Importance of the Resolution of Surface Topography in Indian Monsoon Simulation

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ABSTRACT

The influence of surface topography resolution in Indian summer monsoon simulation is investigated. Three sets of six-member ensemble simulations with climatological sea surface temperature are conducted with the Community Atmospheric Model, version 5.1 (CAM5.1): COARSE simulation at 1.9° x 2.5° latitude–longitude resolution, FINE simulation at 0.47° x 0.63° resolution, and HYBRID simulation, that is, using COARSE surface topography imposed on the FINE configuration. With regard to the representation of the surface topography, substantial differences occur at the regional scales between the simulations, especially over the foothills and steep flanks of the mountains. In the COARSE and HYBRID simulations, the orographic height of the foothills is overestimated whereas that of the steep flanks adjacent to the foothills is underestimated. The biases are severe (up to 1 km) over the Himalayas and Tibet and have detrimental effects on regional climate through barrier effects on the low-level flow, and the lapse rate and elevated heat source effects. Overall, the simulations show remarkable improvement with an increase in resolution, mainly because of the improved representation of atmospheric and surface processes. However, local climate—surface air temperature, sea level pressure, precipitable water, and wind—of the orographic regions, particularly where large orographic biases exist in COARSE, is found to benefit substantially from increased resolution of surface topography. Local precipitation and evaporation are exceptions, although, as they are negligibly sensitive to topographic resolution, showing strong dependence on the resolution of surface and atmospheric processes. Moreover, resolution of surface topography generally does not have notable remote impacts.

1. Introduction

Numerous studies over the last half-century have addressed the issue of the dependence of climate simulation on horizontal resolution (Manabe et al. 1970; Wellek et al. 1971; Boville 1991; Williamson et al. 1995; Jung and Arakawa 2004; Hack et al. 2006; Wehner et al. 2014; Hertwig et al. 2015; Shields et al. 2016; Ogata et al. 2017). Nevertheless, it remains as an active and key research area, as there is a continuous increase in the resolutions the climate modeling community typically use, with the continuing advancement of supercomputing power—in the 1970s typical model resolution was approximately 5°, whereas it is now 1° in latitude/longitude or less (Haarsma et al. 2016). There is little doubt that supercomputing capabilities will continue to advance and, as a result, the climate modeling community will continue to implement higher model resolutions in concert with available computing power. Since climate models are highly nonlinear, they may not respond to changes of resolution linearly; model response to a change in resolution from 5° to 4° may be different from the response to a change from 2° to 1° in latitude/longitude. Thus the issue of resolution dependence will remain a topic of interest as long as model resolutions increase. In addition, there is often an assumption that increases in resolution improve the simulation quality, based on the fundamentals of computational fluid dynamics (i.e., a finer grid spacing improves the numerical solution). While this is generally true, it is not universal.
because 1) model physics are resolution dependent, and 2) models often contain compensating biases and so an improvement in one aspect can, in some instances, degrade the simulation. The climate modeling community has been working to resolve these issues; for instance, developments of scale-aware physical parameterizations and/or constraints on model parameters with observations are two notable efforts. Nevertheless, the potential improvements gained from increases in resolution and their root causes need to be better understood.

There are two key ways in which higher resolution can impact a climate simulation. In the first, it is the physics and dynamics of the climate system that are better represented, and in the second, it is the lower boundary (surface topography), which exerts a key direct influence on the climate system, that is improved. In this second category, surface topography influences the atmospheric circulation, and in turn the climate, by mechanical and thermal effects. It also triggers waves in the atmosphere that affect the climate remotely. In view of this, it is desirable to represent the surface topography with highest possible accuracy. Furthermore, when it comes to the simulation of a phenomenon like the Indian monsoon, which is strongly influenced by surface topography, a simulation is expected to benefit from the finer depiction of surface topography. However, what is its contribution to the overall improvement of the simulation, relative to that coming from the refinement of the atmospheric and surface processes?

In this paper we will examine the issue raised above in detail for the Indian monsoon using the Community Atmospheric Model, version 5.1, developed at the National Center for Atmospheric Research (NCAR). The model simulations are analyzed for the extended Indian monsoon region—latitudinal extent of 20°S–40°N and longitudinal extent of 40°–120°E—for boreal summer (June–September). Three sets of six-member ensemble simulations are conducted for April–September (i.e., starting the model simulation 2 months prior to the monsoon season). One simulation set is carried out at about 2° horizontal resolution, another set at about 0.5° horizontal resolution, and in the third surface topography is prescribed at 2° horizontal resolution but for rest of the model (atmospheric and surface processes) a 0.5° horizontal resolution is used. Together these are classified as the COARSE, FINE, and HYBRID simulations, respectively.

While the issue has yet to be addressed explicitly, several studies have explored the impacts of horizontal resolution on the Indian and Asian monsoons more generally (Sperber et al. 1994; Lal et al. 1995; Kar et al. 1996; Lal et al. 1997; Martin 1999; Chandrasekar et al. 1999). Sperber et al. (1994) examined the sensitivity of the summer monsoon to horizontal resolution of the ECMWF model at four different horizontal resolutions (spectral resolutions T21, T42, T63, and T106) and showed improvement in the simulation with increased resolution. They also showed that T106 captures most of the synoptic features of the Indian and East Asian monsoons. Lal et al. (1995) demonstrated that ECHAM3 at T106 resolution also successfully simulates synoptic-scale features of the Indian monsoon. Kar et al. (1996) showed the performance of the JMA global model in simulating the Indian monsoon and its variability at T42 and T106 resolutions. Their results show that T42 is sufficient for capturing broad-scale climatological aspects, but T106 is required to capture key regional aspects, such as the precipitation distribution in western and northwestern parts of India. Lal et al. (1997) examined the simulation of an Indian monsoon climatology in ECHAM3 and its sensitivity to horizontal resolution using T21, T42, and T106 spectral truncations, finding that for large-scale features of the monsoon circulation T42 is adequate but for regional features T106 is required. Martin (1999) examined the performance of the Met Office (UKMO) Unified Model simulating the Asian monsoon and its sensitivity to horizontal resolution using approximately 300 × 300 and approximately 100 × 100 gridpoint resolutions. Furthermore, Martin (1999) showed that the higher resolution captures the finer details of precipitation but that the systematic errors with the mean interannual and intra-seasonal variations of precipitation persist at the higher resolution perhaps as a result of errors in model physics. Chandrasekar et al. (1999) examined the effects of horizontal resolution on the simulation of the Asian summer monsoon in a Meteorological Research Institute (MRI) GCM using longitude–latitude horizontal resolutions of 5° × 4°, 3.3° × 3°, and 2.5° × 2°. Their results show that most of the features of Asian monsoon improve with an increase in resolution. However, they also noticed some deterioration with certain features, which they attribute to model physics.

