SPECIAL ISSUE

# Monsoon circulation interaction with Western Ghats orography under changing climate

## Projection by a 20-km mesh AGCM

**K. Rajendran · A. Kitoh · J. Srinivasan · R. Mizuta · R. Krishnan**

**Abstract** In this study, the authors have investigated the likely future changes in the summer monsoon over the Western Ghats (WG) orographic region of India in response to global warming, using time-slice simulations of an ultra high-resolution global climate model and climate datasets of recent past. The model with approximately 20-km mesh horizontal resolution resolves orographic features on finer spatial scales leading to a quasi-realistic simulation of the spatial distribution of the present-day summer monsoon rainfall over India and trends in monsoon rainfall over the west coast of India. As a result, a higher degree of confidence

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appears to emerge in many aspects of the 20-km model simulation, and therefore, we can have better confidence in the validity of the model prediction of future changes in the climate over WG mountains. Our analysis suggests that the summer mean rainfall and the vertical velocities over the orographic regions of Western Ghats have significantly weakened during the recent past and the model simulates these features realistically in the present-day climate simulation. Under future climate scenario, by the end of the twenty-first century, the model projects reduced orographic precipitation over the narrow Western Ghats south of 16°N that is found to be associated with drastic reduction in the southwesterly winds and moisture transport into the region, weakening of the summer mean meridional circulation and diminished vertical velocities. We show that this is due to larger upper tropospheric warming relative to the surface and lower levels, which decreases the lapse rate causing an increase in vertical moist static stability (which in turn inhibits vertical ascent) in response to global warming. Increased stability that weakens vertical velocities leads to reduction in large-scale precipitation which is found to be the major contributor to summer mean rainfall over WG orographic region. This is further corroborated by a significant decrease in the frequency of moderate-to-heavy rainfall days over WG which is a typical manifestation of the decrease in large-scale precipitation over this region. Thus, the drastic reduction of vertical ascent and weakening of circulation due to 'upper tropospheric warming effect' predominates over the 'moisture build-up effect' in reducing the rainfall over this narrow orographic region. This analysis illustrates that monsoon rainfall over mountainous regions is strongly controlled by processes and parameterized physics which

need to be resolved with adequately high resolution for accurate assessment of local and regional-scale climate change.

## 1 Introduction

There is increasing awareness of the impact of climate change on mountains. Mountains play a major role in influencing regional and global climates. They force the air to rise, increasing the amount of precipitation on their windward side and creating drier areas or rain shadows downwind. Mountain areas have very complex terrain and so their climates vary considerably over short distances. Under changing climate, the climate pattern over these regions and their highly fragile ecosystems are experiencing accelerated rates of change, with potentially significant consequences for the rest of the world.

The motivation for the present study comes from the findings of recent studies which have focused on the possible influence of increasing emissions of greenhouse gases (GHGs) on the Indian summer monsoon (e.g. Rajendran and Kitoh (2008) and reference therein). These studies suggest that the simulated precipitation response to global warming in climate models is accompanied by changes in the large-scale southwest monsoon flow (e.g. Rajendran and Kitoh 2008; Stowasser et al. 2009; Sabade et al. 2010; Krishnan et al. 2012). For example, Rajendran and Kitoh (2008) investigated the impact of global warming on the Indian monsoon rainfall using time-slice simulations of ultra high-resolution 20-km Meteorological Research Institute (MRI) global general circulation model (GCM). They noted a likely increase in the simulated monsoon rainfall over the interior regions of the Indian subcontinent under the future climate scenario and a significant reduction in orographic rainfall over the west coasts of Kerala and Karnataka. The rainfall reduction over parts of Western Ghats (hereafter referred to as WG) was mostly to the south of 16° N and was accompanied by a drastic reduction in the southwesterly winds and moisture transport into the region. Several studies have also suggested the possibility of the weakening and stabilization of the tropical large-scale overturning circulation in response to global warming (e.g., Knutson and Manabe 1995; Kitoh et al. 1997; Douville et al. 2000; Sugi et al. 2002; Cherchi et al. 2010). For example, Sugi et al. (2002) noted that a significant increase in dry static stability in the tropical troposphere and little increase in tropical precipitation (or convective heating)

are the main factors contributing to the weakening of the tropospheric circulation.

Given that the summer monsoon precipitation over the Indian subcontinent involves interactions between the large-scale monsoon circulation and the small-scale convective processes, it would be interesting to understand whether observed changes in monsoon precipitation over smaller regions (e.g. the WG mountains) are related to changes in the large-scale summer monsoon flow under changing climate, with an aim to analyse causative mechanism for the change. Hence, the present study addresses the following issues:

1. How much change in WG climate has occurred in the recent past as per diagnostic analysis of observed climate datasets?
2. What are the likely future climate change over WG orographic region due to global warming?
3. What are the dominant factors contributing to the potential future climate change based on the interaction of monsoon circulation with WG orography under global warming scenario?

These are carried out through the analysis of ultra high-resolution time-slice simulations of present-day and end of the twenty-first century climates by MRI 20-km mesh global climate model and observed climate datasets. In this context, it is important to note that GCMs often fail to capture the fine-scale structures that affect regional climate due to their coarse resolution (with grid size of 100 km). This aspect partially accounts for the deficiencies shown by GCMs in reproducing important aspects of the regional distribution of the Indian summer monsoon meteorological parameters (Sperber and Palmer 1996; Gadgil and Sajani 1998; Solomon et al. 2007) and wide variations among Intergovernmental Panel for Climate Change Fourth Assessment Report (IPCC AR4) model projections (e.g. Kripalani et al. 2007; Annamalai et al. 2007; Krishna Kumar et al. 2010). These coarse resolution climate models cannot adequately resolve the fine spatial scale features of orographic rainfall along the narrow Western Ghats whose maximum zonal width does not exceed 100 km. On the other hand, nesting of high-resolution regional model that can resolve the topographic features is known to have high dependency on the lateral boundary forcing and significant inability to represent regional–global scale interaction due to lack of two-way nesting with the forcing GCM. For example, in a study using a regional climate model (Rupakumar et al. 2005) which resolved high-resolution orographic features over India, the climate change impact under

A2 and B2 scenarios (Nakicenovic et al. 2000) was found to increase the monsoon rainfall over the entire country, with some regional variation. Alternately, by enhancing the global GCM resolution considerably, the regional–global scale interactions can be incorporated and regional climate information such as land–sea distribution, lakes, soil characteristics and orography can be better represented so that the simulation will be useful for local impact assessments.

In view of these aspects, the use of the MRI ultra high-resolution global climate with horizontal mesh size of approximately 20 km used in the present study overcomes the problems of inadequate horizontal resolution in representing the WG mountains to a great extent and incorporates the global–regional climate interactions that are important for South Asian monsoon. An added advantage of using the GCM employed in this study is its reasonable fidelity in representing the regional distribution of the present-day Indian summer monsoon rainfall and the seasonal variation of all-India summer monsoon rainfall (Rajendran and Kitoh 2008).

The details of the model, simulations and climate datasets used in the study are discussed in Section 2. In Section 3, we show the observed climate and climate trends over WG in the recent past. The model fidelity in simulating present-day climate and trends over WG is presented in Section 4. The projected future climate change over WG is presented in Section 5. Changes in summer mean circulation and causative processes behind the projected changes over WG orographic region are also analysed in this section. Section 6 concludes the results.

## 2 Model, climate simulations and data

A global ultra high-resolution GCM with a spatial grid size of about 20 km and 60 vertical levels, jointly developed by Japan Meteorological Agency (JMA) and MRI, is used for global warming projection (Mizuta et al. 2006; Rajendran et al. 2008; Rajendran and Kitoh 2008). The model corresponds to a triangular truncation 959 with linear Gaussian grid in the horizontal comprising $1,920 \times 960$ grid cells of about 20 km. Cumulus parameterization scheme used in this hydrostatic model is the Arakawa–Schubert scheme with Randall and Pan (1993) type closure. The effect of entrainment and detrainment between the cloud top and cloud base in convective downdraft instead of re-evaporation of convective precipitation is included. Introduction of a two-level semi-Lagrangian scheme (Yoshimura and Matsumura 2005) made possible for use of long-time

step in time integration. A detailed description of the model and its parameterization schemes are given in Mizuta et al. (2006).

### 2.1 Simulations

For the present-day climate simulation, observed historical sea surface temperature (SST) from Hadley Centre HadISST dataset (Rayner et al. 2003) during 1979–2007 was prescribed. The observed concentrations of GHGs ($CO_2$, $CH_4$ and $N_2O$) are specified as global constant values with year-to-year variation. For example, $CO_2$ changes from 337.1 ppm in 1979 to 384.3 ppm in 2007. A 'time-slice experiment' was performed for the future climate simulation towards the end of the twenty-first century from 2075 to 2099 under IPCC A1B scenario (the experiment details are given in Rajendran and Kitoh 2008). The boundary SST dataset was prepared by superposing (1) the trend in the multi-model ensemble (MME) of SST projected by the World Climate Research Program Coupled Model Intercomparison Project multi-model dataset, (2) future change in MME of SST ($\Delta$SST) and (3) the de-trended observed SST anomalies for the 1979–2007 period. Future change in MME of SST was evaluated by the difference between the twentieth century simulations and future simulations under IPCC A1B emission scenario. The experimental design retains observed year-to-year variability and El Niño and Southern Oscillation events in future climate but with a higher mean and clear increasing trend in SST (Mizuta et al. 2008; Rajendran and Kitoh 2008).

### 2.2 Observed datasets

The validation data for the present-day rainfall simulation of the 20-km model are taken from the Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE) precipitation dataset from 1951 to 2007. The daily gridded estimates were at $0.25° \times 0.25°$ spacing over Asia (Yatagai et al. 2009). For rainfall validation, we have also used the daily India Meteorological Department (IMD) gridded rainfall data on $0.5° \times 0.5°$ grid for the period 1979–2007 (Rajeevan et al. 2006). This dataset is based on 1,803 stations with a minimum 90% data availability during the period. Meteorological circulation fields are estimated from Japanese Reanalysis (JRA-25) data for the period 1979–2007 on $1.125° \times 1.125°$ grid provided by the Electric Central Institute and the JMA (Onogi et al. 2007).

