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Regional climate model applications on sub-regional scales over the Indian monsoon region: The role of domain size on downscaling uncertainty

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[1] Regional climate models are becoming increasingly popular to provide high resolution climate change information for impacts assessments to inform adaptation options. Many countries and provinces requiring these assessments are as small as 200,000 km^2 in size, significantly smaller than an ideal domain needed for successful applications of one-way nested regional climate models. Therefore assessments on sub-regional scales (e.g., river basins) are generally carried out using climate change simulations performed for relatively larger regions. Here we show that the seasonal mean hydrological cycle and the day-to-day precipitation variations of a sub-region within the model domain are sensitive to the domain size, even though the large scale circulation features over the region are largely insensitive. On seasonal timescales, the relatively smaller domains intensify the hydrological cycle by increasing the net transport of moisture into the study region and thereby enhancing the precipitation and local recycling of moisture. On daily timescales, the simulations run over smaller domains produce higher number of moderate precipitation days in the sub-region relative to the corresponding larger domain simulations. An assessment of daily variations of water vapor and the vertical velocity within the sub-region indicates that the smaller domains may favor more frequent moderate uplifting and subsequent precipitation in the region. The results remained largely insensitive to the horizontal resolution of the model, indicating the robustness of the domain size influence on the regional model solutions. These domain size dependent precipitation characteristics have the potential to add one more level of uncertainty to the downscaled projections.

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1. Introduction

[2] Global general circulation models (GCMs) are the primary tools used to understand and project changes in climate due to increasing greenhouse gas concentrations [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. The increasing complexity of current GCMs and the need for century long ensemble simulations to produce robust future projections result in high computing costs. As a consequence, GCMs are often integrated using a relatively coarse horizontal grid spacing of few hundreds of kilometers. This results in loss of the smaller physiographic details (such as the topography and land use distribution) that can strongly influence the local climate. Several dynamical and statistical techniques are in use to derive fine scale local climate information from the coarse resolution GCMs for local impact assessments. These techniques are referred to as climate downscaling [*IPCC*, 2007; *Frías et al.*, 2006; *Gachon and Dibike*, 2007; *Wilby et al.*, 2004]. Recently, *Fowler et al.* [2007] reviewed the strengths and weaknesses of downscaling methods in different regions and seasons, and concluded that physically based dynamical downscaling methods provide some advantages over statistical techniques.

[3] One of the most popular dynamical downscaling approaches involves the implementation of a high spatial-resolution limited area regional climate model (RCM) embedded in a coarse resolution GCMs [*Dickinson et al.*, 1989; *Jones et al.*, 1995; *Giorgi*, 1990; *Laprise*, 2008]. In this approach, the RCM is coupled with the GCM using a one-way nesting technique in which the RCM receives climate information from the driving GCM about the global drivers of regional climate (for example, the influence of ENSO on the Indian summer monsoon). However, for climate change applications, the one-way nested modeling approach requires the large scale circulation of the driving global model over the regional model domain to be similar to that of the regional climate model over the same domain [*Jones et al.*, 1995]. This necessary, though not sufficient,

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condition for the successful applications of the one-way nested RCMs can be achieved either by identifying an optimum domain [*Bhaskaran et al.*, 1996] or by nudging the large-scale circulations of the regional model toward the large scale circulations of the driving global model [*von Storch et al.*, 2000; *Separovic et al.*, 2012].

[4] In the selection of an optimum domain size, the aim is to identify a domain that is not too small to be overly constrained by the driving model, suppressing the development of key meso scale features. On the other hand, the domain should not be so large that the simulation deviates significantly from the large scale features of the driving model. Therefore earlier considerations for choosing an optimum domain size were concerned with assessing the simulation over the entire model domain. However, increasingly, climate change assessments are required for sub-regions, which are often much smaller than the domain of a typical one-way nested RCMs but highly relevant for developing country or state level climate change assessments (for example, Indian sate governments and countries like Bangladesh). There is also a growing demand to implement an RCM with as large domain size as possible to capture as many countries as one can, to minimize costs and maximize benefits.

[5] In this study, we analyze regional model simulations carried out using two different domains centered over the Indian subcontinent, to study the sensitivity of the subdomain hydrological cycle to the model domain size. The uniqueness of this paper is that it specifically assesses how the domain size influences the hydrological cycle of a small but user relevant sub-region within the model domain on seasonal and daily timescales, while the large scale circulation features over the wider common validation area (CVA) – the largest area common to both domains – are similar.

[6] RCMs have been shown to successfully capture fine scale details of the monsoon precipitation associated with the local forcing conditions in late 1990s [*Bhaskaran et al.*, 1996, 1998; *Jacob and Podzun*, 1997]. Since then several limited area models have been developed and comprehensively tested for their ability to simulate Indian summer monsoon [see, e.g., *Dobler and Ahrens*, 2010; *Saeed et al.*, 2012], with a view to employ them for sensitivity studies [*Dash et al.*, 2006] and climate change assessments [*Dobler and Ahrens*, 2011]. *Lucas-Picher et al.* [2011] inter-compared multiple RCMs and assessed their ability to simulate the Indian summer monsoon. They found most models are reasonably realistic in reproducing the Indian summer monsoon features.

[7] Recently, *Yang et al.* [2012] carried out a study to assess the sensitivity of the East Asian monsoon to various lateral boundary conditions derived from different reanalysis of observations with a fixed domain. They found that the simulated East Asian summer monsoon precipitation is highly sensitive to the driving reanalysis, largely due to the differing characteristics of moisture information they contained. In this study, as mentioned above, we address how the hydrological characteristics of a sub-region in the Indian monsoon domain are influenced by domain size, while the large-scale circulations of the domains are similar. This is relevant as the similarity of the large-scale circulations between the driving and regional models is generally used as a necessary condition for downscaling unique and physically consistent surface variables. The robustness of the domain size influence is also assessed by halving the regional model spatial resolution and repeating the above analysis. Section 2 describes the model implemented, diagnostics derived and the methodology employed. Section 3 discusses the results and section 4 provides summary and concluding remarks. In this study all presented diagnostics are for the monsoon season of June–September (JJAS), unless otherwise stated. Monsoon season and JJAS are used interchangeably.