These studies are suggestive of the potential benefits of increased resolution for simulations of the Indian and Asian monsoons. Unaddressed, however, is the source of such improvements. Of course, the studies provide speculative explanations that higher resolutions better resolve both surface topography and atmospheric processes. Yet, none of the studies objectively examined the relative importance of these factors. This is an important question and can be answered through numerical experimentation. Stephenson et al. (1998), Pope and Stratton (2002), Gao et al. (2006), Cannon et al. (2017), and Johnson et al. (2016) addressed some relevant issues.

Stephenson et al. (1998) examined the dependence of the Asian monsoon simulation on model resolution in detail, and through numerical experimentation they
showed that smooth orography reduces excessive precipitation biases over the steep topography of the Tibetan Plateau as well as over India. However, smoothing did not alleviate precipitation biases over the equatorial Indian Ocean. Gao et al. (2006) examined the role of resolution and topography in the simulation of East Asian precipitation using the Regional Climate Model, version 2 (RegCM2), a regional climate model. They conducted two sets of simulations: one including 45-, 60-, 90-, 120-, 180-, 240-, and 360-km resolutions, and one using the parent CSIRO GCM at the same resolutions but with their topography resolved at the coarsest resolution. They showed that simulation of precipitation improves with an increase in resolution and that high-resolution simulations with coarse topography perform better than for coarse simulations generally. Their results reveal that the use of RCM topography alone fails to add significant value, suggesting that resolution of simulated physical and dynamical processes is more important than the resolution of topography for the East Asian monsoon simulation. Johnson et al. (2016) examined the sensitivity of the South Asian monsoon to the resolution of the Met Office Unified Model and showed that an increase in resolution leads to an improved Somali jet simulation and a marginal increase in precipitation over peninsular India. Their diagnoses indicate that better representation of East African topography at higher resolution improves the simulation of the Somali jet. Cannon et al. (2017) examined the effects of topographic smoothing on the simulation of winter precipitation in the Asian high mountains using the Weather Research and Forecasting (WRF) Model. They performed two sets of experiments: one with native model resolution topography (6.67 km) and one with smoothed topography from a global circulation model (1.875° × 1.25°). They showed that coarse (i.e., smooth) topography is favorable for the intensification of the atmospheric circulation associated with westerly disturbances and generates stronger cross-barrier winds, which in turn lead to enhanced water vapor transport to the region.

Collectively, these studies support the idea that model resolution affects the simulation of the Indian monsoon, and simulations generally improve with an increase in resolution. Yet one cannot objectively answer the question raised in the preceding discussion regarding the root source of the improvement. The aim of this paper is to address this question.

In section 2, we briefly describe the model used, simulations performed, and observational and reanalysis data used. In section 3, we present results from the model simulations and explain the differences in surface topography, surface air temperature, sea level pressure, precipitation, surface evaporation, precipitable water, wind at 200 and 850 hPa, and seasonal, intraseasonal, and diurnal variations of precipitation. Finally, in section 4, we summarize our finding and provide a discussion of its broader implications.

2. Model, simulations, and verification data

The atmospheric component of the Community Earth System Model (CESM), the Community Atmosphere Model, version 5.1 (CAM5.1), with CAM4 physics option is used for this study. CAM5.1 is the seventh generation of atmospheric general circulation models (AGCMs) developed by the atmospheric modeling community in collaboration with the NCAR. Source code and input datasets of the model are freely available at the CESM website. Neale et al. (2010) provide a detailed description of the model. For the deep convection parameterization, the modified Zhang and McFarlane (1995) parameterization scheme is used (Neale et al. 2008). For the parameterizations of shallow convection the Hack (1994) scheme and for stratiform processes the Rasch and Kristjánsson (1998) and Zhang et al. (2003) schemes are used. For the land surface processes, the Community Land Model, version 4 (CLM4; Lawrence et al. 2011), is used. CLM4 simulates biogeophysical processes, which includes interaction of soil and vegetation canopy with shortwave and longwave radiation, transport of momentum and turbulent fluxes from soil and vegetation canopy, transport of heat in snow and soil, hydrological processes of canopy, snow, and soil, and stomatal physiological and photosynthesis processes in vegetation canopy (Lawrence et al. 2011). For the numerical computation, the CAM finite-volume dynamical core (CAM-FV; Lin 2004) is used for the simulations.

Three sets of six-member ensemble simulations are conducted to investigate the relative importance of surface topography resolution and atmospheric processes for simulation of the Indian monsoon. The first set is conducted at 2.5° × 1.9° longitude–latitude resolution, referred to as the COARSE simulation. The second set is conducted at 0.63° × 0.47° resolution, referred to as the FINE simulation. The third set (the HYBRID simulation) is carried out such that the surface topography of the COARSE simulation is prescribed using the FINE simulation CAM5.1 resolution. The CLM4 grid is same as that of the CAM5.1 grid and hence the HYBRID simulation uses 0.63° × 0.47° longitude–latitude resolution for CLM4 and the land surface properties and characteristics as in the FINE simulation. Between the HYBRID and FINE simulations, the resolution of surface topography is the only difference, whereas between COARSE and HYBRID, the resolution of the atmospheric and surface processes is the only difference. Comparison of
the former two will reveal the impact of the resolution of surface topography and of the latter two will indicate the impact of the resolution of atmospheric and surface process on monsoon simulation. The three sets of ensemble simulations are conducted with climatological SST (50-yr climatology of HadISST) as boundary condition. However, snow cover and soil moisture were computed and predicted by the model. The simulations are started from 1 April and run through the end of September, that is, the months prior to the season [June–September (JJAS)] of the Indian monsoon. The ensemble simulations are made by slight perturbations with the initial conditions. The ensemble means are constructed and used for the analyses.

