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Hadley circulation dynamics in the IITM-Earth System Model simulations: evaluation and future projections

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Abstract

It is known that the Hadley circulation (HC) is responsible for the typical wet climate of the tropics and the dry climate of the subtropics. Previous studies have shown that the HC exhibits a poleward expansion of ~0.5–1° latitude per decade with significant regional and seasonal variability. Owing to its pivotal role in controlling the climate over tropics and subtropics, it is important to predict the evolution of HC in a future warming scenario from the perspective of formulation of adaptation strategies. In this regard, the current study employs the climate model simulations from the Indian Institute of Tropical Meteorology-Earth System Model (IITM-ESM) archived in the latest Coupled Model Inter-comparison Project 6 (CMIP6) to identify the long-term changes and future projections in the width of the ascending and descending branches of the HC, after validating it against the latest generation ERA5 reanalysis. Results show that the model is able to capture the observed changes in the total width of the HC and its ascending regions. Analysis of trends in the future projection of the width of the HC ascending and descending regions brings out results that are consistent with earlier reports using multi-model simulations archived in CMIP6. The future projections of HC intensity show weakening tendencies in both NH and SH. The trends in the model's future projection of zonal mean precipitation under two high forcing scenarios show hemispherical asymmetry with SH exhibiting relatively strong trends in both ascending and descending regions of the HC. The results are discussed in the light of the present understanding on HC dynamics. The significance of the present study lies in evaluating IITM-ESM, which is the first model from India to participate in CMIP, using ERA5 reanalysis and discussing the future projections of HC dynamics and its implications on long-term trends in precipitation under high forcing scenarios.

1 Introduction

Hadley circulation (HC) is the planetary scale circulation over the tropics characterized by large-scale ascent of moist air over the tropics and subsidence over the subtropics. This circulation is responsible for the typical wet, humid climate of the tropics and the dry climate of the subtropics. According to the sixth Assessment Report (AR6) from Intergovernmental Panel for Climate Change (IPCC), the circulation is exhibiting a poleward expansion of ~0.5–1° latitude per decade, with significant regional and seasonal variability (Lucas and Nguyen 2015; Mathew and Kumar 2018; Staten et al. 2018). Such changes in HC manifest as a shift in precipitation patterns, poleward movement of jet streams and storm tracks, changes in the distribution of climatically important trace gases in the stratosphere as well as changes in the ocean circulation (Seidel et al. 2008; Lucas et al. 2014). The biodiversity of the tropics which lag to track these changes is put under threat (Issac and Turton 2014), and the economies aligned along the edges of the tropical belt find it difficult to put up with the wrath of the changing weather. Previous studies have identified that change in precipitation as a result of HC expansion happens at the edges of the HC ascending and descending regions (Mathew and Kumar 2019a). This implies that the regions at the edges of the tropics which are adapted to an arid climate now experience more weather phenomena resulting in floods, and those of the extra-tropics which earlier received marginal rainfall experience droughts.

Studies have attributed many factors contributing to the expansion of the HC and the tropics, which include tropospheric warming due to greenhouse gas forcing,

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Fig. 6 Trends in future projections of edges of HC ascending regions (**a**, **d**), HC descending regions (**c**, **f**), and HC intensity (**b**, **e**) in the NH (red) and SH (blue) over the period 2014–2100 under SSP370 scenario (left panel) and under SSP585 scenario (right panel). Vertical bars represent the 95% confidence interval (CI) of the estimated trends

times of the year. Analysis of the trends in intensity of the NH and SH HCs is carried out and is shown in Fig. 6b. It can be inferred from Fig. 6b that the hemispheric HC intensity, in general, shows a decreasing trend in both hemispheres for most parts of the year. A few exceptions are the significant SH HC strengthening during October and the NH HC strengthening during November–December. The figure brings out that while SH HC intensity significantly decreases during 8 out of 12 months in a year, NH HC intensity significantly decreases only during 3 out of 12 months in a year. The weakening of SH HC is at the rate of ~ 0.02–0.03 $\times 10^{10}$ kg/s per decade, maximizing during the month of July. For NH, the maximum weakening trend occurs during March and has a magnitude of ~ 0.03 $\times 10^{10}$ kg/s per decade. Thus, it can be summarized from Fig. 6a–c that the future changes in width and intensity of the HC are more prominent in the SH than the NH. The SH HC is projected to undergo expansion and weakening in the SSP370 scenario.