2. Model, Diagnostics and Methods

2.1. Model

[8] The RCM used in this study comes from a version of the Met Office unified model. A global climate version of the atmospheric component of the unified model is configured into a regional climate model version, known as HadRM3P, to generate fine scale climate information over a limited area of the globe. A brief description of the model is given here. HadRM3P is a primitive equation model employing the hydrostatic assumption and with a full representation of atmospheric and land-surface physics (see *Jones et al.* [2004] for a fuller account). The atmosphere is discretized on 19 vertical levels with sigma coordinates used for the bottom four levels, pressure coordinates for the top three and a linear combination in between. A quasi-uniform resolution is achieved by employing a rotated coordinate system, in which the RCM 'equator' passes through the middle of the domain. A buffer zone with a width of eight horizontal grid boxes is employed at the lateral boundaries to relax the RCM solutions toward the external lateral boundary conditions.

2.2. Diagnostics

[9] The diagnostic quantities extracted from the model output include evapotranspiration, precipitation, precipitable water, specific humidity, and u and v wind components. We employed area-averaged water vapor conservation equation suggested by *Peixoto and Oort* [1992] to understand changes in the hydrological cycle.

$$E - P = S + D \tag{1}$$

where E is the evapotranspiration rate and P is the precipitation rate, S is the local change in the atmospheric water vapor storage, and D is the divergence of the vertically integrated atmospheric water vapor flux. The terms S and D are defined by

$$S = \frac{\partial W}{\partial t} \quad \text{where} \quad W = \frac{1}{g}\int_{Pt}^{Ps} q dp$$

$$D = \nabla \cdot Q \quad \text{where} \quad Q = \frac{1}{g}\int_{Pt}^{Ps} qv dp$$

q is the specific humidity, v is the horizontal wind vector, P_s is the pressure at surface level and P_t is the pressure at the top of the atmosphere, and g is the gravitational acceleration. Vertical integration is performed from the pressure level 925 hPa to 200 hPa using data from standard pressure levels. For the numerical calculations of these terms from model variables see, for example, *Trenberth* [1999].

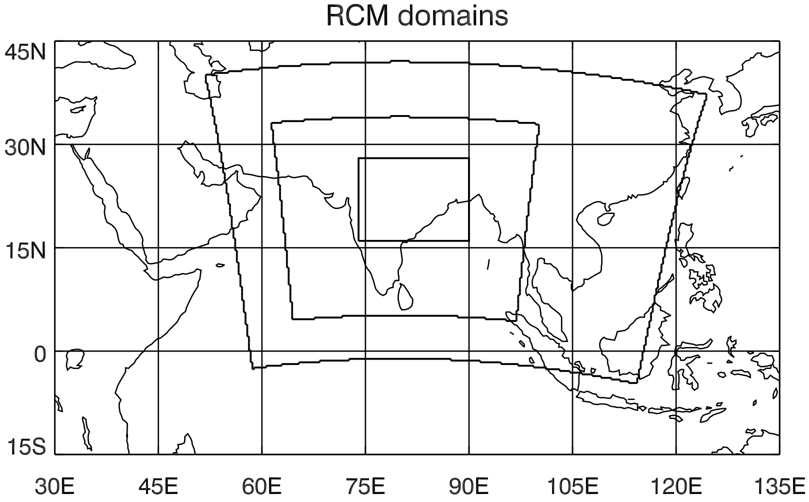


Figure 1. Domains used for RCM simulations. The innermost box represents the central Indian (CI) region. The outermost box is R2 region and the middle box is the R1 region.

[10] On seasonal timescales in near equilibrium conditions the change in locally available precipitable water content (S) is negligible relative to the magnitudes of large-scale divergence and evapotranspiration [*Oki et al.*, 1995; *Trenberth*, 1999]. Therefore equation (1) can be written as

$$E - P \sim D. \tag{2}$$

2.3. Methods

[11] Four 13-yearlong experiments were carried out using two domains over the Asian monsoon region at two horizontal resolutions of 25 and 50 km (Figure 1). The lateral and sea surface boundary conditions were derived from the European Centre for Medium Range weather Forecasts reanalysis data sets (ERA40) [*Uppala et al.*, 2005]. The model integrations were carried out from 1979 to 1991, to capture a range of global and regional climatological features, such as strong ENSO-monsoon cycles of 1982–83 and 1987–88. We allowed a spin-up of one year for the four-layer soil model to reach an equilibrium state with the atmosphere, and therefore discarded the data from the first one year of the simulations.

[12] A large domain may be considered by a climate change assessment specialist to capture as many countries as possible to optimize resources. On the other hand, a relatively smaller domain may be preferred by the assessors to minimize the computational time and costs. Therefore we have chosen one large and one small domain centered over the Indian subcontinent. We have adjusted these domains in such a way that the large scale circulation features were similar to each other over the common validation area, to study the impact of the domain size on the hydrological characteristics of a sub-region within the domain, while the large-scale circulation features are kept largely insensitive. Two different horizontal resolutions are employed to assess the role of domain size relative to the horizontal resolution. The experiments with small and large domains are labeled as R1 and R2 followed by either 25 or 50 to indicate the horizontal resolution employed. For example, R125 indicates a small domain RCM experiment with 25 km horizontal resolution. The sub-region considered for this study covers most of the central India of the model domain (CI, 74E to 90E and 16N to 28N), as shown in Figure 1. This region has a reasonably homogeneous mean and standard deviation of the observed seasonal rainfall. This region also experiences strong large-scale convergence and convection during the monsoon season and contributes significantly to the all India seasonal mean precipitation [*Goswami et al.*, 2006]. Therefore we select this region for our study as the results obtained here may be relevant for other tropical monsoon regions of the world. The CI region also includes one of the Major river systems, the Ganges, in India, making it relevant for basin scale future water availability assessments.