Several observational and reanalysis datasets are used for verification and validation of the simulated results. To assess the seasonal cycle and intraseasonal variations of precipitation over the India, daily gridded precipitation data of the India Meteorological Department (IMD) for the period of 1975–2005 is used (Rajeevan et al. 2005). Since IMD data are available only over India and for daily time scales, for analyses involving regions outside India or subdiurnal variability, TRMM products for the period of 2001–10 are used. The TRMM 3B43 3-hourly, 0.25° × 0.25° product (Huffman et al. 2007) is used for the assessment of seasonal mean precipitation over the extended monsoon region. Also, TRMM 3B43 data is used for the assessment of diurnal and certain aspects of intraseasonal variations of precipitation. TerrainBase (TBASE) data at 5-min resolution is used for the assessment of surface topography of the model at the different resolutions. ERA-Interim data for the period of 2001–10 (Dee et al. 2011) are used for the validation of surface air temperature, sea level pressure, precipitable water, surface evaporation, and wind.

3. Results from the model simulations

a. Orography

Figure 1 shows the orographic height (in meters) in the TBASE data and the orographic height anomaly in the model simulations (i.e., COARSE, HYBRID, and FINE) with respect to that in the TBASE data. Since the COARSE and HYBRID simulations use the same surface topography and have the same topographic bias they are shown together in Fig. 1d. Figures 1a,c,e show the entire globe and Figs. 1b,d,f show our focus region 20°S–45°N, 40°–120°E. TBASE has a horizontal resolution of 5′ and clearly depicts the complex and intricate features of the orography of our planet. The model successfully represents large-scale orographic features (e.g., the Tibetan Plateau); however, there are remarkable differences between the simulations, especially at regional scales. In the COARSE and HYBRID simulations, regional-scale features are depicted with considerable biases, especially over the foothills and steep flanks of the orography; generally surface elevation over the foothills is overestimated and over the steep flanks it is underestimated. The biases are relatively large over the Andes and the Tibetan Plateau and its neighboring mountainous region. The orographic height is overestimated over the northern as well as the southern foothills of Tibet and underestimated over the steep flanks adjacent to the foothills. Similar biases also occur over the plateau of Iran and Burmese mountain ranges. The magnitude of biases along the Western Ghats, Eastern Ghats, and central India is comparatively small. The biases over the Himalayas and Tibetan Plateau are up to 1 km and are likely to have detrimental effects on the precipitation and circulation through barrier effects in the low-level flow, cooling of the surface by the lapse rate effect, and latent and sensible heating of the atmosphere by the elevated heat source effect. As expected, the surface topography characteristics improve with increase in resolution (see Figs. 1e,f). The biases in the FINE simulation are minimal; FINE captures orography height pretty well, even at the regional scales, but marginal biases still remain over the steep orographic regions of the Himalayas and Tibet. Over Antarctica the model biases do not show any such changes with the resolution change. It indicates that there are considerable differences in the surface topography between the TBASE and the model used USGS datasets, and that difference is seemingly hiding the effect of the resolution over this region.

b. Surface air temperature

Figure 2 shows the June–September mean surface air temperature from ERA-Interim and the three simulations, COARSE, HYBRID, and FINE, as well as the bias in the model simulations with respect to the ERA-Interim data, with contour lines depicting the surface elevation. The model, even at the coarse resolution, reasonably captures the broad features of the temperature distribution quite well, including high temperature over northwest India and the Arabian Peninsula and low temperature over the Tibetan Plateau; relatively high temperature over the Bay of Bengal and eastern Arabian Sea as compared to the equatorial Indian Ocean; and positive meridional temperature gradient from the equatorial Indian Ocean extending into India. However, the model at the coarse resolution is unable to capture the regional and local features, especially over the small–medium-scale orography, steep terrain, small and/or narrow landmasses, and coastal regions (e.g., Western Ghats, Eastern Ghats, Aravali, Burmese mountains, Maritime Continent, and coastal India). Also, the temperature pattern is too smooth and lacks...
intricate regional variations. This is largely expected, because, as discussed in the preceding section, the model at the coarse resolution cannot represent the finer-scale topography and landmass details in its lower boundary conditions (see the overlaid contours in Fig. 2). In addition, the model at the coarse resolution possesses severe biases over the Arabian Peninsula, mountainous region of Afghanistan, Iran, and Pakistan, the foothills of the Himalayas, the Tibetan Plateau, Western Ghats, Eastern Ghats, and Vindhya and Satpura mountain ranges of northern India. We have seen in the difference plots (simulated minus observed; see Figs. 2e–g) that surface air temperature is overestimated (underestimated) wherever the surface topography is underestimated (overestimated), which is due to the atmospheric lapse rate effect. These biases are seen over the foothills and steep flanks of the topography, which are indicated in the preceding section. Also, the surface temperature is overestimated over the narrow and intricate water bodies of the Gulf of Oman, the Persian Gulf, and the Red Sea. It is notable that the overestimation of temperature over northern India and the monsoon trough leads to overestimation of the meridional temperature gradient over the Indian longitudes, which causes a too strong land–ocean contrast and can lead to too strong monsoon circulation and precipitation. The FINE simulation shows a great deal of improvement in all these aspects. A more realistic distribution with finer features is simulated, especially over India and maritime continents. Most of the aforementioned biases have reduced significantly. Furthermore, low temperature contours along central and eastern India are captured well in the FINE simulation. In ERA-Interim data, extremely low
temperatures are noticed in the northwestern part of the Tibetan Plateau—a characteristic that is picked up in the fine simulation. However, the cold bias over the southwest corner of Saudi Arabia has become worse and spread to the entire west coast of Saudi Arabia as resolution is increased. Over Iran, Iraq, and Turkey, the model at finer resolution develops some fine features, which closely resemble the observed pattern; however, the magnitude does not have as much spatial contrast as it has in the observations. The warm bias over the foothills of the Himalayas, the Tibetan Plateau, Western Ghats, Eastern Ghats, the Vindhya and Satpura mountain ranges of northern India, and the monsoon trough has significantly decreased, which alleviates the too strong meridional temperature gradient and land–ocean contrast over the Indian longitudes as seen in the COARSE simulation, and expected to simulate the monsoon circulation and precipitation more realistically. Largely the FINE simulation is doing an impressive job, but it also has developed cold biases over the Arabian Sea and southern Bay of Bengal that were not present in the COARSE simulation. Interestingly the characteristics of the simulated surface air temperature in the HYBRID simulation falls between that in the COARSE and FINE simulations. It resembles the COARSE simulation over the Tibetan Plateau, the Himalayas, Burmese mountains, and the mountainous regions of Pakistan, Afghanistan, Tajikistan, and Kazakhstan, where complex orographic features and large orographic biases are present. Over small mountains (Western Ghats and Eastern Ghats), narrow water bodies (Gulf of Oman, Persian Gulf, and Red Sea), narrow landmasses (the Maritime Continent and peninsular India), complex land ocean boundaries (coastal zones of South Asia), flat terrain (Indo-Gangetic Plain), and the neighboring water surface of the Arabian Sea, the Bay of Bengal, and the Indian Ocean the characteristics in the HYBRID are far better than that in the COARSE simulation and tend toward those in the FINE simulation. It should be noted that COARSE and HYBRID use the same topography but HYBRID uses higher resolution (0.47° × 0.63°) for the representation of the rest of the model (surface and atmospheric process) whereas COARSE uses 1.9° × 2.5° for everything; on the other hand, the difference between HYBRID and FINE is the surface topography only. This reveals that resolution of surface topography has impacts on surface air temperature in regions with large orographic features, where topographic biases are present, but it does not have considerable impact on the neighboring flat terrain (the Indo-Gangetic Plain) and ocean regions (the Arabian Sea, the Bay of Bengal, and the Indian Ocean). Rather they and the narrow landmass, estuary, gulf, and coastal zones are found to be sensitive to the resolution of atmospheric and surface processes, and show appreciable improvements in HYBRID with respect to the COARSE simulation. In addition, surface air temperature over the monsoon trough in HYBRID is found to be much better than that in COARSE and closer to that in FINE, which is
mainly attributable to the finer representation of the atmospheric processes in the HYBRID simulation, because the underlying surface is a flat and broad terrain (Indo-Gangetic Plain) stretching over several hundred kilometers with no complex mountains so its surface geometry and characteristics are well captured even at coarse resolutions. This indicates that for accurate simulation of the monsoon trough, one needs to use fine enough resolution to adequately resolve atmospheric processes. However, increasing resolution will not necessarily improve the quality of simulation in all respects and may incur new biases, such as the cold bias over the west coast of Saudi Arabia and the Arabian Sea in the FINE simulation, which is attributable to the changes in the resolution of the atmospheric and surface processes (as similar biases are also observed in the HYBRID simulation).