Analysis of trends in HC parameters for the SSP585 scenario is charted out in Fig. 6d–f. These figures bring out that, similar to the SSP370 scenario, the SSP585 scenario also projects a prominent expansion and weakening trend in the SH HC. As per Fig. 6d, maximum significant expansion in SH ascending region edges is shown during September (~ 0.3 deg lat/dec), with the same magnitude but delayed by 1 month as compared to the SSP370 scenario. For NH, the ascending region edges show significant contraction in 4 out of 12 months (Jan, Jul, Sep, and Oct) as compared to the mostly insignificant trends given by the SSP370 scenario. Note that significant expansion (~ 0.1 deg lat/dec) of the NH ascending region edges during Dec and significant contraction (~ 0.3 deg lat/dec) of these edges during January are striking features in the annual cycle of trends in the NH ascending region edges for the SSP585 scenario. Figure 6f brings out the annual cycle of trends in the hemispheric HC edges for the SSP585 scenario. Significant expansion of ~ 0.1–0.3 deg lat/dec is shown by the NH edges during December and January–April in the SSP585 scenario, with the magnitude of expansion maximizing during March. Seven out of 12 months in a year show significant expansion for the SH HC edges in the SSP585 scenario. SH HC edges show expansion of ~ 0.1–0.3 deg lat/dec, which is significant during January through September. Maximum expansion of the SH edges also occurs during March. Thus, HC edges in both hemispheres show an expansion trend during most of the year in the SSP585 scenario, with the exception during July and October for which the NH edges contract. Figure 6e shows the trends in NH and SH HC intensity in the SSP585 scenario. It is evident from this figure that 6 out of 12 months in a year witness a significant weakening of the SH HC with the trends during June–September being more pronounced (~ 0.02–0.03 $\times 10^{10}$ kg/s per decade). For the NH, trends are generally insignificant for most of the year. There are however a few exceptions. NH HC intensity is significantly negative during January, May, and August and significantly positive during November, with the absolute magnitude for these trends remaining more or less the same (~ 0.01 $\times 10^{10}$ kg/s per decade). Thus, from Fig. 6e and f, it is evident that relatively more changes are noted in SH HC width and strength as compared to NH in the SSP585 scenario, similar to that in the SSP370 scenario.

3.3 Future trends in precipitation patterns

It is known that any changes in HC boundaries will affect well-established precipitation patterns over tropics and subtropics. In order to bring out the implications of the projected trends in ascending and descending branches of the HC, the changes in precipitation for SSP370 and SSP585 scenarios are analyzed as shown in Fig. 7a and b, respectively. The figure shows the annual cycle of precipitation trends (in mm/day/decade) for SSP370 and SSP585 scenarios, significant at the 80% confidence level. The striking feature of this figure is the positive trend in precipitation in the ascending regions and the negative trend in the descending region edges in the SSP370 scenario. The trends are relatively large and coherent in the SH as compared to NH. In NH, during April–August, the precipitation trends in SSP370 are significantly negative near the edges of the NH ascending region and significantly positive (~ 0.02 mm/day/decade) near the edges of the NH descending region. As discussed in the previous section, decreasing (increasing) trends in precipitation near the HC descending (ascending) region edges in the SH is line with the projected expansion of the SH edges of the HC. An increase (decrease) in precipitation within HC descending (ascending) regions during boreal summer is indicative of a contraction in HC width during this season, which is also suggested by Fig. 6. Precipitation trends for the SSP585 scenario are quite similar to that of SSP370 scenario, except for a few key differences within the NH ascending regions. The trends in precipitation near NH ascending regions are insignificant during most of the year in SSP585 as compared that for SSP370. Overall, it can be inferred from Fig. 7 that the projected trends in precipitation changes for the two future warming scenarios match well with the trends projected for the width of the HC ascending and descending regions.