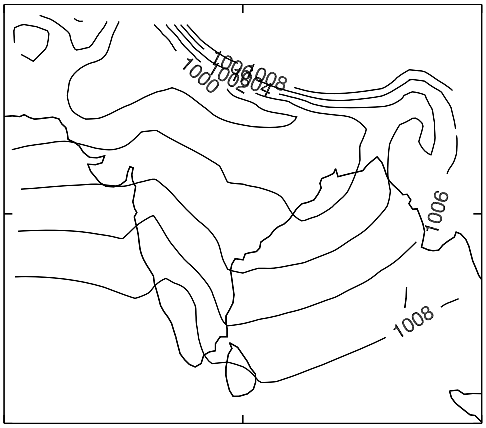
3. Results and Discussion

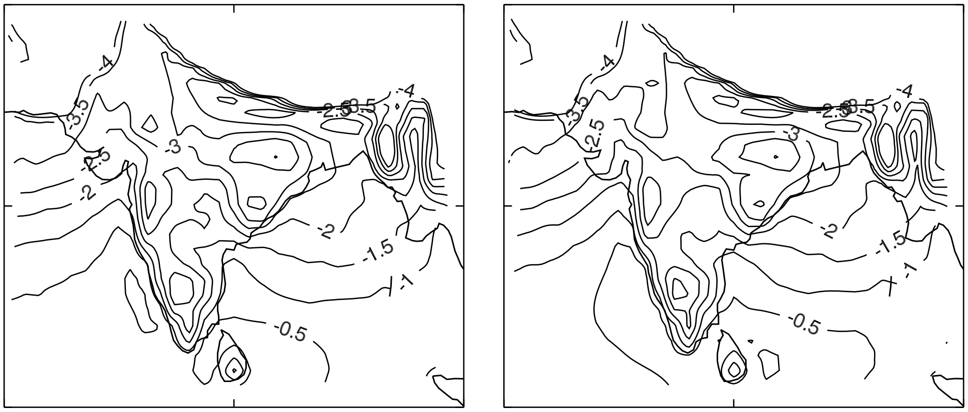
3.1. Seasonal Means

3.1.1. Large-Scale Circulation

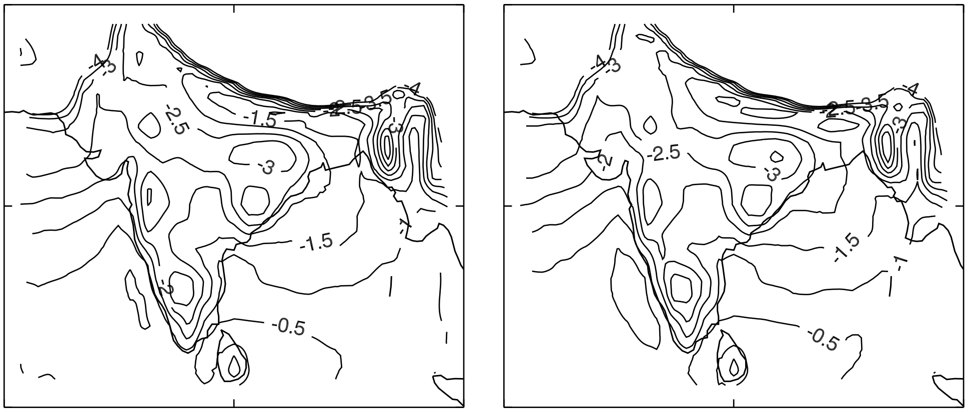
[13] The Indian monsoon trough is a quasi-permanent feature of the monsoon circulation during JJAS (Figure 2a). The intensity and location of the monsoon trough indicate the strength of the low-level monsoon flow associated with the cross equatorial jet and the low level convergence in the trough region. Since the axis of the trough also acts as a guide for the major rain bearing depressions over central India, its location influences the spatial distribution of rainfall in the region.

[14] In order to determine the sensitivity of the large-scale low level monsoon circulation to domain size, we have aggregated the mean sea level pressure (MSLP) simulated by the RCMs up to a lower resolution of 150 km. This aggregation is done for two reasons: 1) we are interested in the large scale circulation features of the RCMs; and 2) to enable comparison with the driving model whose horizontal resolution is approximately 150 km. Figures 2b–2e show the RCM simulated differences in mean monsoon MSLP distribution for both domains at 25 and 50 km resolutions with respect to the driving model (Figure 2a). It is clear that all RCM simulations produce a stronger monsoon trough, as the models underestimate pressure values over the monsoon trough region but gradually relaxed toward the driving model


(a) mslp ERA


(b) mslp R125

(c) mslp R225


(d) mslp R150

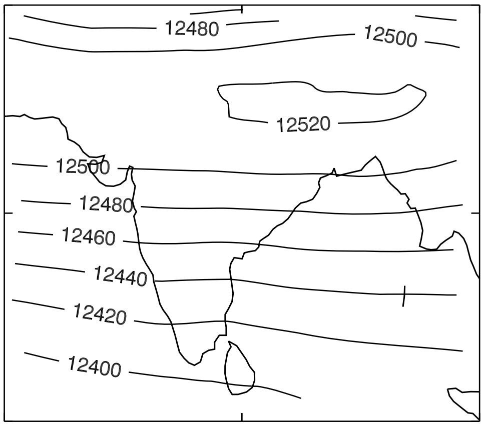
(e) mslp R250

Figure 2. Spatial distribution of mean sea level pressure (MSLP) for the monsoon season in hPa. (a) Climatological seasonal means for ERA40. (b–e) Difference distributions for all four RCM versions with respect to ERA40 climatological mean. See text for details.

values to the south of the trough. Although these maps provide an idea of the errors in the regional model, their main purpose is to establish how similar the low level circulations features are between the models. The simulated differences across the Indian latitudes are all comparable in all four simulations, especially over the Bay of Bengal and Arabian Sea which are the two key moisture sources for the monsoon rainfall. The orientation and intensity of the monsoon trough are also very similar, extending from the northwest India to the Head Bay of Bengal. Basically all four model versions produce similar MSLP gradients in the north-south direction, though their gradients are relatively stronger compared to that found in the driving ERA40 analysis (Figure 2a).