c. Sea level pressure

Figure 3 shows sea level pressure in ERA-Interim and the three simulations as well as the biases in the simulations with respect to ERA-Interim for the JJAS season. The observed sea level pressure is characterized by the following: it decreases from south to north across the Indian subcontinent, and the lowest pressure zone is present over the east coast of the Arabian Peninsula, Iran, Pakistan, and northwest India, which extends farther through the Indo-Gangetic Plain into the head of Bay of Bengal and is known as the monsoon trough (see Fig. 3a). On the northern side of the monsoon trough, over the Tibetan Plateau, a high pressure zone is present. The model simulates most of its broad features; however, there are issues with its magnitude and finer spatial features. In the COARSE simulation, the Tibetan high is relatively weak. Also it fails to capture the small-scale features over India, the Arabian Peninsula, Pakistan, Afghanistan, the Tibetan Plateau, and the Maritime Continent. It simulates a too intense and too large monsoon trough, which extends all the way from the east coast of Saudi Arabia to the head of the Bay of Bengal. In contrast, the sea level pressure over the Indian Ocean is pretty close to that observed, indicating that the meridional pressure gradient force over India will be stronger in the COARSE simulation than that in observations, which is likely lead to stronger monsoonal circulation and precipitation; this is consistent with the too strong meridional temperature gradient over the Indian longitudes. The FINE simulation shows a remarkable improvement in these biases as both large-scale and regional-scale features are well simulated. Nevertheless the monsoon trough remains slightly too strong in the FINE simulation. If we compare the HYBRID and FINE simulations, between which the resolution of surface topography is different, we can see the significant improvement in FINE particularly over the regions of highest topography (Tibetan Plateau, the Himalayas, Burmese mountains, and mountainous regions of Pakistan, Afghanistan, Tajikistan, and Kazakhstan). On the other hand, if we compare the COARSE and HYBRID simulations, between which difference is the resolution of atmospheric and surface processes, we can notice remarkable improvement in the HYBRID simulation over the flat terrain of the Indo-Gangetic

![Figure 3](https://example.com/figure3.png)

FIG. 3. As in Fig. 2, but for sea level pressure (hPa).
Plain and neighboring seas. However over the small mountains, narrow water bodies, narrow landmass, and coastal zones of South Asia, HYBRID does not possess significant improvements, unlike as seen with surface air temperature, because pressure fields do not exhibit steep gradients as the surface topographic height and surface air temperature.