## 3 Observed mean summer monsoon

### 3.1 Rainfall climatology

The most striking feature of the Indian west coast is the presence of the Sahyadri range (or the Western Ghats), which runs parallel to a narrow coast (Fig. 1), a few tens of kilometres wide extending up to the foothills of WG. From the foothills, the slopes of the Ghats rise abruptly in the form of an escarpment to an average elevation of 700 m. At several places, the escarpment is broken by river valleys. The axis of the range lies perpendicular to the prevailing summer–monsoon winds. It can be seen from Fig. 1 that the 20-km model is able to capture the orographic features of WG to a great extent, especially when compared to the current models (see Solomon et al. 2007). The high-resolution models resolves the peaks and spatial distribution of elevation not only over WG but over the peninsular India as well (Fig. 1).

Rainfall over the Indian land mass is significantly modulated by the orographic features of WG. Figure 2 reveals numerous regional details of the summer mean (June, July, August, September average, hereafter referred to as JJAS) rainfall over WG and India (inset) based on two different observations (APHRODITE

rainfall and IMD rainfall for the period 1979–2007). Over India, the major monsoon rainfall maximum is oriented along the Indo-Gangetic plain with orographic rainbelts over the Himalayas and WG. Orographic influence on summer mean monsoon rainfall over WG can also be seen in detail. The region has two distinct topographical and climatic features: to the west lies a coastal plain with heavy rainfall (windward side) and to the east lies a plateau with less rainfall (leeward side). The moisture-laden monsoon winds cause heavy rainfall on the windward side of the range, distinguishing it from the much drier leeward side. Most of the west-coast rainfall (90%) occurs during June–September, there being comparatively less rainfall during the rest of the year. There is a close comparison between the two datasets in representing the prominent features of summer mean rainfall and its spatial gradient over the Ghats. We hereafter present the results of the analysis of APHRODITE dataset as it is of higher spatial resolution than IMD rainfall.

### 3.2 Trends in rainfall and circulation

Over the Western Ghats mountain lies one of the major rainbelts over India (Gadgil and Sajani 1998)
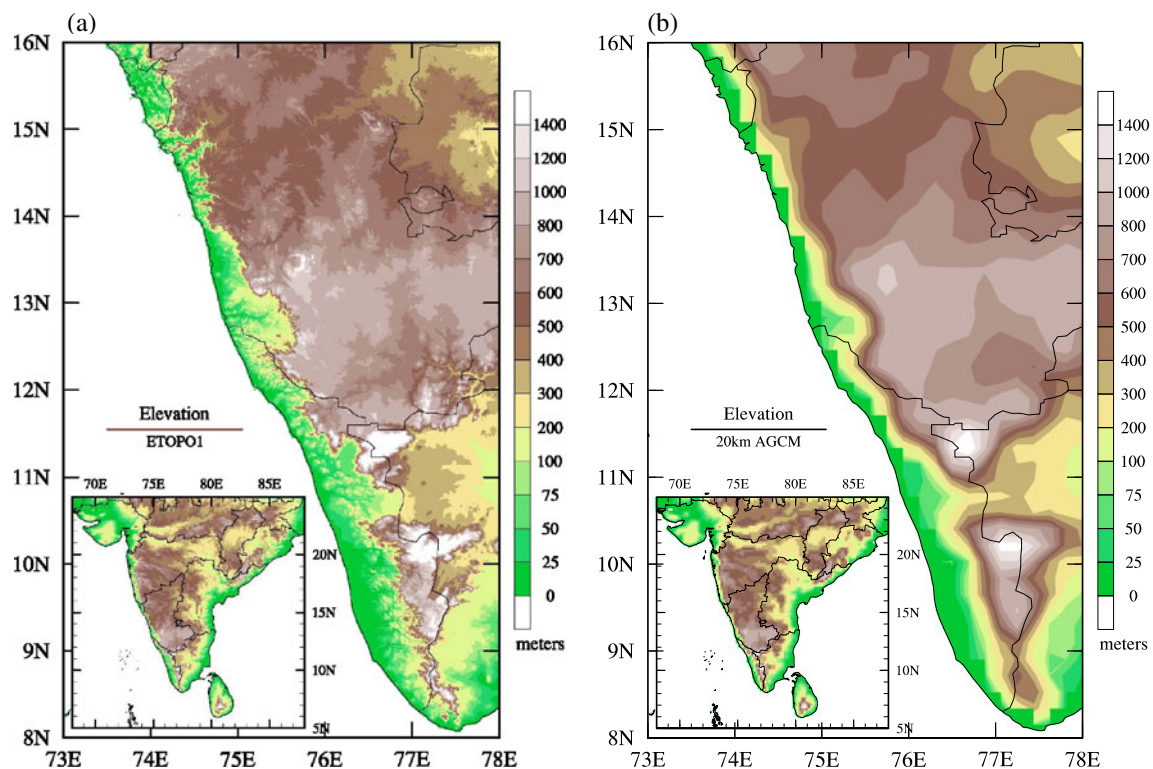


**Fig. 1** The region of study; southern part of Western Ghats (WG) and Indian Peninsula in *inset*. The topography of the region (in metres) as in **a** ETOPO1 (DEM) dataset (*left*, online documentation: http://www.ngdc.noaa.gov/mgg/global) and **b** 20-km model (*right*)
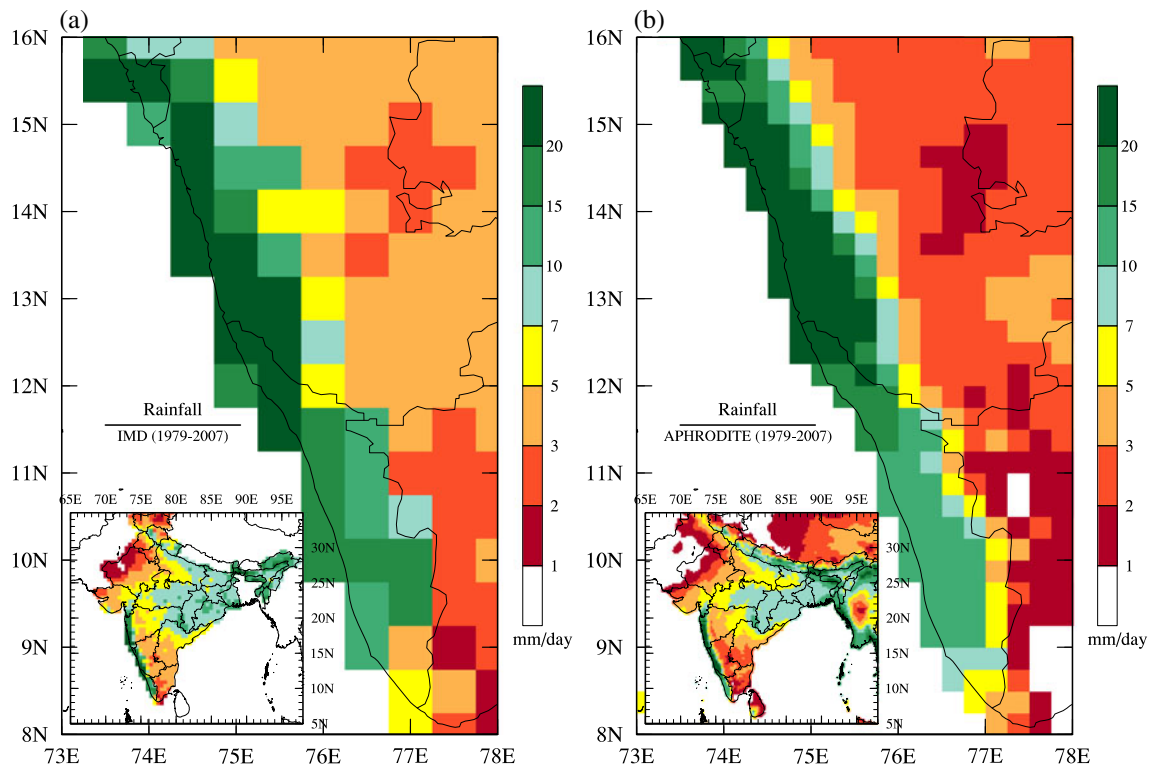
**Fig. 2** Climatological summer mean (JJAS) rainfall over WG and rainfall over India (in millimetres per day) in *inset* from **a** IMD rainfall (*left*) and **b** APHRODITE rainfall (*right*)

during the summer monsoon season (Fig. 2). Trends in summer mean rainfall and 500-hPa vertical pressure velocities ($-100 \times \omega$) are shown in Fig. 3. Over WG, there is a substantial rainfall reduction and a significant decreasing trend in seasonal mean rainfall which is more prominent in the trend over the last half century (Fig. 3b). On the other hand, there is an increasing trend over the leeward side of WG. However, the trend over most part of India, especially the leeward side of WG, becomes statistically significant when the entire period of 1951–2007 is used for the trend analysis. There are intermittent decreasing trends in monsoon rainfall along the east coast of Indian Peninsula and some parts of Indian subcontinent. Consistent to the decreasing trend in rainfall, over the southern peninsular region, significant decreasing trends in seasonal mean vertical velocities at 500 hPa which is a measure of the large-scale ascent, can be noticed (Fig. 3c).