[15] Since the monsoon is governed by the large-scale deep convection, as opposed to the shallow convection, its characteristics are described in full by both lower and upper level circulation features [*Webster et al.*, 1998]. The north-south gradient in the geopotential height values is a measure of the

(a) gph200 ERA



(b) gph200 R125 (c) gph200 R225

(d) gph200 R150 (e) gph200 R250

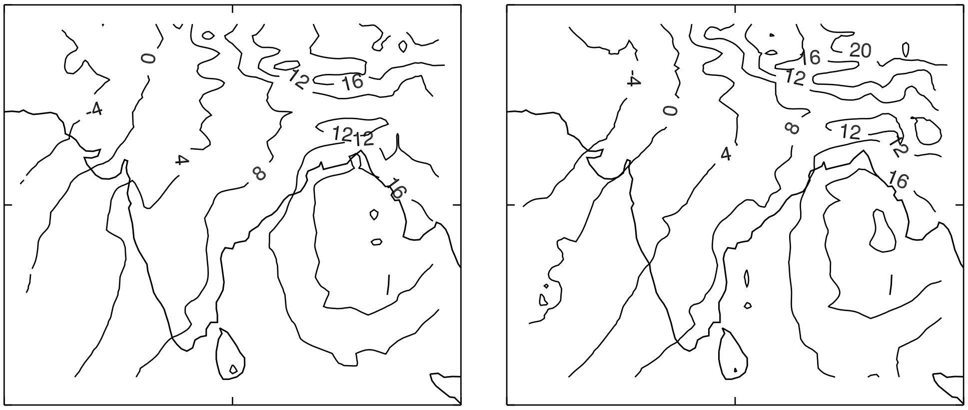


Figure 3. Same as Figure 2 but for the 200 hPa geopotential height anomalies in m.

strength of the easterlies in the region associated with the deep convective heating in the northern landmass and upper level outflow in the western Pacific (Figure 3a). Figures 3b–3e show the climatological spatial distributions of geopotential height differences at 200 hPa for all four RCM simulations with respect to the driving model. The RCM simulated geopotential height fields are also aggregated up to the 150 km horizontal grid before the difference maps were produced. Although the models overestimate over the Bay of Bengal and underestimate over the northwestern Indian region, the error patterns and gradients are similar in all four simulations (Figures 3b–3e). This suggests that the spatial patterns of meridional gradients in R1 simulations are quite similar to that of R2 simulations, and both R1 and R2 simulations are comparable with the driving model. The spatial correlations between R1 and R2 simulations for both MSLP and 200 hPa geopotential height are above 0.90 for both 25 and 50 km horizontal resolutions. As mentioned earlier, it is not our intention to comprehensively validate the regional model used in this study. This has already been done in earlier studies. For example, for a more extensive validation of the regional climate model used in this study, please refer to *Bhaskaran et al.* [1996, 1998] and *Lucas-Picher et al.* [2011]. Here our goal is to show how similar the large-scale circulation features are between the all four RCM versions, to highlight the largely insensitive nature of the large-scale circulations to domain size.

[16] In summary, the simulated upper and lower level large-scale monsoon circulation features are reasonably realistic and largely insensitive to the domain size. These results are not sensitive to changes in the horizontal resolution (compare Figures 2b and 2c with Figures 2d and 2e and compare Figures 3b and 3c with Figures 3d and 3e). This is consistent with an earlier regional modeling study [*Bhaskaran et al.*, 1996] that suggested that the large-scale circulations are relatively insensitive to domain size in the tropical regions, relative to the extra-tropical regions.

3.1.2. Precipitation

[17] Here we assess the RCM simulations of monsoon precipitation over the target study region. Figures 4b–4e show the seasonal mean precipitation differences corresponding to all four simulations with respect to the observations (Table 1), to give an idea of the models' ability to simulate mean monsoon rainfall to the reader. However, as mentioned earlier, the main purpose of this comparison is to examine the sensitivity of the simulated precipitation to domain size. Climatologically R125 and R150 area averaged precipitation values are similar, and so are the area-averaged precipitation values of R225 and R250 (the differences are 1% and 2.1% respectively – see Table 2). This suggests that within a given domain the precipitation values for the CI region is not influenced by changes in the horizontal resolution. However, there exist clear differences in precipitation totals between the models with the small and large domains, irrespective of their horizontal resolutions. For example, R125 simulated 9.4% more than R225 whereas R150 simulated 10.9% more than R250. These differences are statistically significant (tested via bootstrap technique [see *Crawley*, 2005]), and depending on whether they represent an increased wet bias, reduced dry bias or change in sign of bias, are likely to affect the interpretation or application of climate scenarios constructed with data from these simulations. Therefore differences in the regional model solution that may arise due to an imperfect choice of the domain could affect its ability to downscale reliably global climate model projections, especially at sub-regional (e.g., river catchment) scales. We note that this ten percent difference could be at the lower end of the influence due to domain choice, as the chosen domains were already constrained by the large-scale circulations of the models.

[18] In summary, two different domains could have similar large scale circulation features (see Figures 2 and 3), but end up producing two different precipitation patterns (see Figure 4). The implication of this is that ensuring the similarity of large-scale circulation features between the regional and driving models does not guarantee unique downscaled surface variables. We refer to this "downscaling uncertainty" here.

[19] In order to identify the source of this downscaling uncertainty (that is, differences in precipitation simulations), we need to understand the source of the additional moisture for the increased precipitation in the small domain regional model simulations (i.e., R125 and R150). For this purpose, we employed a regional water budget analysis for the CI region. The hydrological cycle over a limited domain depends on the amount of water vapor that enters the domain from the lower boundary through evapotranspiration and at the lateral boundaries through horizontal advection. Evapotranspiration can be considered as an internal source of moisture for the precipitation within the domain, whereas the horizontal advection represents the external moisture source.

3.1.3. Evapotranspiration

[20] As precipitation increases, the corresponding evapotranspiration also increases by 11.5% and 9.9% respectively in R125 and R150 simulations, suggesting an enhanced internal recycling of moisture. Despite increase in evapotranspiration, the positive changes in $P - E$ (see Table 2) suggest wetter soil conditions and an additional transport of moisture into the region. The contribution of internal moisture source relative to the external moisture in influencing the seasonal mean rainfall over the CI region is discussed below.

3.1.4. Precipitation Minus Evapotranspiration

[21] Climatologically the monsoon precipitation exceeds evapotranspiration in all four simulations, suggesting net moisture inflow into the CI region. This is consistent with the current understanding of monsoon processes over the Indian subcontinent. However, the simulated $P - E$ values are larger for small domains relative to the corresponding large domains. For example, R125 simulates 7.8% increase in $P - E$ relative to R225 and R150 simulates 11.5% increase relative to R250. This suggests that there is a role for external moisture source, in addition to the influence of internal moisture source through evapotranspiration, in influencing the rainfall changes in the models with small domain.