d. Precipitation

Figure 4 shows the June–September mean precipitation in TRMM 3B43 observations and the three simulations, as well as the biases in the simulations with respect to the observations. In TRMM observations it is seen that heavy precipitation (>10 mm day$^{-1}$) falls in the foothills of the Himalayas, the monsoon trough over the Indo-Gangetic Plain, the Western Ghats and west coast of India, the northern Bay of Bengal, the Burmese mountains and west coast of Myanmar, the south equatorial Indian Ocean, and the west coast of Sumatra. On the other hand, dry regions include northwest India, the lee side of the Himalayas and Western Ghats, the southern tip of the east coast of India, the western Arabian Sea, the southwestern Bay of Bengal, and the western equatorial Indian Ocean. The model simulations successfully capture the broadest features of total precipitation; however, certain regional features have notable biases. Over the mountains, especially where the topographic height is underestimated, precipitation is found to be overestimated, accompanied with underestimation of the same over its windward side, which suggests that the model is unable to create as much barrier effect as it should. Among the simulations, FINE is closest to the observations, both in magnitude and spatial structure; the pattern correlation coefficients and root-mean-square errors of COARSE, HYBRID, and FINE with the TRMM observations over our region are 0.53 and 5.69, 0.66 and 3.68, and 0.74 and 3.08, respectively. It captures most of the broad-scale and regional features mentioned above; however, it overestimates precipitation over the foothills of the Himalayas, Western Ghats, Burmese mountains, and southeastern Arabian Sea, and it underestimates precipitation over the southeastern equatorial Indian Ocean. The severe wet biases over the southeastern Arabian Sea and dry bias over the southeastern equatorial Indian Ocean are longstanding issues with NCAR models (Mishra 2011a,b; Mishra and Sahany 2011a,b; Mishra 2012; Evans et al. 2013), which have been noticed even in CAM3 and CAM4 (i.e., the predecessors of the model used herein, and irrespective of the dynamical cores, model resolutions, and time step sizes and thought to be associated with some physical parameterizations of the model). These biases are worse in the COARSE simulation. Overall, precipitation is overestimated over most of the domain (e.g., northern and peninsular India, Burma, and Myanmar, the Tibetan Plateau, and the Arabian Sea), which was suspected as a result of the too strong meridional temperature gradient and land–sea
contrast in the COARSE simulation (see sections 3b and 3c). In addition, there is dry bias over the central India accompanied with a wet bias over peninsular India, especially in the COARSE simulation, although the monsoon circulation is too strong (shown in section 3f), which is due to the fact that the low-level westerly that supplies moisture for the monsoon precipitation over India is displaced southwest in the model and passes over peninsular India. Furthermore, the COARSE simulation possess severe biases over the foothills of the Himalayas, the narrow mountainous regions over the peninsular India and Burmese mountains. From comparisons of precipitation in the three simulations, it is noted that the HYBRID simulation exhibits remarkable improvements over the COARSE simulation and resembles closely that in the FINE simulation in many respects, even in the regions of the greatest topographic biases. This indicates that for the simulation of precipitation resolution of atmospheric processes (e.g., advection, convection, clouds, radiation, boundary layer, microphysics, and macropahysics) and surface processes (e.g., mass, momentum, and energy transports at the surface and exchanges with the atmosphere) is crucial and more important than the resolution of surface topography, as the resolution of surface topography is the only difference between HYBRID and FINE simulations, whereas the resolution of the atmospheric and surface processes are the differences between COARSE and HYBRID.

e. Precipitable water, evaporation, and large-scale moisture convergence

Figure 5 shows precipitable water and surface evaporation and Fig. 6 shows large-scale moisture convergence from ERA-Interim data, and model simulations (i.e., COARSE, HYBRID, and FINE) for June–September. The simulations agree with ERA-Interim to a reasonable degree with smaller biases in the FINE simulation. In the reanalysis data, maximum precipitable water paths are seen over the northern Bay of Bengal, monsoon trough, central and northeastern India, west coast of India, Myanmar, and eastern equatorial Indian Ocean. Precipitable water biases estimated by subtracting ERA-Interim from the simulations, shown in Figs. 5c–g, show strong negative values over most of India, the Bay of Bengal, and the northeastern Indian Ocean. On the other hand, precipitable water is overestimated over the western Arabian Sea, the southern equatorial Indian Ocean, the lee side of the Himalayas over the Tibetan Plateau, and the Arabian Peninsula. As one moves from the COARSE to FINE simulations, most of these biases decrease. For instance, the strong negative bias along the range of the Himalayas and in the northwestern and northeastern India diminishes. The underestimation of precipitable water over the equatorial Indian Ocean and the overestimation over the Tibetan Plateau decrease significantly. Over mountainous regions (e.g., the Himalayas, Tibetan Plateau, Western Ghat, Eastern Ghats, Burmese mountains, and Somalia), the biases in the COARSE and HYBRID simulations are very similar, although reduced in magnitude in HYBRID. Over the surrounding seas and ocean, biases in the HYBRID simulation resemble those in the FINE simulation. This indicates that in the simulation of precipitable water, resolution of surface topography plays a dominant role over mountainous regions, but it is less important for remote biases in the surrounding sea, ocean, and flat terrain. However, an exception is over the dry region of the Arabian Peninsula; over this region HYBRID possesses larger biases than those of the COARSE and FINE resolutions.

Similarly, mean JJAS evaporation is shown in Figs. 5h–k from ERA-Interim data and the three simulations, and the biases in the simulations with respect to the reanalysis data are shown in Figs. 5l–n. The three simulations show similar biases characterized by an underestimation over most of India and its surrounding ocean, eastern China, Burma, Laos, Thailand, Vietnam, and Cambodia. Elsewhere evaporation is overestimated. The underestimation over the Arabian Sea, Bay of Bengal, and Indian Ocean is considerable (up to 4–5 mm day$^{-1}$). Over the ocean surfaces, the biases in the FINE and HYBRID simulations are more severe than those in COARSE. All other biases become progressively smaller from the COARSE to the HYBRID to the FINE simulation, and the overall characteristic features in the HYBRID simulation resemble closely those in the FINE simulation. This suggests that in the simulation of surface evaporation the resolution of surface topography does not play any such decisive role.

Figure 6 shows large-scale moisture convergence (LMC) over the region from ERA-Interim and the three simulations (COARSE, HYBRID, and FINE). All three simulations overestimate LMC over the monsoon regions, and closely resemble the rainfall distribution over the region. Moreover, close inspection of Fig. 6 suggests that the noticed overestimation of the precipitation over the monsoon region in the model simulations is primarily due to the overestimation of LMC. The bias in the COARSE simulation is up to 20 mm day$^{-1}$ over the Western Ghats, the foothills of the Himalayas, Burma, and Myanmar, about 75%–100% of the observed values. The biases are relatively less in the HYBRID simulation and least in the FINE simulation. Overall, the HYBRID simulation possesses closer resemblance to the FINE simulation than the COARSE simulation.