According to the IMD, percentile thresholds for moderate-to-heavy rainfall events based on daily rainfall data can be defined as the daily rainfall amount between the 75th and 95th percentiles (e.g., Joshi and Rajeevan 2006). Correspondingly, the rainfall amounts associated with the moderate-to-heavy rainfall events over WG are typically in the range of 20–100 mm/day;

20–80 mm/day can be broadly classified as moderate-to-heavy rainfall for all the rainfall subdivisions of India (Dash et al. 2009). Figure 4 shows the spatial distribution of trends in number of days with relatively low rainfall (<20 mm/day) and moderate-to-heavy rainfall (20 ≤ rainfall < 100 mm/day) events over WG and India (inset) during the summer monsoon season based on the APHRODITE dataset. While there is a decreasing trend in the frequency of moderate-to-heavy rainfall days over WG and some parts of India, there is an increasing trend in the occurrence of relatively low rainfall days over WG. Recently, Krishnan et al. (2012) pointed out that the declining trends in orographic precipitation over the WG during the last few decades are consistent with a weakening of the summer monsoon local Hadley circulation and the accompanying southwesterly monsoonal winds that impinge the WG. The trends over the leeward side of WG are nearly opposite to those over the windward side for light rainfall. But it is seen that moderate-to-heavy rainfall events are predominant events and more frequent over several locations along WG (not shown). This indicates that the substantial reduction in seasonal mean rainfall occurs through reduction in moderate-to-heavy rainfall events.
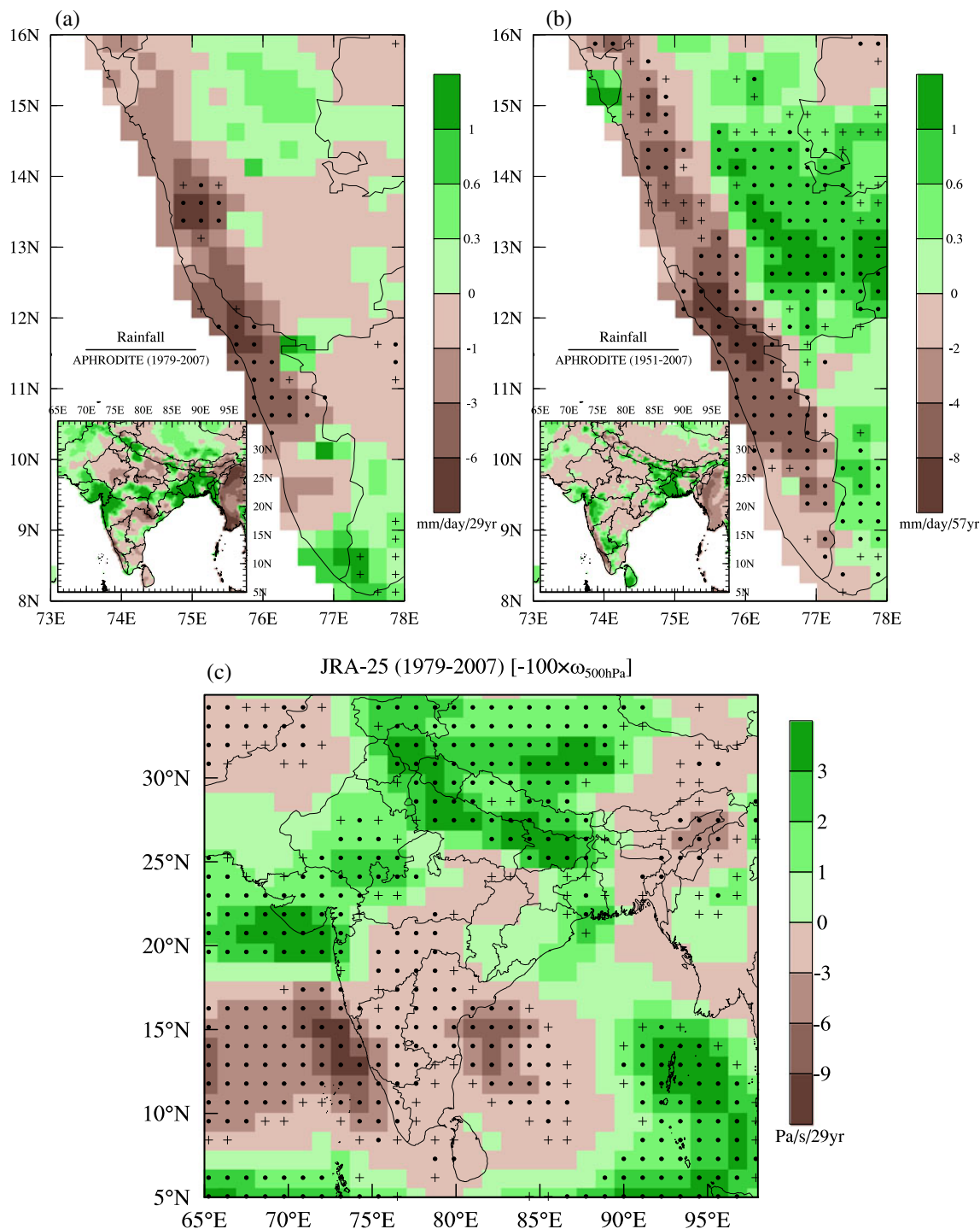
**Fig. 3** Trends in seasonal mean (JJAS) distribution of **a** rainfall based on APHRODITE data for 1979–2007, **b** rainfall based on 1951–2007 APHRODITE data and **c** vertical pressure velocity $(-100 \times \omega)$ based on JRA-25 data for 1979–2007. Trends significant at 90% (80–90%) are highlighted with *dot* (*plus*) symbols

## 4 Model fidelity: present-day climate simulation

Many studies have shown that the most difficult parameter for the GCMs to simulate is the mean monsoon rainfall occurring in the season (e.g., Sperber and Palmer 1996; Gadgil and Sajani 1998). Thus, the fidelity of the model in representing the present-day climatological features is crucial for building confidence in its
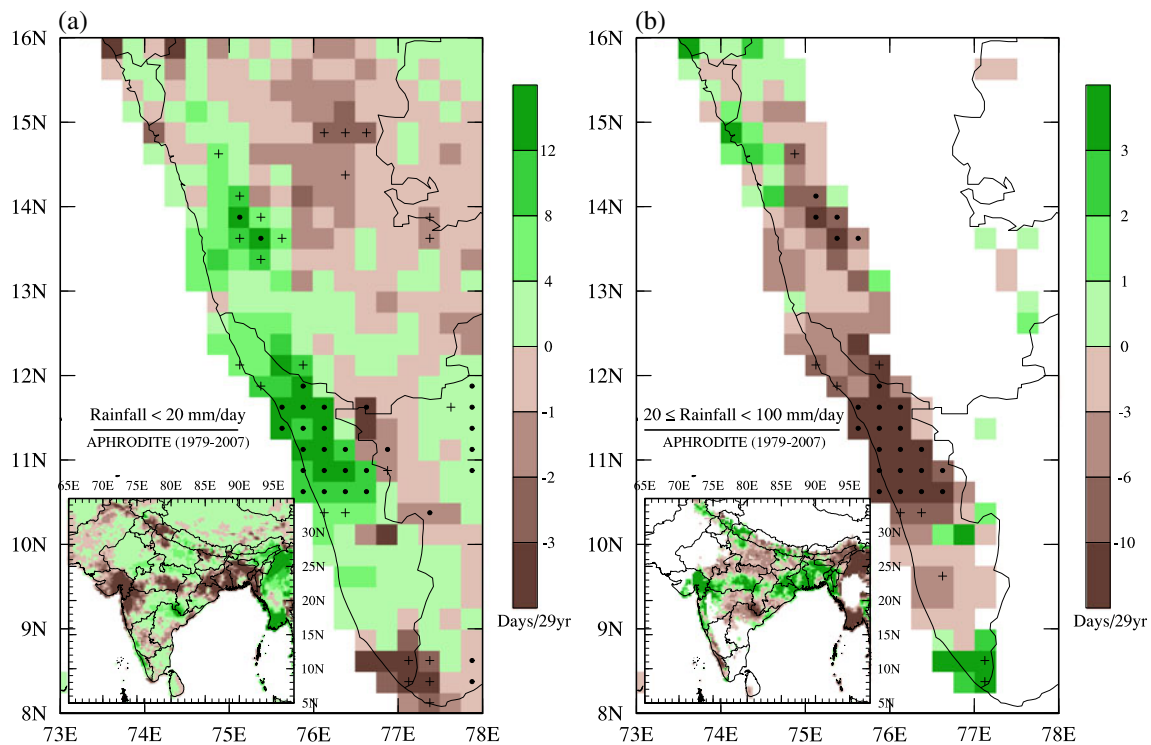
**Fig. 4** Trends in the number of days with **a** light rainfall (<20 mm/day) and **b** moderate-to-heavy rainfall (20 ≤ rainfall < 100 mm/day) during the summer monsoon season (JJAS) based on APHRODITE dataset (1979–2007). Trends significant at 90% (80–90%) are highlighted with *dot* (*plus*) symbols

future projections. Figure 5 shows the mean summer monsoon (JJAS) rainfall over WG from the ultra high-resolution simulation. Comparison with Fig. 2 reveals the skill of the model in representing the regional details of the observed rainfall pattern and illustrates the importance of high resolution in providing crucial regional climate information, in particular the orographic nature of rainfall with its small-scale structures over WG. The distribution of mean summer monsoon rainfall over India is shown in inset. The 20-km simulation captures some of the important aspects, such as the relative maxima over parts of the Indo-Gangetic plains, central India and the northeast region, and meridionally oriented orographic maximum along the west coast of the Indian Peninsula. On the southeastern part of the Indian peninsula, precipitation is relatively weak as in observation. However, there is a slight rainfall underestimation over the West Bengal region. The primary manifestation of the Indian monsoon, which is crucial for an accurate simulation of the mean monsoon and its variability, is the distinct seasonal variation of precipitation over the Indian region (Gadgil and Sajani 1998). On all-India average, the simulated rainfall seasonal variation (annual cycle) was also found to be simulated well by the model (Rajendran and Kitoh 2008).

The trend in summer monsoon rainfall from the 20-km present-day simulation over WG and India is shown in Fig. 6. Comparison with Fig. 3 shows the model's fidelity in simulating the observed rainfall trend and its spatial variation and heterogeneity over WG. For other parts of India especially the leeward side of WG, the simulated trend corresponds reasonably well with the observed trend over the last half of the century (Fig. 3b). A notable aspect of the simulation is the near opposite trends on either side of WG as seen in the observation.

