2020). In a recent review on climate change impacts on wind power generation, Pryor, Barthelmie, Bukovsky, et al. (2020) did not identify CPRCM climate change projections focusing on wind yet, but they emphasized their high potential in providing higher fidelity wind simulations.

It has been suspected for a long time that the growing number and size of wind farms could affect downstream atmospheric conditions by the enhanced vertical mixing of near-surface and high-level atmosphere due the action of the wind turbines (Zhou et al., 2012; Roy & Traiteur, 2010). In the absence of long-term and reliable high-resolution weather observational networks, CPRCMs have been used as a virtual laboratory to estimate wind farm impacts using idealized experiments (Roy & Traiteur, 2010; Roy, 2011; Fitch et al., 2012) and real-word simulations (Jiménez et al., 2015; Xia et al., 2017, 2019; Pryor et al., 2018a,b). Different methods discussed in Fitch, Olson, and Lundquist (2013) and Pryor, Barthelmie, and Shepherd (2018b) suggested to represent wind farms through increasing the roughness length, rotor parameterization (Roy, 2011), and momentum sink (Fitch et al., 2012; Fitch, Lundquist, & Olson, 2013). While some studies found significant impacts of wind farms on atmospheric conditions (Roy & Traiteur, 2010; Roy, 2011; Fitch et al., 2012), other studies estimated that wind farm impacts were very limited (Pryor et al., 2018a,b, 2020; Xia et al., 2017, 2019). Some studies also used CPRCMs to estimate the wind resource losses due to the wake disturbances caused by the wind turbines (Jiménez et al., 2015; Prosper et al., 2019). Using observations from MODIS, Xia et al. (2017) emphasized that their CPRCM is able to simulate the impacts of real-world wind farms through a moderately successful reproduction of the observed spatiotemporal variations of land surface temperature. Xia et al. (2019) found that the vertical divergence of heat flux and resolved-scale 3D temperature advection are two important physical processes that could explain the simulated wind farm impacts on temperature. Finally, using a CPRCM projection where 20% of U.S. electricity is produced from wind, climate impacts of wind farms were judged modest compared to that induced by historical changes in land cover and to the global temperature perturbation induced by producing an equivalent amount of electricity with coal (Pryor, Barthelmie, & Shepherd, 2020).

6 | CONCLUSIONS: NEXT STEPS FOR EXPLOITING CPRCM BENEFITS

CPRCMs emerged as a promising tool to reduce uncertainties of climate change projections, especially those associated with precipitation extremes (Fosser, Kendon, Stephenson, & Tucker, 2020). They also advance the closing of the gap between GCMs and end-users (Fowler et al., 2007; Maraun et al., 2010), thanks to the use of explicit deep convection and higher horizontal resolutions. This review presented a summary of the methodology and good practices to take full advantage of the CPRCM potential, and provided an overview of the studies that demonstrated the added value and the improved realism of CPRCMs. Then, climate change studies where CPRCMs sometimes provided different climate projections when compared to those from conventional RCMs were exposed. Some applications of CPRCM outputs in different impact studies were finally highlighted.

Despite the recent interesting developments of CPRCMs, many of the initial hopes associated with their emergence (Prein, Rasmussen, & Stephens, 2017) are yet to be confirmed, and CPRCMs do not always show an added value compared to conventional RCMs. One of the main challenges associated with the use of CPRCMs lies in their heavy computational requirements and demanding output storage sizes (Schär et al., 2020). Consequently, simulations are mainly performed over small domains, for short periods, with projections performed in time slice mode, and with ensembles of only few members to assess inter-model variability and robustness. In addition, the large datasets of CPRCM simulations and less-established simulation protocols lead to difficulties in the analysis, data storage, and data exchanges. Another challenge lies in the lack of reliable high temporal and spatial resolution gridded observations, affecting the evaluation of the CPRCM simulations, and especially the assessment of their added value, often linked with sub-daily time scales and extremes.

The above challenges limit the characterizations of the different sources of CPRCM uncertainties and hamper their uptake in climate change assessments and impact studies. Recent progress in computing power, model algorithms, merged radar-weather station gridded observed products, together with numerous ongoing coordinated projects brings good momentum in better characterizing the uncertainties and increasing the confidence in climate change impacts at the kilometer scale. Additional work is underway to develop hybrid downscaling techniques, with the help of artificial intelligence, that aim to emulate CPRCM outputs at a lower computational cost, allowing to fill more easily GCM, RCM and CPRCM matrices to better assess uncertainties (Walton et al., 2015; Erlandsen et al., 2020).