f. Wind

Mean JJAS wind at 200 and 850 hPa from the ERA-Interim reanalysis data and the three simulations—
COARSE, HYBRID, and FINE—are shown in Fig. 7 (Figs. 7a–d for 200 hPa and Figs. 7h–k for 850 hPa). The contours in the background of the wind field represent wind speed. Primary features of the circulation at 200 hPa include the anticyclonic flow over the Tibetan Plateau centered around 30°N, 85°E flanked by the subtropical westerly jet stream on its northern side and the tropical easterly jet on its southern side passing over India and the Arabian Sea and extending up to Africa. There is northeasterly flow over the Bay of Bengal that reaches up to the equatorial Indian Ocean, crosses the equator, and merges with the subtropical westerly jet stream of the Southern Hemisphere. In the lower troposphere (850 hPa), the flow includes strong subtropical easterly flow in the Southern Hemisphere over the Indian longitudes, the cross-equatorial flow above the Mascarene high, the Somali jet at the east coast of Somalia, and the westerly jet extending over peninsular India to the South.
China Sea. The strength and positions of the upper-level westerly jet streams are closely linked with the meridional temperature gradient through the thermal wind relationship. The low-level westerly flow is a key source of moisture for the monsoon precipitation over India. The Tibetan anticyclone depends upon the surface temperature of the Tibetan Plateau, which in turn depends on its height of the Tibetan Plateau. Flohn (1968) suggested that the effect of latent heat release over the southeast corner of Tibet was responsible for maintaining a thermal anticyclone over the Himalayas and was the primary mechanism for maintaining the Asian summer monsoon (Hahn and Manabe 1975). Similarly, the Somali jet is thought to be strongly influenced by the mountains over Somalia. Thus, ideally one would expect that the representation of topography is crucial for the simulation of the circulation over this region. We examine this possibility in these simulations. In the COARSE simulation, the anticyclone and the axis of the subtropical westerly jet are displaced northward and the tropical easterly jet stream over India is too strong. In the lower troposphere, the flow (including the Southern Hemisphere subtropical easterlies, the cross-equatorial flow, the Somali jet, and the westerly jet over India) is too strong, which was suspected as a result of the too strong meridional temperature gradient and land–sea contrast over the Indian longitudes (see sections 3b and 3c). The westerly jet is displaced southward over India and passes over peninsular India and extends farther, too far, into the South China Sea. The location of the Tibetan anticyclone is realistically simulated in the FINE simulation. Similarly the orientation and strength of the northeasterly flow over the Bay of Bengal and the tropical easterly jet are improved. Also the low-level flow shows considerable improvement, as for instance the bias in the Somali jet has lessened and the westerly jet has become more realistic with regard to strength, location, and longitudinal extent. However, the subtropical westerly jets do not show much improvement; all model simulations show a northward shift of the strong westerly subtropical jet. In most respects, the HYBRID simulation shows significant improvement over the COARSE simulation (e.g., the Tibetan anticyclone, tropical easterly jet, northeasterly flow over the Bay of Bengal, Somali jet, and low-level westerly jet) and shows close resemblance with the FINE simulation except over the Himalayas, Tibet, and the mountainous regions of Pakistan, Afghanistan, Tajikistan, and Kazakhstan where mountains and large topographic biases are present.

g. Seasonal variations

In this section we analyze the seasonal cycle of the Indian monsoon using pentad data for precipitation, surface evaporation, large-scale moisture convergence, and precipitable water (Figs. 8a–d, respectively). For precipitation the IMD data are used (average of 10 yr) for validation and verification purposes whereas for the other parameters ERA-Interim data are used. IMD observations show the sudden increase in precipitation in early June associated with the monsoon onset, followed by the peak monsoon in the month of July, and the withdrawal phase of monsoon in August and September. The advance and withdrawal phases are not symmetric as the onset is a rapid process whereas the retreat is relatively gradual. The seasonal cycle of the all-India monsoon precipitation generally has a smooth profile with few abrupt fluctuations. This contrasts with the model simulations, which show strong and abrupt fluctuations—with high peaks and deep troughs—particularly in the COARSE simulation. This can also be correlated with high values of filtered and unfiltered variance, which are maximum for the COARSE case and steadily decrease for the FINE and HYBRID resolutions (see section 3h). With regard to the phase of the seasonal cycle, the timing of onset, peak, and retreat, the model simulations are doing a reasonably good job. However, the precipitation magnitude is excessive in all three and is approximately consistent in time in JJAS at about 3–4 mm day$^{-1}$, which is an error of 30%–50%. Precipitation variations for the HYBRID and FINE
simulations are similar in amplitude and the peak precipitation in both occurs in July, which agrees with the IMD data. In comparison to the COARSE simulation there is a significant improvement in the HYBRID simulation as both amplitude and phase are similar to the FINE simulation.

As precipitation is mainly the result of local evaporation and large-scale moisture convergence (e.g., Fasullo and Webster 2002), it is desirable to examine these two variables and understand how they vary and what their relative role is in the precipitation simulation. If one compares the magnitude of precipitation, surface evaporation, and large-scale moisture convergence, one finds that around 60%–70% of the precipitation is supplied by the large-scale moisture convergence and the remaining 30%–40%, from local evaporation. Both are temporally coherent with precipitation in the advance phase; however, in the withdrawal phase evaporation, unlike large-scale moisture convergence, does not show any such decrease. The asymmetry of precipitation—rapid advance phase and gradual withdrawal phase—in the onset and retreat phases is due to the fact that in the advance
phase both evaporation and large-scale moisture convergence contribute to the moisture supply for monsoon precipitation over India and hence the rate is faster, whereas in the withdrawal phase, although large-scale moisture convergence decreases, evaporation remains more or less same, and hence it is slower. The model overestimates evaporation in the premonsoon month of April by about 0.5–1 mm day\(^{-1}\) and during the monsoon season by around 0.5 mm day\(^{-1}\), which is about a 15%–20% error with respect to the ERA-Interim data. All three simulations show similar performance, but HYBRID is closer to the FINE simulation and the monsoon season underestimation is more severe in the COARSE simulation. With regard to the large-scale moisture convergence, the simulations overestimate it during the monsoon season, outweighing the underestimated evaporation and contributing to the overestimation of precipitation. Like precipitation, large-scale moisture convergence shows abrupt and strong fluctuations during the monsoon period, especially in the COARSE simulation. As with other fields, HYBRID and FINE reproduce observed convergence variability better than the COARSE simulation.