## 5 Future climate change

### 5.1 Changes in mean rainfall

In response to global warming, the model predicts an increase in precipitation at the end of the twenty-first= century which is significant at 95% level, in most parts of the Indian region where rainfall is rather strong during the monsoon season (Fig. 7 inset). However, in the southern half of the west coast of the peninsula, parts of eastern India and the Jammu–Kashmir region, future decrease in rainfall has been projected. The spa-
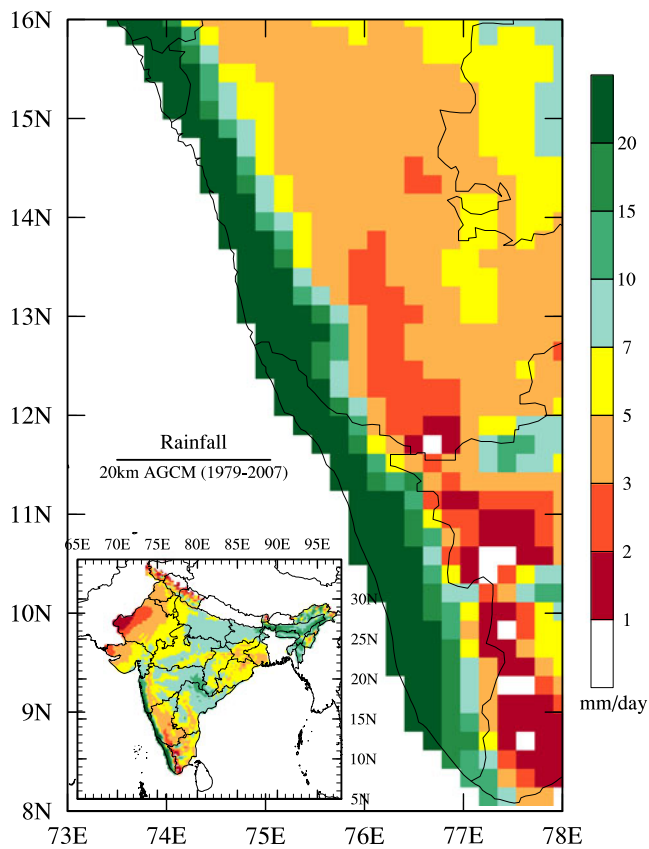
**Fig. 5** Climatological summer monsoon (JJAS mean) rainfall from the present-day simulation of the 20-km model over WG and India (*inset*)



**Fig. 6** Trend in summer monsoon (JJAS mean) rainfall over WG from the present-day simulation of the 20-km model. In *inset*: Summer monsoon rainfall trend over India. Trends significant at 90% (80–90%) are highlighted with *dot* (*plus*) symbols

tial distribution of precipitation change due to global warming is uneven with distinct spatial inhomogeneity over India.

Different factors can contribute to the change in the hydrological cycle due to global warming. Increase in the saturation-specific humidity or the capacity to hold water vapour with rise in temperature can increase the actual water vapour content in the atmosphere ('moisture build-up effect'). Thus, if the mean residence time of water vapour in the atmosphere does not change, both precipitation and evaporation would increase with exponential dependence on temperature. But, regional factors which are resolvable with 20-km resolution, like orography, the availability of surface moisture and horizontal convergence/divergence of air flow in the lower atmosphere, modulate the concentration of water vapour evaporated from the surface or transported into the area. Thus, the resultant spatial distribution of atmospheric moisture and the precipitation changes can be uneven.

Future scenarios for the Indian summer monsoon rainfall even using high-resolution regional climate models so far have projected relatively uniform climate
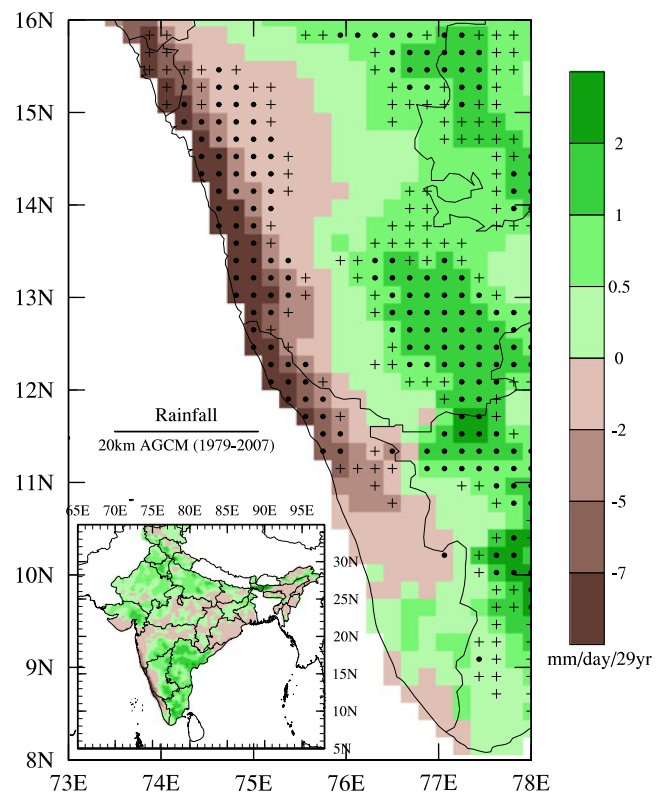
change (e.g. Rupakumar et al. 2005). But, with the 20-km simulation, the projected changes show considerable spatial heterogeneity (Fig. 7). Over WG, the projected changes indicate significant weakening of monsoon rainfall in the future, in response to the anticipated increase in GHG concentration and resultant widespread warming of surface temperature (not shown). In the leeward side of WG, significant increase in future rainfall is predicted by the model. The projected future changes over WG orographic region are qualitatively similar to the recent trends in observation and simulation (Fig. 3).

## 5.2 Changes in monsoon circulation

Figure 8 shows the seasonal mean changes in (a) precipitable water ($P_{WAT}$) and column-integrated moisture transport, (b) evaporation, (c) horizontal wind and moisture convergence at 850 hPa and (iv) vertical pressure velocity ($-100 \times \omega$) at 500 hPa over peninsular India, projected by the model in response to future
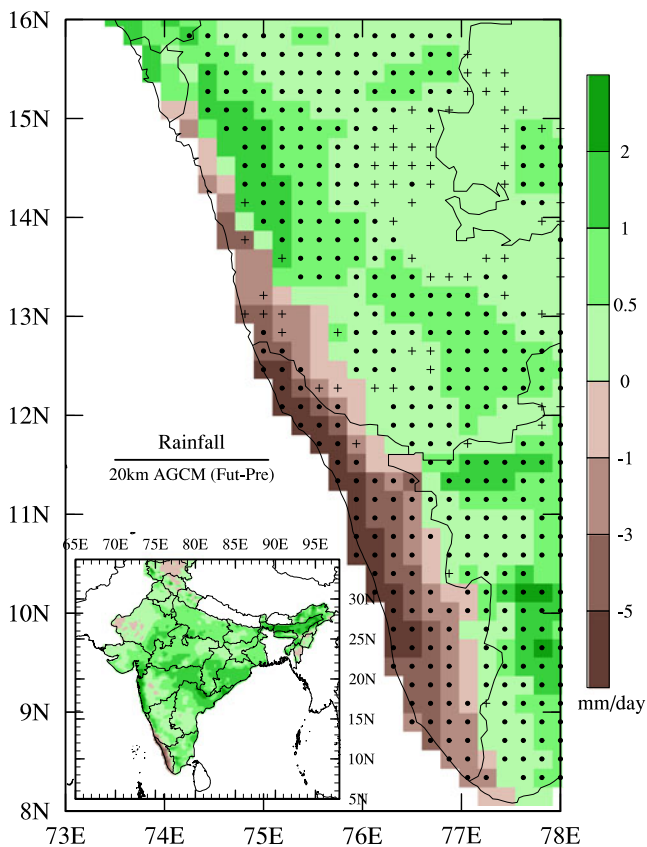
**Fig. 7** Climatological summer (JJAS) mean difference in rainfall between future projection and present-day simulation of the 20-km model for WG and India (*inset*). Differences significant at 90% (80–90%) are highlighted with *dot* (*plus*) symbols

warming. Associated with the increased specific humidity due to future warming, there is a widespread increase in $P_{WAT}$ over the entire region but with strong quantitative spatial variation (Fig. 8a). The maximum increase in $P_{WAT}$ can be seen over the coastal regions including the west coast and some interior parts of the peninsula. Strong future increase in evaporation (Fig. 8b) also occurs over most parts. The positive changes in $P_{WAT}$ (evaporation) are found to be significant over entire peninsula (most parts of the peninsula). Over southern WG, there is a significant anticyclonic anomalous flow over the Arabian Sea (Fig. 8a, c) that is consistent with the reduction in resultant precipitation changes (Fig. 7). Over this region, as the reduction in future orographic rainfall is associated with positive changes in $P_{WAT}$ and evaporation, the effect of steep orography (Fig. 1) on the circulation in the region appears to play a dominant role offsetting the moisture build-up effect.

Major features of mountain effect are found to be the rapid and systematic changes in climatic parameters such as temperature and precipitation over short

distances (Becker and Bugmann 1997) due to the complexity of their topography and associated systematic variation in circulation, radiation and soil types. The 20-km model, unlike projections using models which are generally too crude to adequately represent the topographic details, projects spatially varying global warming impact over steep and narrow orographic region of WG. For example, height and zonal extent of orography are the largest in the southern half of the Western Ghats (Fig. 1) where the model projects drastic reduction of westerly winds and large-scale moisture convergence above the boundary layer (Fig. 8c).