[22] Using the equation (2), one can discuss the relative contributions of moisture sources to increase in precipitation in the models with smaller domains over the CI region. At 25 km resolution, the increase in precipitation of 0.65 mm/day is approximately balanced by the increase in the internal moisture source (E) of 0.33 mm/day and the external moisture source ($-D$) of 0.34 mm/day. At 50 km resolution, 0.74 mm/day increase in rainfall is accounted for by 0.27 mm/day of internal moisture source and 0.48 mm/day of influx of moisture into the region. This roughly translates into 40–50% of the required moisture for the increase in local precipitation is supplied by evapotranspiration and the rest comes from outside the CI region.

[23] In summary, over the CI region there is ten per cent more precipitation in model simulations with the small domain. About half (third) of the additional moisture for this increased precipitation is supplied through local evapotranspiration and the rest is transported into the region in simulations with 25 km (50 km) resolution. This suggests that an increased moisture transport into the study region drives the increase in rainfall. In turn, this increase in rainfall leads to wetter soil conditions resulting in enhanced evapotranspiration and local recycling of moisture. Enhanced evapotranspiration and precipitation also lead to relatively lower surface air temperatures in R1 domain simulations. The results are largely insensitive to the model horizontal resolution in that in both resolutions additional moisture is supplied from the regions external to the study region (about 50% in 25 km and 65% in 50 km), an indication of robustness of the processes taking place inside the smaller domain during the monsoon season. This also indicates the relative importance of the domain size to the horizontal resolution employed in the regional model simulations.

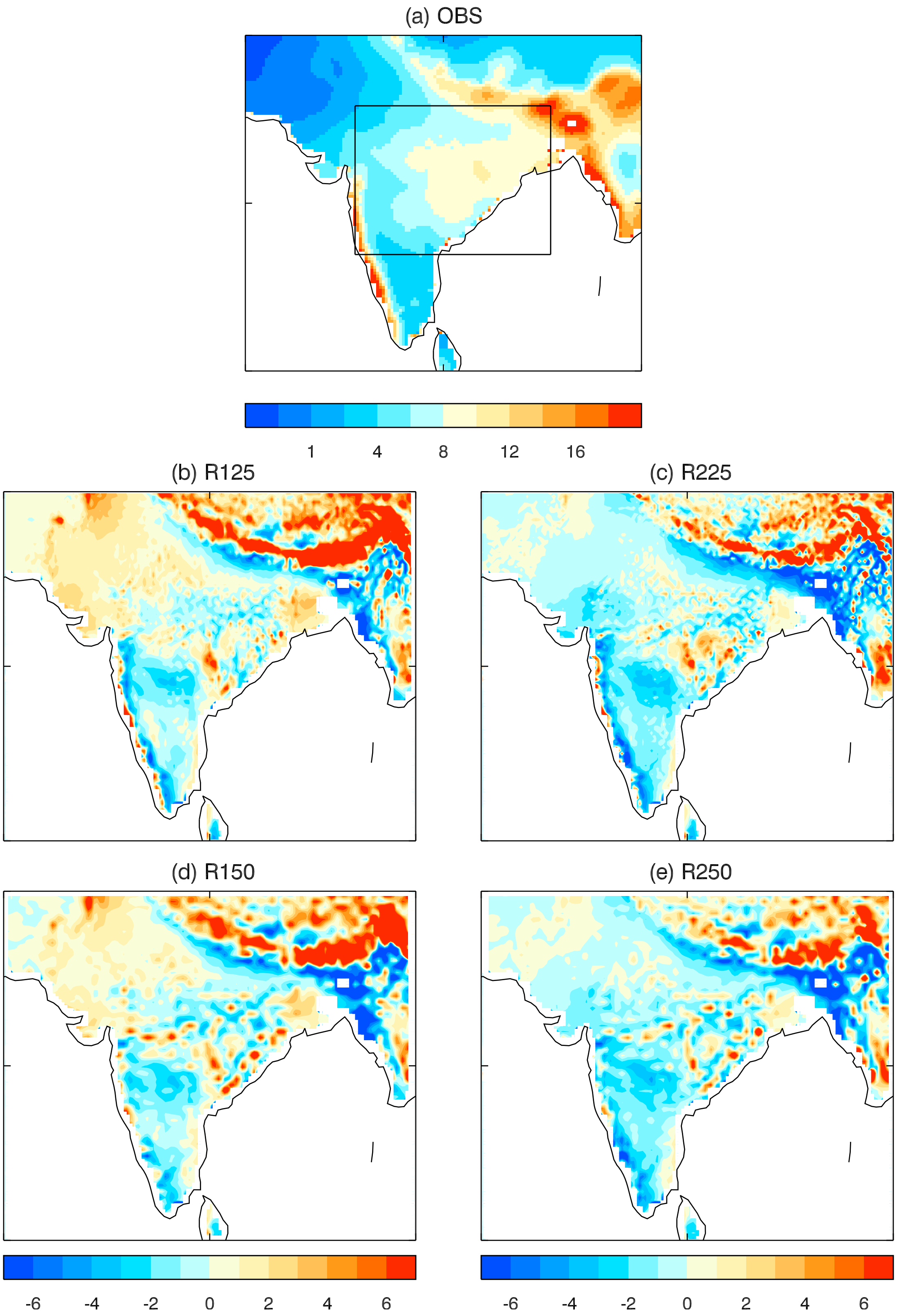


Figure 4. Same as Figure 2 but for the monsoon precipitation in mm/day. Observations represent the mean of CRU, UOD and GPCC data sets instead of ERA40 (see Table 1). Observations and model values were aggregated to produce values at 50 × 50 km grid. Boxed region shows the study region.

Table 1. Observed Precipitation Data Sets Used in This Study[a]

Data Sets	Reference	Period
GPCC Precipitation	*Beck et al.* [2005]	1980–1991
CRU Precipitation	*Mitchell and Jones* [2005]	1980–1991
UOD Precipitation	*Legates and Willmott* [1990]	1980–1991

[a] GPCC and UOD precipitation data sets were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/.

3.2. Daily Variations

[24] In order to understand the processes responsible for the increased seasonal mean precipitation and its association with the daily precipitation, we diagnosed variations in daily precipitation over the CI region (Figure 5a). The probability density function (pdf) of daily precipitation suggests that the frequency of the moderate precipitation events (that is, 6–12 mm/day) is higher in smaller domains (that is, in R125 and R150) relative to the corresponding larger domain simulations. There is also a decrease in weak precipitation events (that is, <6 mm/day), while no significant change is found in the number of heavy precipitation days (that is, >12 mm/day). Again the results are largely unaffected by changes in the horizontal resolution.