Unlike the asymmetry with precipitation, it shows a symmetric structure in time about the peak monsoon, indicating that the precipitable water progressively increases in the premonsoon period and advance phase and then gradually decreases in the retreat phase. All simulations capture this aspect successfully. However, they underestimate precipitable water slightly in the premonsoon period by 4–5 kg m\(^{-2}\). In the month of June they agree well with observed values but after that again they have certain biases: COARSE underestimates precipitable water and HYBRID and FINE overestimate it by 1–2 kg m\(^{-2}\). Overall, HYBRID more closely resembles the FINE simulation.

**h. Intraseasonal variations**

Figure 9 shows intraseasonal variation of area-averaged (India) daily precipitation in the Indian summer monsoon season in IMD observations (Figs. 9a–f) and model simulations [COARSE (Figs. 9g–l), HYBRID (Figs. 9m–r), and FINE (Figs. 9s–x)]. Figures 9a–f show the variations in six representative but arbitrarily chosen normal monsoon years: 2003, 1996, 1989, 1984, 1969, and 1967, respectively, from the IMD observations. The other columns show the variations in the six ensemble members.
of each simulation (i.e., the COARSE, HYBRID, and FINE simulations). The black line in Figs. 9a–f represents the daily climatology of IMD data for 1951–2013. Similarly, black lines in Figs. 9g–x represent their respective ensemble means for the corresponding model resolutions. In observations, it can be seen that the precipitation has intraseasonal variations, with active and break phases. In strong monsoon years, generally the active phases are prolonged and/or the break phases are short whereas in deficit years the opposite happens.

All three simulations overestimate the daily precipitation (black lines), which is consistent with the overestimation of precipitation seen in their seasonal cycle and mean distribution. The intraseasonal variations in the simulations are not realistic; the HYBRID and FINE simulations have large variations at a higher frequency (rapid fluctuations) and the COARSE simulation has excessively high amplitude of variations. In all these aspects HYBRID very closely resembles the FINE simulation.
Figure 10 shows unfiltered and filtered variances of precipitation over the extended monsoon region from the model simulations and TRMM data. Unfiltered variance is estimated for 120 days of JJAS whereas a bandpass filter for 20–100 days (intraseasonal time scale) is used for the estimation of filtered intraseasonal variance of the same period. The unfiltered variance consists of the synoptic, intraseasonal, and some part of seasonal variations, and hence is always and everywhere greater than the filtered variance. Higher values of both unfiltered and filtered variance are noticed over the Western Ghats, off the coast of Myanmar in the Bay of Bengal, and over the eastern equatorial Indian Ocean (i.e., regions of high precipitation). A moderate amount of variance is seen over the Indian mainland and eastern Arabian Sea and very low variance is observed over northwestern India, the western Arabian Sea, and the western Indian Ocean. The model simulations capture the broad spatial distribution. In general FINE and HYBRID are very similar, very close to the observations, and significantly better than the COARSE simulation. A unique characteristic, however, is that the COARSE simulation realistically estimates lower variance in regions of Arabian Peninsula as opposed to the FINE and HYBRID simulations, which show relatively higher variability in both unfiltered and filtered values in this region. Over India, the FINE and HYBRID simulations overestimate variance, which is a reflection of the overestimation of the mean precipitation.

Figure 11 shows the power spectrum illustrating the temporal variation of total precipitation during the Indian summer monsoon period in the model simulations (COARSE, HYBRID, and FINE) and observations (TRMM). A bandpass filter for 20–100 days is used for filtering.

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Figure 11 shows the power spectrum illustrating the temporal variation of total precipitation during the Indian summer monsoon period in the model simulations (COARSE, HYBRID, and FINE) and observations (TRMM). A bandpass filter for 20–100 days is used for filtering.
synoptic peak are much better than those in the COARSE simulation. The HYBRID simulation shows significant improvement over the COARSE simulation and is closer to the FINE simulation in all the above aspects.

i. Diurnal variation

Diurnal variation is one of the remarkable characteristics of rainfall over the Indian region and realistic simulation of the same in the climate models remains one of the most challenging issues. Since mountains are one of the factors that cause diurnal variation of rainfall through thermomechanically triggered convection, it is suspected that resolution of surface topography would affect the simulation of diurnal variation, which is examined in the following. Figure 12 shows the diurnal variation of precipitation in JJAS over the extended monsoon region from TRMM data and the model simulations (i.e., COARSE, HYBRID, and FINE). Figure 12 is plotted using 3-hourly data. Observations show an early morning peak in precipitation over the foothills of the Himalayas and a late afternoon–evening peak in precipitation over the Tibetan Plateau. Over India and the Maritime Continent precipitation peaks in the evening. Over the northwestern Bay of Bengal, peak precipitation occurs near noon local time. Over the eastern part of the Arabian Sea (adjacent to the Western Ghats) precipitation peaks in the late night or early morning as it does in the equatorial Indian Ocean, and especially in its western half. The COARSE simulation fails to capture these characteristics. Over the Himalayas and Tibet it shows better agreement, although the timing and spatial contrasts are not precisely captured. The amplitude of peak precipitation is also severely underestimated everywhere in the extended monsoon region except over the Tibetan Plateau. The FINE and HYBRID simulations display very similar patterns and agree favorably with observations in most respects. They also show a reasonable agreement with observations over the Bay of Bengal, Arabian Sea, and Indian Ocean. In southern India, the FINE and HYBRID resolutions show satisfactory performance in simulating the peak precipitation in the late evening. However, over central and northern India all three simulations fail to correctly capture the observed timing; the model simulations have peak precipitation around noon whereas late evening is observed.

In general, the accuracy of the diurnal cycle of precipitation increases as we proceed from coarse to fine atmospheric resolutions, with HYBRID and FINE mostly showing very similar patterns. The similarity of the FINE and HYBRID simulations and their remarkable difference from the COARSE simulation indicates...
that the resolution of surface topography plays a secondary role in the simulation of diurnal cycle. However, over the Himalayas and the steep flanks of the Tibetan Plateau, important differences between the FINE and HYBRID simulations are noticed; in FINE the features have sharp contrast with the neighboring regions (Tibet and the monsoon trough), whereas HYBRID is spatially more diffuse. This suggests that the resolution of surface topography is important over the foothills and steep flanks of the Himalayas.