Negative rainfall anomalies are associated with significant reduction in vertically integrated moisture transport into the region (Fig. 8a). Such decrease in transport and large-scale low level convergence (Fig. 8c) can reduce vertical ascent (Fig. 8d) and hence convection/precipitation (Fig. 7). Increased northerly/easterly components in moisture transport (Fig. 8a) along the steep mountains dominate over the increased moisture effect (positive changes in $P_{WAT}$) to result in the reduction of local rainfall over the southern WG. As the atmospheric moisture content is the largest in the lower troposphere, the pattern of the vertically integrated atmospheric moisture transport (Fig. 8a) and low-level moisture convergence (Fig. 8c) resemble to a large extent to the wind pattern in the lower troposphere (Fig. 8c). It is to be noted that, in a classical study using a quasi-geostrophic model for rotating stratified flow over obstacles, Gadgil (1977) has illustrated the remarkable influence of meridionally oriented Western Ghats on Indian summer monsoon circulation. In this study, upstream summer monsoon circulation was found to induce a southward component at all levels above a meridionally oriented ridge. This implies that the interaction of monsoon circulation with meridionally oriented modest orography of WG seems to induce forced ascent of warm moist air to result in abundant rainfall on the windward side of the Ghats. Thus, the interaction of monsoon circulation with WG orography is an important factor for seasonal mean orographic rainbelt (Fig. 2) over this region, and hence, it is pertinent to examine the potential changes in this interaction when the whole atmosphere is warmer and moistened under future scenario.

In contrast to the southern part, significant westerly moisture transport sustains over the Arabian Sea north of 16° N (north of Kerala and Karnataka coasts) and the Indian subcontinent, extending further into the central Indian region (Fig. 8a). Although the westerly wind changes at 850 hPa in the central Indian region are only slightly enhanced in the future (Fig. 8c), the westerly moisture transport in the total column is considerably
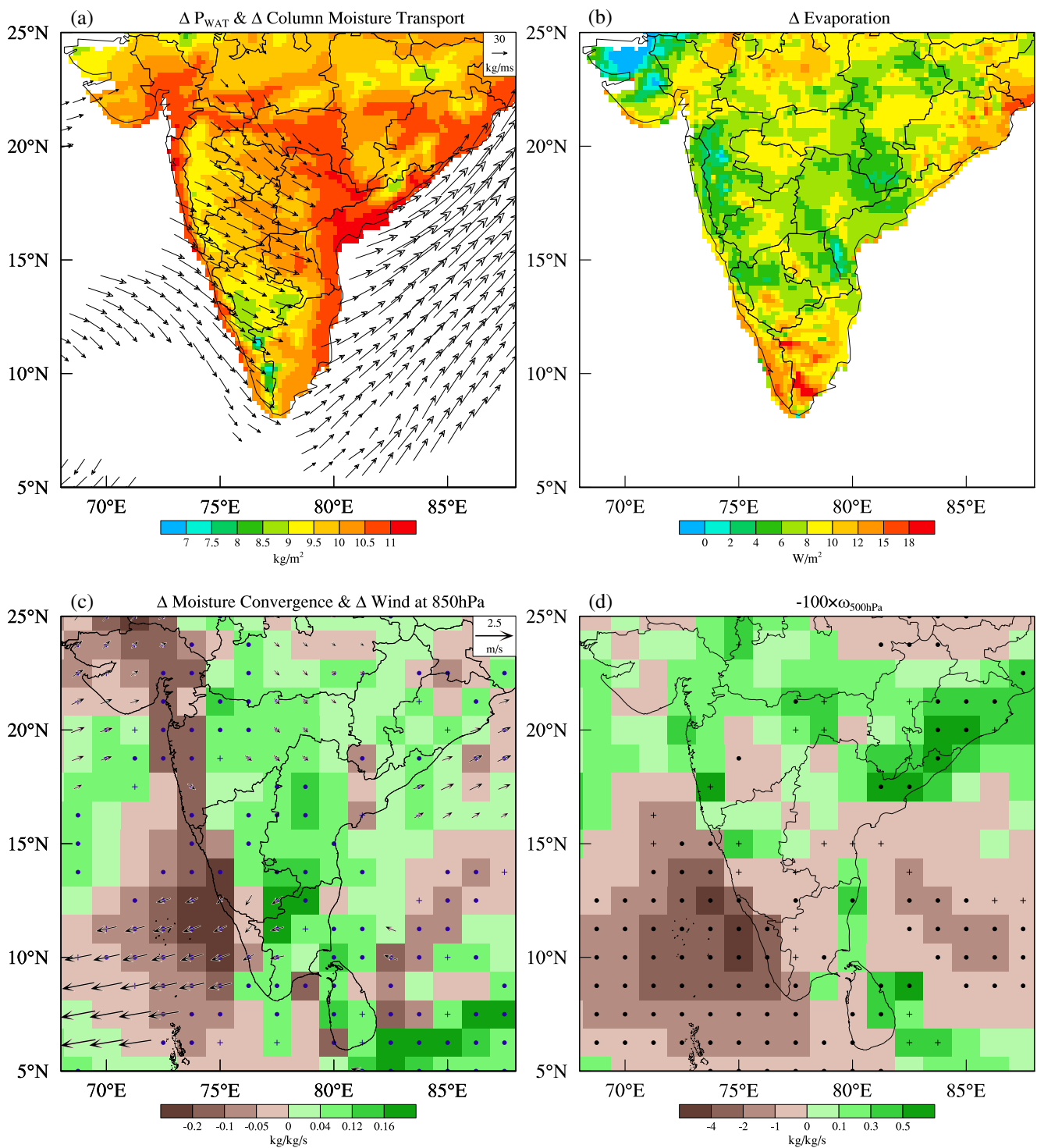
**Fig. 8** Climatological summer (JJAS) mean difference between future projection and present-day simulation by the 20-km model for **a** precipitable water ($P_{WAT}$) overlaid with column-integrated moisture transport significant at 90% level, **b** evaporation, **c** 850-hPa wind vectors (significant at 90% level) and moisture convergence and **d** vertical pressure velocity ($-100 \times \omega$) at 500 hPa. The positive changes in $P_{WAT}$ (evaporation) are found to be significant over the entire peninsula (most parts of the peninsula). Changes in 850-hPa moisture convergence and pressure velocity at 500 hPa, significant at 90% level (80–90% level), are stippled using *dot* (*plus*) symbols

increased in this region (Fig. 8a). Obviously, the future increase in the monsoon rainfall over these regions (Fig. 7) is due to the intensification of moisture flux into the central Indian region, which in turn is related to an additional increase in future atmospheric moisture content other than the increase due to increased specific humidity under general warming (resulting in positive changes in $P_{WAT}$).

In view of these changes, it is important to examine concurrent changes in the summer monsoon meridional circulation over WG. The summer mean local meridional circulation is illustrated in Fig. 9 as the latitude–pressure section of WG longitudinal averaged (68°–75° E) vertical pressure velocity ($-100 \times \omega$) overlaid with corresponding ($v$, $\omega \times 100$) vectors significant at 90% level. In present-day simulation, during summer monsoon, strong ascending motion occurs around WG region along with a secondary branch of upward motion over the near-equatorial region (around 5° S) with the descending branch of the meridional circulation (characterized by strong subsidence) located over the southern subtropical Indian Ocean between 20° S and 30° S (not shown). The ascending and descending branches of the monsoon meridional circulation are

linked by southerly flow from the Indian Ocean into the subcontinent in the lower troposphere and a return northerly flow in the upper troposphere (not shown). The changes in the meridional circulation projected by the model in future scenario (Fig. 9) shows anomalous subsidence between 10–16° N in the entire column, in accordance with the suppression of ascending motion over WG. The simulated change in meridional circulation shows a significant reduction in its intensity, which is consistent with the weakening of the summer mean circulation over WG (Fig. 8) in a warmer future scenario.

### 5.3 Changes in rainfall regimes

Global warming can affect rainfall in a number of ways, including changing its frequency, intensity and timing of occurrence in different classes of rainfall. Thus, it is important to determine how the character of different rainfall regimes could change in response to GHG-induced global warming in the future. Projected changes in low and moderate-to-heavy precipitation events suggest that at the end of the twenty-first century, the 20-km simulation predicts a decrease (increase) in moderate-to-heavy (low) rainfall events over southern parts of WG and India (in inset) as shown in Fig. 10b (Fig. 10a). The changes over almost entire southern WG are found to be significant at 90% level.

For extreme rainfall ($\geq 100$ mm/day), while the southern WG showed insignificant changes, parts of northern west coast exhibited substantial increase with peak positive anomalies of up to 30 days (not shown). Intensification (reduction) of moderate-to-heavy rainfall (low) events also occurs in the projected future climate over these regions (Fig. 10a, b). The changes in extreme precipitation were found to be related to changes in large-scale atmospheric flow during summer (e.g. Fig. 8) over the northern west coast. Enhanced anticyclonic flow at the upper levels increases when coupled with positive anomalies in tropospheric moisture and moisture transport. This suggests enhanced forcing of synoptic scale ascent and hence clouds and precipitation over these regions (see Rajendran and Kitoh 2008). Although such changes could have initiated the precipitation–soil moisture–evaporation feedback, it is also possible that the larger-scale changes resulted from the changes in surface moisture balance (Pal and Eltahir 2003). But, for moderate-to-heavy rainfall regime, the model predicts substantial reduction in future over the west coast south of around 15° N (Fig. 10b). Further analysis is required to ascertain the full nature of monsoon thermodynamics and its interaction with WG orography. The results of this
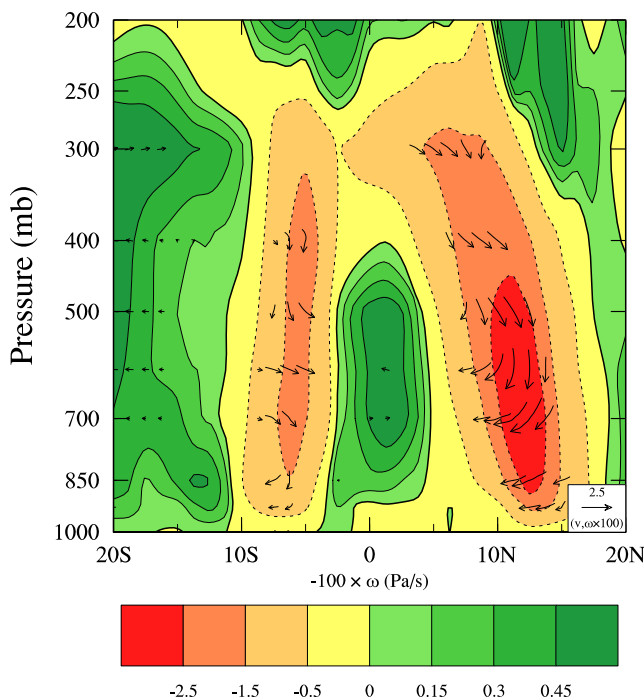