[25] These results should be considered in the context of a recent study by *Goswami et al.* [2006], which reported that there is an increase in the intensity and frequency of heavy rainfall events and a decrease in the frequency of moderate rainfall events over the same CI region in a warming environment. Although in our study the domain size influences the frequency of moderate and weak rainfall events, as opposed to the heavy and moderate rainfall events reported by *Goswami et al.* [2006], the results have implications as they suggest that the domain size influence could be as significant as the change observed in the second half of the 20th century. Although model biases in the simulated present-day climate have no direct relevance to the simulated climate change signals, many impacts models, especially the interactively coupled ones, do use the absolute values of a few future climate variables whose thresholds play an important role in the simulated impacts.

[26] To diagnose the changes in daily precipitation and its association with the large scale convergence and convection, we constructed a dynamic precipitation index (DPI) based on vertical velocity and the available moisture at a given pressure level. That is,

$$DPI = \Omega \cdot q \quad \text{where} \quad \Omega = \frac{dp}{dt}.$$

Table 2. Terms From Water Balance Equation (1) in mm/day for the Monsoon Season

Model	S	P	E	D	$P - E$
R125	0.15	7.61	3.20	−4.56	4.41
R225	0.13	6.96	2.87	−4.22	4.09
ΔR25		0.65 (9.3%)	0.33 (11.5%)	−0.34 (8.1%)	0.32 (7.8%)
R150	0.18	7.55	3.00	−4.73	4.55
R250	0.17	6.81	2.73	−4.25	4.08
ΔR50		0.74 (10.9%)	0.27 (9.9%)	−0.48 (11.3%)	0.47 (11.5%)

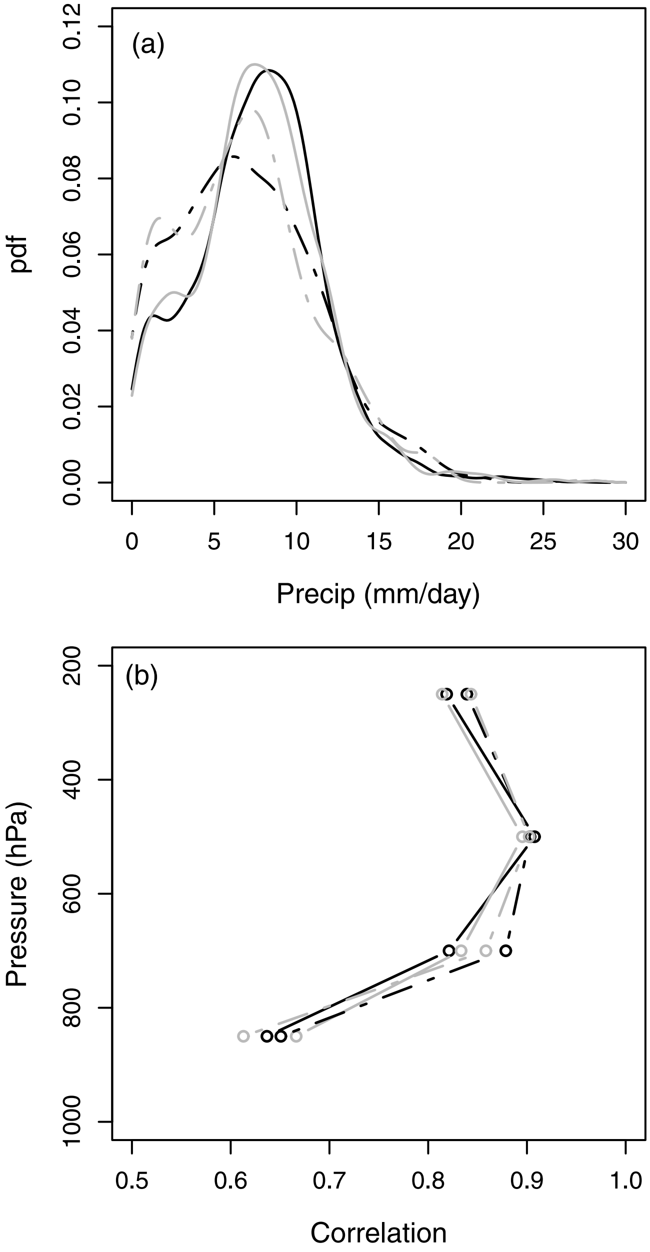


Figure 5. (a) Probability density function (pdf) of monsoon precipitation in mm/day over the Central Indian region (CI). Solid lines represent R1 simulations and dashed lines represent R2 simulations (black line – 25 km and gray line – 50 km). (b) vertical distribution of dynamical precipitation index in g/kg * Pa/s. Solid lines represent R1 simulations and dashed lines represent R2 simulations (black line – 25 km and gray line – 50 km).

[27] Figure 5b shows the relationship of DPI at various pressure levels with precipitation for both 25 km and 50 km simulations. The DPI index has the highest correlation with the precipitation at 500 hPa in all four model configurations (Figure 5b). Therefore we use this index, DPI500, to explore the relationships between the daily vertical transport of moisture and the daily precipitation events at various precipitation intensity levels. Prior to carrying out this analysis, the precipitation and the corresponding DPI500 values were