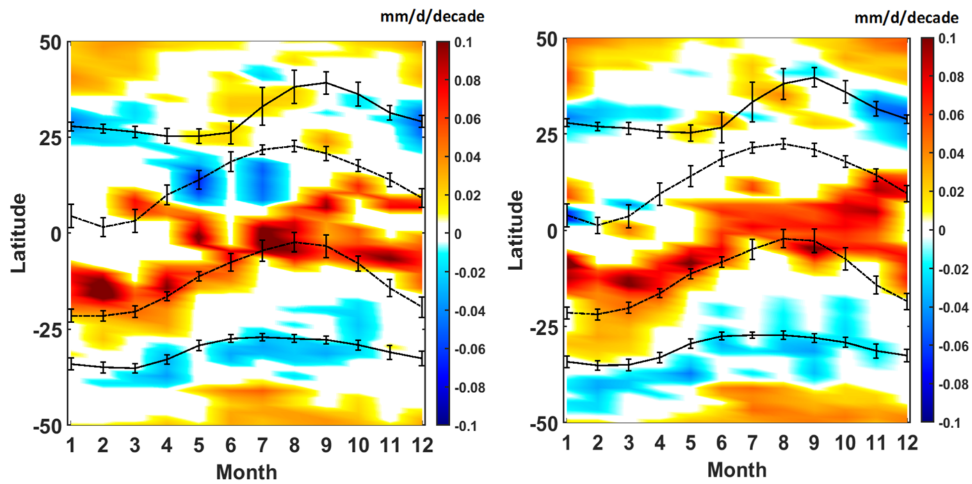

Fig. 7 Annual cycle of trends in IITM-ESM zonal mean precipitation for (**a**) SSP370 scenario and (**b**) SSP585 scenario. The shaded regions are the precipitation trends significant at an 80% confidence level. Solid black lines indicate HC descending region edges, and dashed black lines indicate HC ascending region edges

4 Discussion

The present study evaluates the performance of IITM-ESM, which is fine-tuned for the tropical regions, in simulating the features of the HC and its long-term changes. Evaluation of the model in capturing the HC dynamics is done by comparing it with a newest generation reanalysis-ERA5. A comparison of MSF estimated from the model and reanalysis shows that the model is able to reproduce the structure and intensity of the HC as given by the reanalysis. The ascending and descending region edges delineated from the model are found to agree fairly well with the boundaries obtained using ERA5 reanalysis, especially in the SH. The mean removed perturbations of HC total width and the width of ascending region agree very well between the model simulations and ERA5. The future projections of the model till the year 2100 are analyzed, which show significant expansion of the SH ascending and descending regions for SSP370 as well as SSP585 scenarios of IITM-ESM throughout the year, and are accompanied by a weakening of the HC. On the other hand, descending region boundaries of NH HC are projected to show insignificant or negative trends (contraction) during boreal summer months and positive trends (expansion) during boreal winter months, whereas future trends in NH ascending region boundaries are mostly insignificant or negative (contraction). At the same time, the strength of HC in NH is projected to have weakening trends during 4 out of 12 months and show insignificant trends during other months. Analysis of the annual cycle of trends in zonal mean surface precipitation for the SSP370 and SSP585 scenarios brings out results that are in conjunction with the projected trends in the HC ascending and descending region boundaries. Precipitation trends are found to be positive near HC ascending region boundaries and negative near HC descending region boundaries in the SH during boreal summer as well as winter seasons, which is indicative of the expansion of the HC ascending as well as descending regions. Similar trends are seen for NH during the boreal winter season. However, during boreal summer months, the precipitation trends near the HC ascending (descending) regions are observed to be negative (positive), indicating a contraction in HC widths. Moreover, the precipitation trends in SH are in good agreement with the HC parameters as compared to those in the NH. The projected trends in width of the HC descending region boundaries fall in line with the multi-model mean trend in their historical simulations brought out in previous studies. For instance, multi-model mean trends in HC width from AMIP and historical runs of CMIP6 models reported by Grise and Davis (2020) over the period 1979–2008 showed NH HC contraction during MAM and JJA seasons and expansion during DJF and SON seasons. The trends were found to compare well with ERA5 reanalysis, except that the trends were slightly larger in reanalysis than in models for DJF and SON. These authors also projected from SSP585 runs during the 1920–2100 period that HC will undergo expansion, especially in the SH, which is in close agreement with the present study.

Modeling studies have attempted to explore the reason behind HC expansion by simulating the response of the circulation to different forcings such as increasing CO_2 concentration and other greenhouse gases, stratospheric ozone depletion, natural/anthropogenic aerosol forcing, and SST changes. Using IPCC AR4 simulations, Son et al. (2009) proposed that the stratospheric ozone recovery in the recent decade will compete with the greenhouse gas (GHG) increase and contract the SH HC. However, projections using the newest generation of models in IPCC (including IITM-ESM used in the present study) bring out SH HC expansion, suggesting that there are other processes that influence the width of the SH HC. Waugh et al. (2015) looked into the reasons behind SH tropical expansion and brought out that stratospheric ozone depletion expanded the SH summertime HC during the time when the ozone hole was present, and after the 1990s, when the ozone has

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