**Fig. 9** Latitude–pressure section of climatological summer (JJAS) mean difference between future projection and present-day simulation of the 20-km model for mean vertical pressure velocity ($-100 \times \omega$) overlaid with ($v$, $\omega \times 100$) vectors significant at 90% level, averaged over 68°–75° E
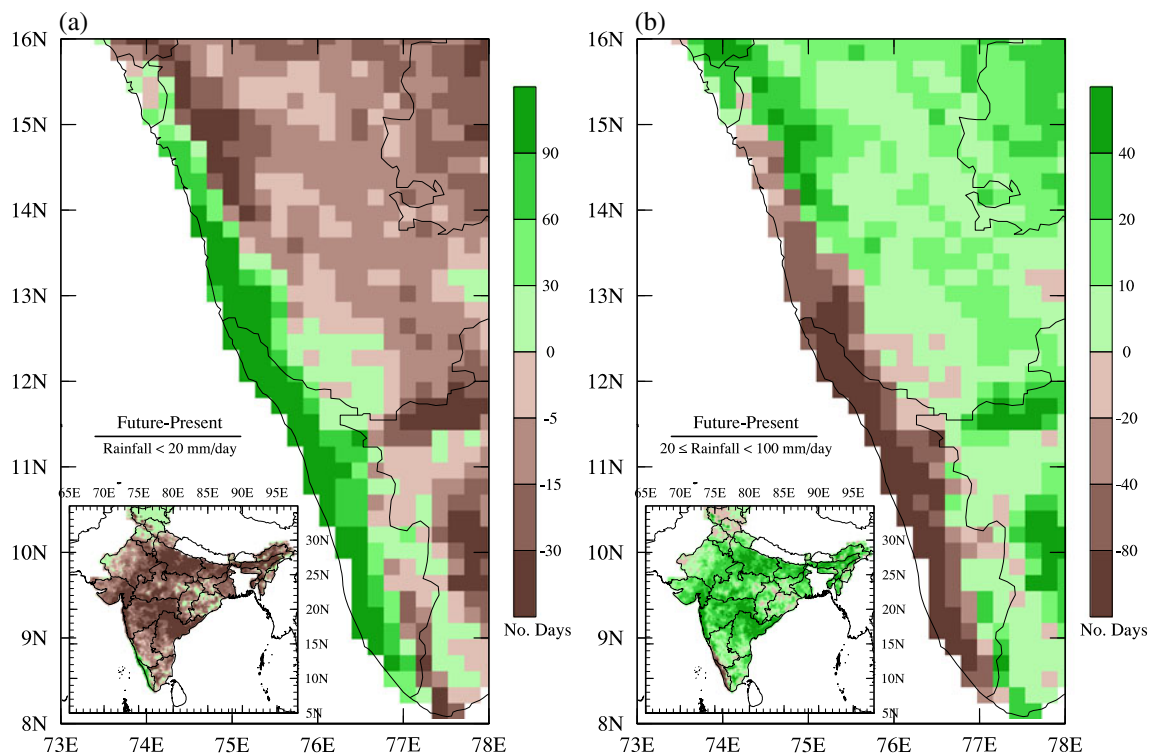
**Fig. 10** Difference in the number of days in JJAS season **a** for rainfall <20 mm/day and **b** for 20 ≤ rainfall < 100 mm/day, between the future climate simulation and present-day simulation of the 20-km model

20-km experiment seems to indicate that such interactions could exert critical control on the regional response of different rainfall regimes to anthropogenically elevated GHG concentrations.

The pattern of anomalies in moderate-to-heavy precipitation event frequency is similar to that of seasonal mean precipitation changes (Fig. 7), including peak anomalies in precipitation event frequency of up to 30 days over the northern parts of the west coast (Fig. 7 inset). Over the southern part of WG, as seen in the pattern of precipitation anomalies (Fig. 7), Fig. 10b implies a weakening of the orographic rain, due in large part to the changes in moderate-to-heavy precipitation regime. For instance, positive anomalies in mean precipitation on the northern half of the west-coast regions are associated with large positive changes in the frequency of moderate-to-heavy rainfall. In contrast, over the southern WG, negative anomalies in seasonal mean precipitation are associated with negative changes in the frequency of moderate-to-heavy rainfall days. Precipitation increase over northern parts of WG could have resulted from GHG-related increases in the moisture content of air being carried across mountain ranges or from increases in up-slope flow on the lee side of those ranges. The contributing processes for the reduction over southern parts of WG are analysed next.

### 5.4 Large-scale rainfall changes

Gadgil (1977) first suggested the importance of WG mountains in inducing a cyclonic circulation (a southward component) above the elevation. Grossman and Durran (1984), based on analysis of a special boundary layer mission flown during the WMO/ICSU Summer Monsoon Experiment, mean highly reflective cloud data and a two-dimensional mountain–flow interaction model with a smoothed profile of the WG mountains provided a typical illustration that large vertical wind shears over the coastal area and mountain crest which would inhibit deep convection. Xie et al. (2006) by analysing recent satellite observations revealed that narrow mountain ranges (focused on coastal narrow mountains of Myanmar which are modest in height (≤1 km) and Bay of Bengal monsoon rainfall) are important organising agents anchoring monsoon convection centres on the windward side because of large-scale orographic lifting as the southwest monsoon impinges on the coastal mountains. Their numerical simulations showed that orographic rainbands are not a local phenomenon but exert effects on continental-scale monsoon. These studies imply that WG rainfall during summer monsoon has substantial contributions from large-scale condensation of moisture due to the

forced ascent of moisture laden southwest monsoon winds upon impingement on the meridionally oriented orographic barrier.

Figure 11 shows the percentage contribution of the large-scale rainfall (hereafter referred to as large-scale (LS) rainfall) component to the total rainfall (sum of the large-scale and convective rainfall) from the present-day simulation of 20-km model (ratio of LS rainfall to total rainfall in Fig. 11a). The simulated LS rainfall ratio shows contribution more than 65% of the total rainfall over parts of the southern west coast of India. It can be seen that LS rainfall over the southern part of WG decreases by as much as 5 mm/day (Fig. 11b) in the future. The mean changes in LS rainfall are significant over most parts of WG. Mizuta et al. (2006) have analysed the contributions of large-scale condensational rainfall relative to the total rainfall in the MRI model at different horizontal resolutions. They noted that the contribution from large-scale condensational rainfall increases over the global tropics as the model resolution is increased because of the ability to better resolve the vertical velocities at higher horizontal resolutions. The parameterisation of conver-

sion from cloud water to large-scale precipitation in the MRI GCM is based on the scheme of Sundqvist (1978) according to which the important parameters affecting the large-scale condensational rainfall are humidity, temperature and vertical motion, wherein the vertical velocity determines the condensation rate and the supply of liquid water content. Reduction in large-scale monsoon circulation (Figs. 8a, c, d and 9) and resultant weakening of vertical velocities over the southern part of the WG (Fig. 8d) are hence expected to reduce the large-scale condensational rainfall in response to global warming. The decrease in moderate-to-heavy rainfall events over southern WG in the future scenario (Fig. 10b) is a typical manifestation of the decrease in LS rainfall over the region.

5.5 Role of atmospheric stability

The issue of weakening of large-scale atmospheric circulation and decrease in the intensity of tropical rainfall/convection in response to global warming has been discussed by several investigators (e.g., Knutson and Manabe 1995; Bengtsson et al. 1996; Sugi et al.
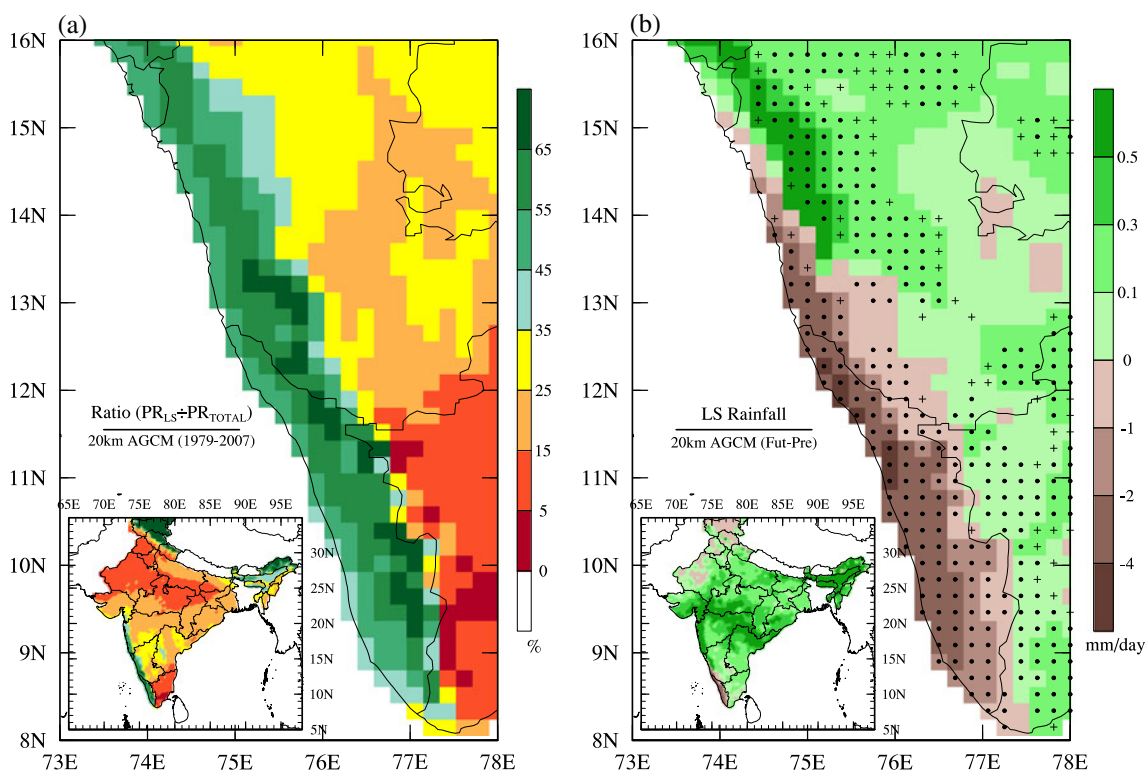