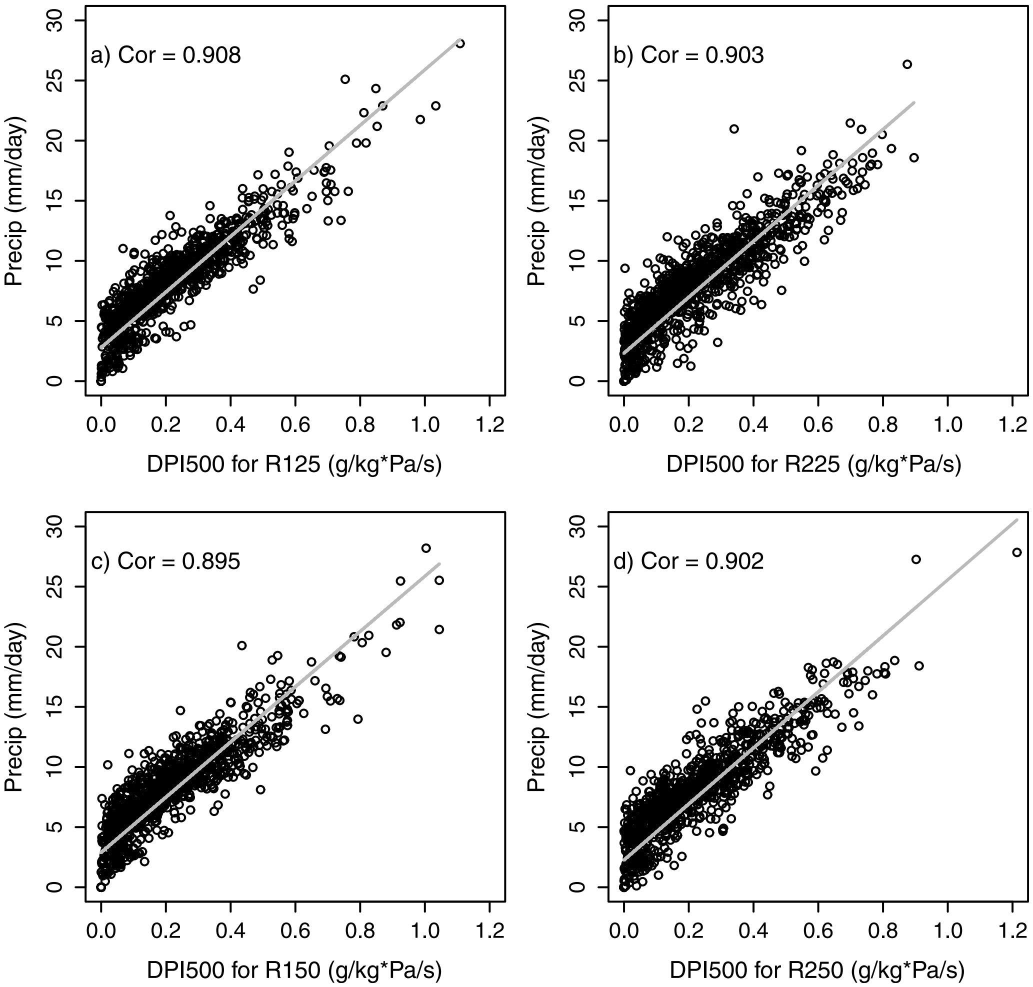


Figure 6. Linear regression fit between adjusted precipitation and adjusted dynamic precipitation index (DPI) at 500 hPa for all four versions over the central Indian region for the monsoon season. See text for details.

adjusted by setting their values to zero at grid points where downward motions were simulated within the study region. This daily adjusted precipitation and the corresponding adjusted DPI500 values were then used to make area averages of the study region. The area-averaged daily adjusted DPI500 explains more than 80 percent of the variance in the daily adjusted precipitation (Figures 6a–6d) for all four simulations. From the linear regression relationship, the DPI500 range corresponding to the moderate precipitation range of 6–12 mm/day is diagnosed for all simulations. In general, the corresponding DPI500 values are in between 0.12 and 0.40 g kg^{-1} Pa s^{-1} (Figure 6).

[28] The pdf characteristics of the adjusted daily precipitation (Figure 7a) are very similar to the unadjusted precipitation (Figure 5a) in the moderate daily precipitation range of 6–12 mm/day. That is, in R1 simulations the number of moderate precipitation days is still relatively higher. Using the regression relationships discussed above in relation to Figure 6, we identify the DPI500 range corresponding to the moderate precipitation range (6–12 mm/day in Figure 7a) in the pdf of DPI500 in Figure 7b. It can be seen that the DPI500 index, a measure of the local upward transport of moisture due to both large-scale convergence and convection, is consistent with the daily precipitation characteristics shown in Figure 7a. For example, in R1 simulations the frequency of upward transport of moisture at 500 hPa corresponding to the moderate precipitation range is higher (Figure 7b). This suggests that on daily timescales, in the smaller domains, the model is constrained to produce more moderate precipitation days by regulating the availability of moisture for convection and condensation within the domain. In sufficiently larger domains the moisture may be allowed to be removed away from the sub-region.

4. Summary and Conclusions

[29] We have carried out four sets of 13-yearlong simulations over the Asian monsoon region using two domains at 25 and 50 km horizontal resolutions. Both domains are centered over the Indian subcontinent, with one domain extending wider than the other in all directions, with a larger extension in the eastern direction (Figure 1). Earlier studies have shown that the large-scale circulation features, and hence the precipitation characteristics, in one-way nested regional models are sensitive to the domain size as well as to the location of the lateral boundaries [*Alexandru et al.*, 2007;

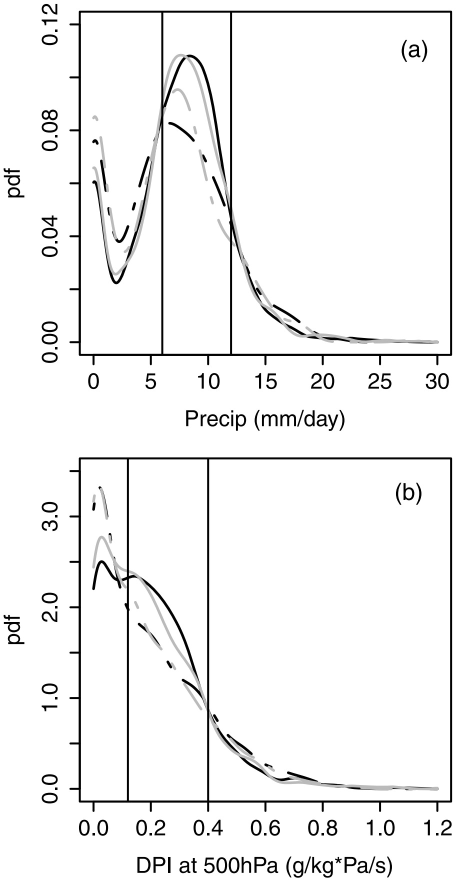


Figure 7. For all four model versions for the monsoon season. (a) Probability density function of the adjusted precipitation over the central Indian region. (b) Probability density function of the adjusted dynamic precipitation index (DPI) at 500 hPa. See text for details. Solid lines represent R1 simulations and dashed lines represent R2 simulations (black line – 25 km and gray line – 50 km). The vertical lines on Figure 7b represent the averaged lower and upper limits obtained from the regression (see Figure 6) corresponding to 6–12 mm/day.