4. Summary and discussion

The importance of the resolution of surface topography in Indian monsoon simulation is investigated using the Community Atmospheric Model, version 5.1 (CAM5.1). Three sets of six-member ensembles are conducted for April–September: one at 1.9° × 2.5° resolution, another at 0.47° × 0.63° resolution, and a third set in which surface topography is prescribed at 1.9° × 2.5° but atmospheric and surface processes are represented at 0.47° × 0.63° resolution. These simulations are referred to as COARSE, FINE, and HYBRID, respectively. The model simulations are analyzed for the extended Indian monsoon region 20°S–40°N, 40°E–120°E for the Indian summer monsoon season (June–September). Precipitation variability from diurnal to seasonal time scales is examined. Observational and reanalysis data are used for model validation.

The model broadly represents the large-scale features of orography at all the three resolutions quite well; however, considerable differences exist between the simulations, especially at regional scales. In the COARSE simulation, regional features show considerable bias, especially over the foothills and steep flanks of the mountains. Orographic height is generally overestimated over the foothills, whereas it is underestimated over the steep flanks. The biases over the Himalayas and some parts of Tibet are up to 1 km and these have a detrimental effect on precipitation and the large-scale circulation through barrier effects in the low-level flow, cooling the surface temperature by the lapse rate effect, and latent and sensible heating of the atmosphere. The HYBRID and COARSE simulations use the same surface topography and thus associated biases are the same in both simulations. Representation of the surface topography improves with an increase in resolution and biases in the FINE simulation are found to be minimal, substantially less than in the COARSE and HYBRID simulations.

The model successfully simulates the broad features of the Indian monsoon at all three resolutions; however,
at regional scales remarkable differences between the simulations exist. The COARSE simulation fails to capture key regional climatic features, particularly over the small–medium-scale orography, steep terrain, and/or narrow landmasses, and coastal zones. Surface air temperature is generally overestimated (underestimated) wherever surface elevation is underestimated (overestimated) as a result of the atmospheric lapse rate. The biases in simulated surface air temperature in the HYBRID simulation fall between those in the COARSE and FINE simulations. We find that the resolution of surface temperature is crucial and more important than the resolution of surface topography. Surface air temperature in the monsoon trough in HYBRID and FINE simulations is found to be much better than in the COARSE runs, indicating that for accurate simulation of the monsoon trough one needs to use fine resolution to adequately resolve atmospheric processes.

In the COARSE simulation, the Tibetan high is relatively weak and the monsoon trough is too intense and zonally extensive, which is consistent with the underestimated surface elevation of the Tibetan Plateau and overestimation of surface air temperature, both there and over the monsoon trough. In contrast, simulated sea level pressure over the Indian Ocean is pretty close to that observed. The meridional pressure gradient force over the Indian longitudes is stronger in the COARSE simulations than that in observations, leading to stronger monsoonal low-level flow and precipitation over most of India. Over mountains, especially where the topographic height is underestimated, precipitation is overestimated, accompanied by an underestimation on the windward side, because of the weaker barrier effect. Although the monsoon circulation is too strong in all simulations and there exists an overestimation of precipitation over most of the domain, there is a dry bias over central India accompanied with a wet bias over the peninsular India, especially in the COARSE simulation. This is attributable in part to the fact that the low-level westerly that supplies moisture for monsoon precipitation over India is displaced southward in the model and passes over peninsular India. All of these biases are significantly reduced in the FINE simulation.

If one compares the HYBRID and FINE simulations, one finds a significant improvement of sea level pressure in FINE, particularly in the regions where topographic biases are present (the Tibetan Plateau, the Himalayas, Burmese mountains, and mountainous regions of Pakistan, Afghanistan, Tajikistan, and Kazakhstan). On the other hand, if one compares the COARSE and HYBRID simulations, one can notice remarkable improvement in the HYBRID simulation over the flat terrain of the Indo-Gangetic Plain and neighboring seas. However, over small mountains, narrow water bodies, narrow landmasses, and coastal zones of South Asia, HYBRID does not achieve any significant improvements.

From a similar comparison of precipitation in the three simulations it is found that the HYBRID simulation shows remarkable improvements over the COARSE simulation and resembles closely the FINE simulation in most aspects in the extended monsoon region, even in mountainous regions. This indicates that for the simulation of precipitation, resolution of atmospheric and surface processes is likely crucial and more important than the resolution of surface topography.

With regard to the seasonal cycle of the Indian monsoon, including the timing of its onset, peak, and withdrawal, the model simulations are overall satisfactory. However, all three simulations overestimate precipitation during the monsoon season (JJAS). The overestimation is about 3–4 mm day$^{-1}$, which is an error of 30%–50%. Precipitation variability is similar for the HYBRID and FINE simulations, and the peak precipitation occurs in July, as in observations. In comparison to the COARSE simulation, there is a significant improvement in the HYBRID simulation in both amplitude and phase, making it closer to the FINE simulation. Similarly, seasonal variations of surface evaporation, large-scale moisture convergence, and precipitable water in the HYBRID simulation are found to more closely resemble the FINE simulation.

In regard to intraseasonal variations of precipitation, the model simulations capture some of the broad-scale features, and in general the FINE and HYBRID simulations are similar, close to the observations, and significantly better than the COARSE simulation. This further suggests that resolution of atmospheric and surface processes plays a crucial role in the simulation of intraseasonal precipitation variability. Similarly, the accuracy of the diurnal cycle of precipitation significantly improves as one proceeds from the COARSE to the HYBRID simulation, but the HYBRID and FINE simulations demonstrate near-identical behavior, suggesting that resolution of surface topography plays a minor role as compared to the resolution of atmospheric and surface processes.

We thus find that the resolution of orography strongly affects some model fields, including surface air temperature, sea level pressure, precipitable water, and wind, locally over the orographic regions, especially over the foothills and steep flanks of major mountain ranges. However, precipitation and evaporation are
rather insensitive to the resolution of surface topography, and depend instead on the resolution of surface and atmospheric processes. While this may appear to be somewhat counterintuitive, one should not conclude that surface topography has an insignificant impact on Indian monsoon rainfall simulation. Surface topography, as shown by many prior studies, is one of the primary drivers of the atmospheric circulation, even if the accuracy with which it is resolved is of secondary importance as compared to the resolution at which atmospheric and surface processes are computed.

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