**Fig. 11** Climatological summer (JJAS) mean **a** ratio of large-scale rainfall (LS rainfall) to total rainfall (sum of LS rainfall and convective rainfall) from the 20-km present-day simulation (in percent) and **b** difference between future projection and present-day simulation of the 20-km model for LS rainfall. Differences significant at 90% (80–90%) are highlighted with *dot* (*plus*) symbols

2002; Held and Soden 2006; Vecchi and Soden 2007; Gastineau et al. 2008; Krishnan et al. 2012). Knutson and Manabe (1995) presented a detailed atmospheric heat budget over the tropical Pacific to understand the weakening of upward motions over the tropical western Pacific simulated by the GFDL-coupled model in response to quadrupled $CO_2$ concentration which suggested that the significant decrease in upward vertical velocity would have to be balanced by an increase in dry statistic stability of the atmosphere. From thermodynamic energy arguments, it has been postulated that the weakening of overturning circulations is induced by increased atmospheric static stability in response to a slower rate of increase of global rainfall relative to the increase in lower tropospheric moisture. We next analyse the possible causative processes leading to the weakening of future vertical velocities in the model.

The vertical profiles of differences in temperature, specific humidity, moist static energy (MSE) and dry static energy (DSE) averaged over southern WG region (68°–75° N, 5°–16° N) between the future climate simulation and present-day simulation of the 20-km model are shown in Fig. 12. A notable feature is the occurrence of substantial increase in temperature in the upper troposphere. The increase of temperature (warming) and the DSE in the future is larger in the

upper troposphere compared to lower levels which can have a more stabilising effect that can lead to weakening of the vertical velocities. The humidity profile shows that there is moisture build-up in the lower troposphere in a warmer climate without much change in the upper troposphere. Due to this, MSE shows a smoother vertical variation. This vertical variation illustrates that the contribution for larger increase in dry static energy and moist static energy at upper levels comes from a larger increase in temperature in these levels. This increase of air temperature with height makes the temperature lapse rate (i.e. $\frac{-dT}{dz}$) less in future atmosphere. If the temperature aloft had not increased more than surface temperatures, surface air parcels would have required less heat to rise and eventually condense into rain. As a consequence, the tropical upper tropospheric warming can strengthen the energetic activity above but enhanced static stability can weaken the energetic activity below and the vertical ascent.

The physical mechanism controlling the amplification of upper tropospheric warming needs greater understanding. In a warmer climate, on one hand, the atmospheric water vapour increases mainly concentrating at lower troposphere, so the atmospheric stability decreases (moisture build-up effect). On the other hand, the vertical profile of the warming induced by latent heating should follow the moist adiabatic process; thus, the atmospheric temperature increases more at higher troposphere than at lower troposphere ('upper tropospheric warming effect', Trenberth et al. 2007). This amplification of upper tropospheric warming can stabilise the atmosphere. The dominance of either of these two opposing effects tends to decide the changes in convection/precipitation under warmer climate.

In Fig. 13, we can see that the change in vertical moist static stability (VMS, the difference between moist static energy of the lower troposphere (998.5–421.8 hPa) and that of the upper troposphere (421.8–113.8 hPa), defined as $MSE_{(421.8–113.8\,hPa)}$-$MSE_{(998.5–421.8\,hPa)}$) also points to increased stability (that can lead to weakened large-scale circulation) over southern WG region. The spatial distribution of VMS clearly shows the opposite nature of atmospheric stability changes (future minus present climates) between the northern and southern parts of WG. This can be understood with the simple model suggested by Neelin and Held (1987) based on a moist static energy budget. Rajendran et al. (2002) used this simple model to demonstrate the association between variations in VMS and precipitation/convection. According to this model, decreased rainfall/convection is associated with increased atmospheric stability and hence an increase in VMS. The peaks of increased stability is found to be confined to the southern WG
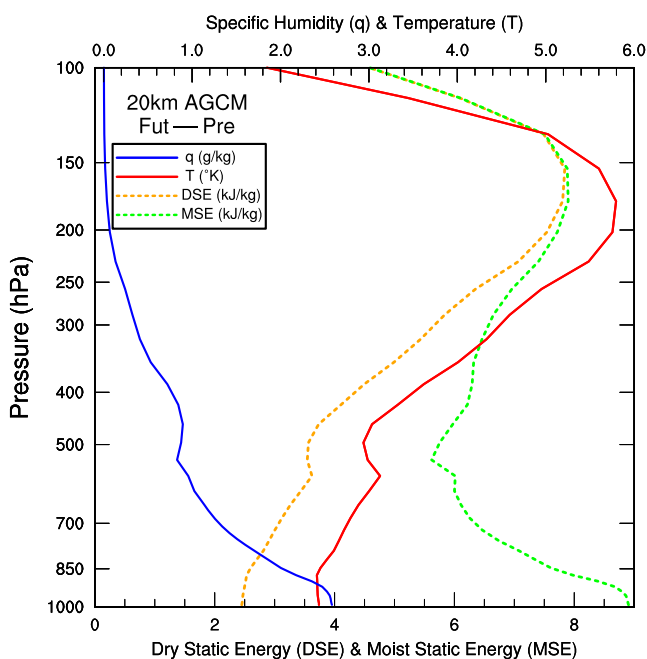


**Fig. 12** Vertical profiles of climatological summer (JJAS) mean difference between the future climate simulation and present-day simulation of the 20-km model for dry static energy (*DSE*), moist static energy (*MSE*), temperature (*T*) and specific humidity (*q*) averaged over the southern WG region (68–75° E, 5–16° N)
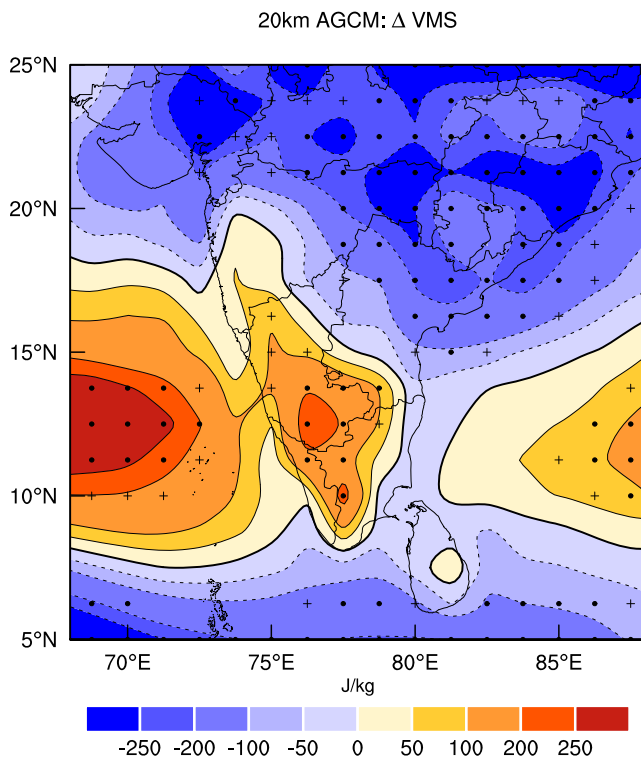
20km AGCM: Δ VMS



**Fig. 13** Climatological summer (JJAS) mean difference between the future climate simulation and present-day simulation of the 20-km model for vertical moist stability (VMS defined as $\mathrm{MSE}_{(421.8-113.8\,\mathrm{hPa})}$-$MSE_{(998.5-421.8\,\mathrm{hPa})}$) over WG region. Differences significant at 90% (80–90%) are highlighted with *dot* (*plus*) symbols

region, while it is the opposite to the north of it. Consistent with the negative changes in vertical velocities (Fig. 8d), all stability indices also indicate stabilisation of large-scale circulation over southern WG under the global warming scenario.

The results ascertain that an increase in the atmospheric stability due to larger upper atmospheric warming would have a far greater impact on the large-scale overturning circulation which can offset moisture build-up effect especially over orographic regions such as southern WG where vertical velocities play a crucial role in producing large-scale condensation and precipitation. This is also in agreement with the qualitative inference put forth by Rajendran and Kitoh (2008) that over the southern WG region, the drastic reduction of wind by steep orography predominates over the moisture build-up effect (that causes enhanced rainfall over other parts) in reducing the local rainfall in warmer future climate. Thus, the resultant response to global warming over southern WG region is dominated by the tropical 'upper tropospheric warming effect', which explains the overall weakening in large-scale ascent and precipitation. In the interior regions of India, the

moisture build-up effect combined with increased atmospheric instability (reduced VMS) increases convection and causes increased rainfall in future scenario.

## 6 Concluding remarks

Based on a detailed analysis of simulations from an ultra high-resolution global climate model and climate datasets of recent past, the present study has addressed the issue of likely future changes in the summer monsoon over the Western Ghats orographic region of India in response to global warming. The MRI model with approximately 20-km mesh horizontal resolution resolves orographic features on finer spatial scales that were till now resolved by using high-resolution regional models which are known to have high dependency on the lateral boundary forcing and significant inability to represent regional–global scale interactions. Further, the ultra high-resolution global model employed in this study shows reasonable fidelity in simulating the seasonal variation and spatial distribution of the present-day Indian summer monsoon rainfall over India and trends in monsoon rainfall over the west coast of India. This indicates that the simulation of local aspects of the climate greatly benefits from the high resolution. In the case of the IPCC AR4 models, the coarse resolution was a major source of uncertainty in assessing some of the regional precipitation changes. From the realistic simulation of climatological rainfall distribution and the trends over WG region, a higher degree of confidence appears to emerge in many aspects of the 20-km model simulations. Therefore, we can have better confidence in the validity of the prediction of future changes in the climate of the region. The findings from the analysis of these simulations and observed climate datasets can be summarised as follows:

1. Analysis of observed APHRODITE rainfall shows that there is a significant decreasing trend in the monsoon rainfall over the Western Ghats mountains (the west coast of Indian Peninsula) during the recent past. Trend analysis of JRA-25 circulation data (1979–2007) supports the rainfall trend with a consistent weakening of the upward vertical velocities over the region. This suggests that the summer mean rainfall, intensity of Indian summer monsoon circulation and the associated vertical velocities over southern parts of WG have significantly weakened during the recent past. The present-day simulation of the model captures these trends over WG realistically.