Jacob and Podzun, 1997; *Leduc and Laprise*, 2009; *Vannitsem and Chomé*, 2005]. It has, therefore, been argued that for climate change applications, the large-scale circulation features of the regional model needs to be similar to that of the driving model over the regional model domain. Here we have shown that even though the large-scale circulations are not sensitive to the domain size, the resulting hydrological characteristics could be highly sensitive on seasonal as well as sub-seasonal timescales. This suggests that ensuring the consistency of the large scale circulation features between the regional and driving models may not guarantee a unique regional model solution. These domain size dependent precipitation characteristics could add one more level of uncertainty to the downscaled climate variables.

[30] On seasonal means, simulations with small domains produce increased precipitation, evapotranspiration and precipitation minus evapotranspiration. It appears that the small domains intensify the regional hydrological cycle over the study region by increasing the water vapor transport into the region and thereby enhancing the precipitation and local moisture recycling. On daily timescales, the number of moderate precipitation days is higher in the small domain simulations relative to the corresponding large domain simulations. Our analysis reveals that the small domain limits the magnitude of daily precipitation variability by regulating the variability of the available moisture and vertical velocity within the study region. The fact that the results are largely unaltered when we halved the horizontal resolution to 50 km confirms the robustness of the domain size constraints on the regional model solutions.

[31] The results from this study have implications, at least, for the Asian monsoon region. It again raises the question of optimum domain size in the context of climate change assessments over a sub-region within the model domain. While we can attribute the differences in hydrological characteristics to domain size, it is not clear whether the domain size or the location of the domain produces the differences in the hydrological cycle characteristics shown here. It is likely that both contribute to these changes, suggesting implications for other monsoon regions.

[32] We did attempt to assess which domain reproduced the observed climatological precipitation characteristics better over the study region, even though both domains have similar large-scale circulations over the wider CVA. The smaller domain (R1) simulations have lower bias relative to the larger domain (R2) simulations when compared with the observational data sets (Figure 8). The R1 simulations produce consistently higher precipitation during the premonsoon (May) as well as the first quarter of the monsoon (June) over the central Indian region. These months are dominated by severe thunderstorm activity in this region. Our water budget analysis suggests that there is a relatively lower moisture transport into the study region in R2 simulations. Therefore reduced moisture could be one of the reasons for the reduced precipitation in large domain simulations. This may suggest that the small R1 domain is perhaps more suitable for regional model applications over the central Indian region. However, the larger R2 domain may be more suitable for a sub-region over northwest India for regional model applications (see Figure 4). This suggests that there exists no single optimum domain that is suitable for regional model applications for climate change assessments for all relevant sub-regions within the model domain.

[33] We, therefore, conclude that while ensuring the consistency of large-scale circulations between the driving and regional models is necessary, it does not necessarily guarantee a unique regional model solution on sub regional scales. In these situations, a domain that accurately reproduces the observed climatology of the study region may be preferred but as we have shown one domain may not be able to reproduce the observed climate of all sub regions accurately within the domain. Therefore different domains for different sub-regions within a given region may be required, if one aims to reliably downscale global projections. Therefore what would be ideal is to develop a methodology, which is independent of the domain size, that ensures the physical consistency between the driving and regional models. We plan to explore such a technique, based on the large-scale nudging, in the near future.

[34] We summarize our key results here.

[35] 1. Previous studies reported that Indian summer monsoon is sensitive to domain size [see, e.g., *Bhaskaran*

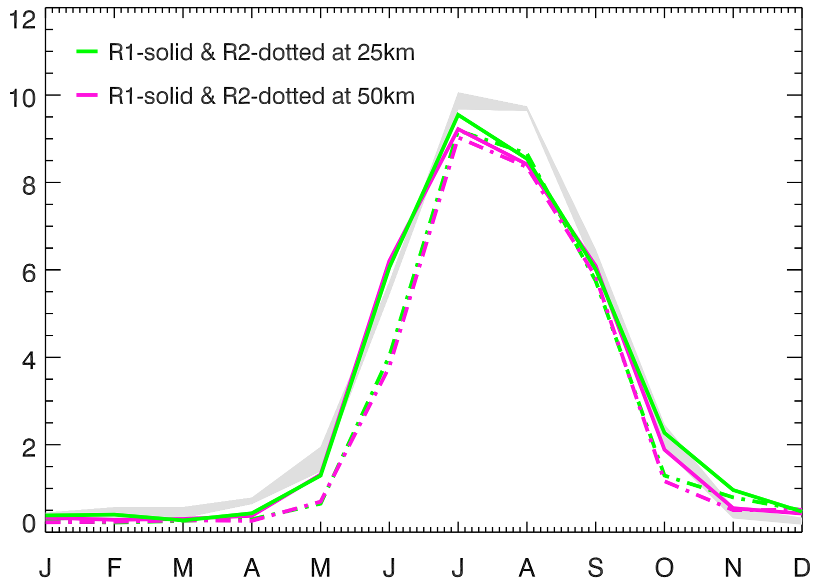


Figure 8. Climatological annual cycles of precipitation for the CI region. The grayed area represents the range of the observational data sets, comprising CRU, UOD and GPCC (see Table 1). Solid lines represent R1 domain and dotted lines represent R2 domain. Both model and observational data sets were re-gridded to a common grid of 50 km before the annual cycle is computed.

et al., 1996]). What we have shown here is the mechanism through which this sensitivity exists by analyzing the seasonal mean hydrological cycle and daily precipitation. Through this analysis we highlight the domain size dependent precipitation characteristics, which were not reported before.

[36] 2. Second, and most importantly, we have shown how this sensitivity contributes to uncertainty in downscaled precipitation over a sub-domain in the Indian monsoon region. Note that this sensitivity can be considered as uncertainty only if the large-scale circulations are not sensitive to the domain size, which we have shown here to be the case. This is a very relevant contribution to the current literature, since the similarity of large-scale circulations of the driving and regional models are generally considered as a necessary condition to downscale physically consistent and unique precipitation values for impacts assessments.

[37] 3. Third, we established the robustness of the results by repeating the experiments and analysis by halving the regional model resolution.

[38] 4. Finally, we attempted to assess which domain produces seasonal mean precipitation close to observations over the study region. We found that different domains may be required for different sub-regions within the model domain.

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