Thus, it seems fair to say that research with CPRCMs is still in its infancy and stands where RCMs were about 20 years ago when large coordinated projects such as ENSEMBLES and NARCCAP were launched. CPRCMs are mostly based on NWP models and progress is underway to improve them and reduce their systematic biases (Kendon et al., 2021). Fortunately, the CPRCM community is now well organized (Coppola et al., 2020; Jacob et al., 2020) and some collaborative initiatives such as the CORDEX-FPS and EUCP projects are already delivering interesting outcomes (Ban et al., 2021; Pichelli et al., 2021). Storyline and PGW approaches are becoming increasingly attractive because they are computationally cheaper and offer to partition uncertainty and assess future risks, including the distinction between thermodynamic and dynamic factors (Shepherd et al., 2018). Moreover, different methods to analyze large CPRCM outputs such as the object-oriented approach (Caillaud et al., 2021; Prein, Liu, Ikeda, et al., 2017) are useful to extract results with a reduced computational burden.

Despite the recent progress listed above, further efforts to overcome some of the remaining CPRCM challenges are encouraged. In order to tackle the issue related to the lack of reliable high-resolution gridded observations and to find optimal CPRCM configurations that are more universally suitable, more transferability studies (Takle et al., 2007; Jacob et al., 2012) where CPRCMs with similar setups are run over different regions could be performed. The advent of multi-satellite estimates (Gebregiorgis et al., 2018; Sharma et al., 2020), merging techniques (Beck et al., 2017, 2019), and alternative precipitation (Beck et al., 2020) datasets are promising to provide more reliable observations in remote regions. Despite the CORDEX FPS projects that address specific scientific questions, additional community efforts would be welcome. To that extent, it would be interesting for the CPRCM community to agree on smaller domains (as the CORDEX domains are too large and restrict CPRCM simulations).

In the coming years, better synergy with the NWP community in favor of the seamless approach would be necessary to improve the calibration of CPRCMs, where compensating deficiencies existing in RCMs may be less actual in more realistic CPRCMs (Brisson, Van Weverberg, et al., 2016). Future gain in computing power should soon allow to perform longer simulations over larger domains and additional simulations to increase ensemble sizes allowing a better characterization of biases and different sources of uncertainties. Biases in some CPRCMs such as the too intense heavy rainfall (Kay et al., 2015) and the wet biases over complex terrain (Wang et al., 2020) need to be addressed (Kendon et al., 2021). Objective automatic calibration such as that proposed by Bellprat et al. (2016) could thus be exploited to reduce the computational cost of CPRCM calibration. Moreover, CPRCMs are mainly atmospheric-only models. Large benefits could be achieved by adding Earth system components (Giorgi & Gao, 2018) to CPRCMs such as lake models (Wu et al., 2020), aerosol schemes (Chen, 2021), oceanic models providing improved sea surface temperature gradients (Van Pham et al., 2016), and more sophisticated surface schemes including irrigation (Qian et al., 2020) and groundwater interactions (Barlage et al., 2021).

For CPRCM outputs to become more increasingly used and lead to more actionable information (Senior et al., 2021; Orr et al., 2021; Hewitt et al., 2021), climate services will have to learn to deal with massive datasets including sub-daily data and targeting more local adaptation issues such as UHI and flash flood studies where CPRCMs can bring new information (Termonia et al., 2018). New bias correction techniques would be needed to adjust finer temporal and spatial scale simulations toward weather station data (Argüeso et al., 2013; Haerter et al., 2015). Even though current developments toward convection-permitting GCMs are underway (Satoh et al., 2019; Stevens et al., 2019), the horizon of a wide use of such models is likely still many decades ahead (Schär et al., 2020). Taking into account the current challenges to perform km-scale simulations with CPRCMs, the advantage of performing such high-resolution simulations over a limited area domain that is less computationally demanding is huge. Thus, contrary to a recent review that announced the end of RCMs (Tapiador et al., 2020), from the current review perspective, the future of RCMs seems much brighter, thanks to CPRCMs. Despite the technical issues of dynamical downscaling (Takayabu, Kanamaru, et al., 2015; Tapiador et al., 2020), CPRCMs are now being widely recognized as a relevant tool to produce higher-resolution climate information (Prein et al., 2015). Being less computationally demanding than their global counterparts, RCMs at convection permitting scales or higher resolutions will remain a step ahead in terms of resolutions, complexity, and ensemble size (or simulation length), offering many opportunities to advance climate change science.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Philippe Lucas-Picher: Conceptualization; investigation; methodology; supervision; visualization; writing - original draft; writing-review & editing. **Daniel Argueso:** Conceptualization; visualization; writing - original draft; writing-review & editing. **Erwan Brisson:** Conceptualization; writing - original draft; writing-review & editing. **Yves Tramblay:** Conceptualization; writing - original draft; writing-review & editing. **Peter Berg:** writing - original draft; writing-review & editing. **Aude Lemonsu:** writing - original draft; writing-review & editing. **Sven Kotlarski:** writing - original draft; writing-review & editing. **Cécile Caillaud:** writing - original draft; writing-review & editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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