2. The global warming time-slice simulation of the MRI 20-km model shows spatially varying climate projection, with significant reduction in orographic rainfall over the west coasts of Kerala and Karnataka along the narrow western Ghats mountains by the end of the twenty-first century. Over this region, the contribution from large-scale rainfall to total rainfall is substantial due to the influence of WG orography.
3. The projected WG rainfall reduction is found to be associated with drastic reduction in the southwesterly winds and column-integrated moisture transport into the region, weakening of vertical velocities and summer monsoon meridional circulation.
4. Our analysis shows that this is due to larger upper tropospheric warming relative to the surface and lower levels, which decreases the lapse rate causing an increase in (which in turn inhibits vertical ascent) response to global warming. Over this region, increased VMS and dry and moist static energies over the west coast region south of 16°N inhibit vertical ascent and reduces vertical velocities. This in turn produces weakening of the summer monsoon meridional circulation. Consequently, the orographically forced ascent of the moist monsoonal winds against the Western Ghats weakens, resulting in decreased LS rainfall. This is further corroborated by a significant decrease in the frequency of moderate-to-heavy monsoon rainfall days over southern WG which is a typical manifestation of the decrease in large-scale condensational rainfall (LS rainfall) over this region. Thus, the changes in seasonal mean rainfall, large-scale condensational rainfall and moderate-to-heavy rainfall are influenced by the interaction of monsoon circulation with fine-scale orography.
5. The causative mechanism behind reduction in WG rainfall appears to be the drastic reduction of vertical ascent and weakening of circulation due to upper tropospheric warming effect that predominates over the moisture build-up effect to result in reducing the rainfall over this narrow orographic region. This study illustrates that Indian monsoon rainfall is strongly controlled by processes and parameterised physics which need to be resolved with adequately high resolution for accurate assessment of local- and regional-scale climate change.

The future changes in the seasonal mean monsoon and extremes of daily rainfall predicted by the 20-km simulation are plausible because of the capability of the model in simulating these aspects of the Indian summer monsoon quite realistically. However, it is to be noted that this is one of several possibilities to be expected in the future. For example, the projected results can be sensitive to the particular scenario for the atmospheric concentrations of the important GHGs in the future. Further, the projection can be sensitive to the initial and boundary conditions used. In order to assess the effects of these uncertainties, an ensemble of global time-slice simulations and coupled ocean atmosphere simulations would have to be performed, with different climate models, initial and boundary forcing and different GHG scenarios prescribed.

## References

Annamalai H, Hamilton K, Sperber KR (2007) The South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. J Clim 20:1071–1092

Becker A, Bugmann H (1997) Predicting global change impacts on mountain hydrology and ecology: integrated catchment hydrology/altitudinal gradient studies. Workshop Report. IGBP Report 43. Stockholm, p 61

Bengtsson L, Botzet M, Esch M (1996) Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? Tellus 48A:57–73

Cherchi A, Alessandri A, Masina S, Navarra A (2010) Effects of increased $CO_2$ on monsoons. Clim Dyn. doi:10.1007/s00382-010-0801-7

Dash SK, Kulkarni MA, Mohanty UC, Prasad K (2009) Changes in the characteristics of rain events in India. J Geophys Res 114:D10109. doi:10.1029/2008JD010572

Douville H, Royer J-F, Polcher J, Cox P, Gedney N, Stephenson DB, Valdes PJ (2000) Impact of doubling CO2 on the Asian summer monsoon: robust versus model-dependent responses. J Meteorol Soc Jpn 78:421–439

Gadgil S (1977) Orographic effects on the southwest monsoon: a review. Pure Appl Geophys 115:1413–1430

Gadgil S, Sajani S (1998) Monsoon simulation in AMIP runs. Clim Dyn 14:659–689

Gastineau G, Le Treut H, Li L (2008) Hadley circulation changes under global warming conditions indicated by coupled climate models. Tellus 60A:863–884

Grossman RL, Durran DR (1984) Interaction of low-level flow with the Western Ghat Mountains and offshore convection in the summer monsoon. Mon Weather Rev 112:652–672

Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. J Climate 19:5686–5699

Joshi VR, Rajeevan M (2006) Trends in precipitation extremes over India. National Climate Centre (NCC) Research Report No. 3: India Met Department, Pune, pp 1–25

Kitoh A, Yukimoto S, Noda A, Motoi T (1997) Simulated changes in the Asian summer monsoon at times of increased atmospheric CO2. J Meteorol Soc Jpn 75:1019–1031

Knutson TR, Manabe S (1995) Time-mean response over the tropical Pacific to increased $CO_2$ in a coupled ocean-atmosphere model. J Clim 8:2181–2199

Kripalani RH, Oh JH, Kulkarni A, Sabade SS, Chaudhari HS (2007) South Asian summer monsoon precipitation variability: coupled model simulations and projections under IPCC AR4. Theor Appl Climatol 90:133–159

Krishnan R, Sabin TP, Ayantika DC, Kitoh A, Sugi M, Murakami H, Turner A, Slingo JM, Rajendran K (2012) Will the South Asian monsoon overturning circulation stabilize any further? Clim Dyn. doi:10.1007/s00382-012-1317-0

Krishna Kumar K, Kamala K, Rajagopalan B, Hoerling MP, Eischeid JK, Patwardhan SK, Srinivasan G, Goswami BN, Nemani R (2010) The once and future pulse of Indian monsoonal climate. Clim Dyn. doi:10.1007/s00382-010-0974-0

Mizuta R, Oouchi K, Yoshimura H, Noda A, Katayama K, Yukimoto S, Hosaka M, Kusunoki S, Kawai H, Nakagawa M (2006) 20-km mesh global climate simulations using JMA-GSM model Mean climate states. J Meteorol Soc Jpn 84:165–185

Mizuta R, Adachi Y, Yukimoto S, Kusunoki S (2008) Estimation of the future distribution of sea surface temperature and sea ice using the CMIP3 multi-model ensemble mean. MRI Tech Report No. 56:1–2

Nakicenovic N, Co-authors (2000) IPCC special report on emission scenarios. IPCC W.G.I. Cambridge University Press, Cambridge, p 599

Neelin JD, Held IM (1987) Modeling tropical convergence based on the moist static energy budget. Mon Weather Rev 115:3–12

Onogi K, Co-authors (2007) The JRA-25 reanalysis. J Meteorol Soc Jpn 85:369–432

Pal JS, Eltahir EAB (2003) A feedback mechanism between soil-moisture distribution and storm tracks. Q J R Meterol Soc 129:2279–2297

Rajeevan M, Bhate J, Kale JD, Lal B (2006) High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. Curr Sci 91:296–306

Rajendran K, Nanjundiah RS, Srinivasan J (2002) The impact of surface hydrology on the simulation of tropical intraseasonal oscillation in NCAR (CCM2) atmospheric GCM. J Meteorol Soc Jpn 80:1357–1381

Rajendran K, Kitoh A (2008) Indian summer monsoon in future climate projection by a super high-resolution global model. Curr Sci 95:1560–1569

Rajendran K, Kitoh A, Mizuta R, Sajani S, Nakazawa T (2008) High-resolution simulation of mean convection and its intraseasonal variability over the tropics in MRI/JMA 20-km mesh AGCM. J Climate 21:3722–3739

Randall D, Pan DM (1993) Implementation of the ArakawaSchubert cumulus parameterization with a prognostic closure. Meteorol Monogr 46:145–150

Rayner NA, Co-authors (2003) Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century. J Geophys Res 108:4407

Rupakumar K, Co-authors (2005) High-resolution climate change scenarios for India for the 21st century. Curr Sci 90:112

Sabade SS, Kulkarni A, Kripalani RH (2010) Projected changes in South Asian summer monsoon by multi-model global warming experiments. Theor Appl Climatol. doi:10.1007/s00704-010-0296-5

Sperber KR, Palmer TN (1996) Interannual tropical rainfall variability in general circulation model simulations associated with the atmospheric model intercomparison project. J Climate 9:2727–2750

Stowasser M, Annamalai H, Hafner J (2009) Response of the South Asian summer monsoon to global warming: mean and synoptic systems. J Climate 22:1014–1036

Solomon S, Co-authors (2007) Climate change 2007: the physical science basis, IPCC W.G.I. Cambridge University Press, New York, p 996

Sugi M, Noda A, Sato N (2002) Influence of the global warming on tropical cyclone climatology: an experiment with the JMA global model. J Meteorol Soc Jpn 80:249–272

Sundqvist H (1978) A parameterization scheme for non-convective condensation including prediction of cloud water content. Q J Royal Meteorol Soc 104:677–690

Trenberth KE, Coauthors (2007) Observations: surface and atmospheric climate change. Climate change 2007: the physical science basis. Cambridge University Press, pp 235–336

Vecchi GA, Soden BJ (2007) Global warming and the weakening of the tropical circulation. J Climate 20:4316–4340

Xie S-P, Xu H, Saji NH, Wang Y (2006) Role of narrow mountains in large-scale organization of Asian monsoon convection. J Climate 19:3420–3429

Yatagai A, Arakawa O, Kamiguchi K, Kawamoto H, Nodzu MI, Hamada A (2009) A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges. SOLA 5:137–140

Yoshimura H, Matsumura T (2005) A two-time-level vertically conservative semi-Lagrangian semi-implicit double fourier series AGCM. CAS/JSC WGNE research activities in Atm and Oce Modeling 35:3.27–28