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ORIGINAL ARTICLE

Retrieval of the Hadley circulation boundaries at regional scales using global positioning system-radio occultation measurements

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Abstract
The present study describes a method to identify the boundaries of both the ascending and descending regions of Hadley Circulation (HC) at regional scales using the Global Positioning System-Radio Occultation (GPS-RO) measurements on board Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC). COSMIC provides high-quality profiles of temperature and water vapor by using Radio Occultation technique. The bulk static stability (BSS) metric is used for identifying the descending region boundaries of HC whereas relative humidity (RH) measurements are employed to decipher the ascending region boundaries, which coincides with the Inter-tropical Convergence Zone (ITCZ). First, zonally averaged HC boundaries obtained from COSMIC measurements are validated with the meridional mass stream function (MSF) metric estimated using ERA 5 reanalysis. Further, using COSMIC measurements, zonally resolved boundaries are estimated at every 10° longitude. Similarly, the latitudinal distribution of RH over a given longitudinal sector at 5 km altitude is fitted with a Gaussian function to retrieve the ascending region boundaries. After characterizing the regional features in zonally resolved HC, to assess the HC expansion impact, the long-term trends in the precipitation during 1980-2020 are estimated and discussed. The significance of the present study lies in describing a method to simultaneously retrieve zonally resolved HC ascending and descending region boundaries exclusively from COSMIC measurements for the first time and demonstrating its application in assessing the impact of HC expansion.

Keywords Global positioning system · Radio occultation · Hadley circulation · COSMIC

Introduction

Hadley Circulation (HC) consists of moist air ascent in the deep tropics, poleward flow aloft at the tropopause level, dry descent in the subtropics, and equatorward flow near the surface. The Hadley cell is responsible for the wet and humid climate of the tropics and the dry and parched climate of the subtropics. In the recent past, a robust poleward migration of the HC edges was reported by several studies (Hu and Fu 2007; Seidel et al. 2008; Nguyen et al. 2013; Birner et al. 2014; Lucas et al. 2014; Mathew et al. 2016; Grise et al. 2018). The poleward expansion of HC has many consequences resulting in regime shifts in climate variables over the tropics and subtropics. A variety of metrics are employed to estimate the HC expansion phenomenon (Solomon et al. 2016; Davis and Birner 2017)using both observations (including reanalysis) and climate model simulations. The poleward expansion rates using observations and reanalysis data products were found to be in the range of 0.2° to 3° per decade whereas in climate model simulations it was found to be in the range of 0.1° to 0.3° per decade (Johanson and Fu 2009; Hu et al. 2013; Lucas et al. 2014; Staten et al. 2020). The large range of observed expansion rates was attributed to usage of a wide variety of metrics, datasets and varying time periods of study. To address these discrepancies between observations and model simulations as well as intercomparison of various metrics employed in the HC expansion studies, two working groups viz., the U.S. Climate Variability and Predictability (CLIVAR) and the International Space Science Institute (ISSI) Tropical Width Diagnostics Intercomparison Project were formed to

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study the current magnitude, causes, and impacts of the HC expansion (Cook and Vizy 2018; Grise et al. 2018; Grise and Staten 2018; Staten et al. 2020). Several seminal studies by these working groups bridged the gap between observations and model simulations as well as bringing consensus among metrics employed in exploring the HC expansion. Grise et al. (2018) re-examined the HC expansion rates using observations and reanalysis and revised these rates below 0.5° per decade by carefully considering the HC metrics. These authors thus narrowed down the differences between the observations and climate model simulations of HC expansion rates.

Most of the earlier studies focused on the zonal mean characteristic of the HC expansion using meridional mass stream function (MSF). A few studies questioned the accuracy of the MSF estimated from the reanalysis owing to the mass conservation issues in some of the datasets (Davis and Davis 2018). It is suggested to have a metric that can be directly measured from observations and an objective criterion to identify the HC boundaries. The tropopause altitude and its latitudinal distribution is one such directly measured metric to identify the HC boundaries. The frequency of occurrence of bimodal distribution of tropopause altitude in the subtropics as well as bulk static stability (BSS) were employed to identify the HC edges (Seidel and Randel 2007; Davis and Birner 2013). Ao and Hajj (2013) using a decade of GPS radio occultation measurements reported the seasonal variability of tropical expansion. These authors noted a robust tropical expansion in the northern hemisphere and weak and inconsistent trends in the southern hemisphere. Most of these studies focused on the zonal mean structure of the HC boundaries. Recently, Grise and Davis (2020)emphasized that HC expansion as well as regional signatures of this phenomenon should be the focus of future studies. Earlier, Chen et al. (2014)reported regional variations in HC over six geographical locations and showed that changes in regional HC poleward edges have a significant impact on regional precipitation anomalies. Mathew and Kumar (2018) demarcated the zonally resolved edges of the HC using COSMIC observations during 2007–2013 by employing BSS metric, which exhibited good co-variability with the zonal mean MSF metrics. All these studies on the regional boundaries of the HC focused on the descending region boundaries and none of them discussed the ascending region boundaries of the HC. In a seminal study using climate model simulations, Su et al. (2014)reported that there are both weakening and strengthening structures within in the ascending region of the HC in the warming climate, which emphasized the importance of having finer details of the HC ascending as well as descending regions. Mathew and Kumar (2019) reported the long-term changes in humidity, cloud fraction and precipitation, which showed distinct trends at the center and edges of the ascending region. These studies emphasized the importance of having boundaries of both ascending and descending regions to identify the pathways through which HC expansion impact the climate variables.

From the above discussion, it is clear that most of the studies in the past reported on the zonal mean structure of the HC and mainly focused on the descending region edges. Though there are a few reports on zonally resolved HC boundaries, these studies also focused on the descending regions. As of now there is no directly measurable metric to identify the zonally resolved HC ascending region boundaries. In this regard, the present study discusses a method to identify the boundaries of the ascending region of the HC from GPS-RO measurements of relative humidity. Earlier studies showed that the Inter-tropical Convergence Zone (ITCZ), the area of convergence of trade winds in both the hemispheres, is known to coincide with the ascending region of the HC (Schneider et al. 2014). Läderach and Raible (2013) employed specific humidity data from ERA reanalysis and identified the location of ITCZ using a Gaussian fit. A similar method was adopted by Basha et al. (2015) using GPS-RO measurements of refractivity. However, the width of the latitudinal distribution of specific humidity and refractivity estimated using a Gaussian fit was too broad to be treated as width of the ITCZ. The latitudinal distribution of RH is employed in the present study to identify the ITCZ center as well as its edges, which represent the ascending region of the HC. The present study also employs the method proposed by Mathew and Kumar (2018) to identify the zonally resolved descending region of the HC using GPS-RO observations. The central objective and relatively new aspect of the present study is the complete characterization of the HC in terms of ascending and descending region boundaries at regional scales using direct observations. The present study is first of its kind to employ GPS-RO observations alone to retrieve the zonally resolved boundaries of both ascending and descending region of the HC. The boundaries of ascending region of HC is as important as descending region boundaries to identify the pathways through which HC expansion influence the weather and climate of the tropics and subtropics at regional scales. The ascending region boundaries of the HC will be useful in localizing the sources for the HC expansion as well as to assess its impact at regional scale. The results provided an opportunity not only to study the regional HC boundaries but also to investigate the trends in precipitation with respect to HC boundaries at regional scales for the first time.

Data and methodology

The COSMIC GPS-RO measurements of temperature and water vapor profiles in the altitude range of 0.1–40 km with 100 m vertical resolution during 2007–2015 form

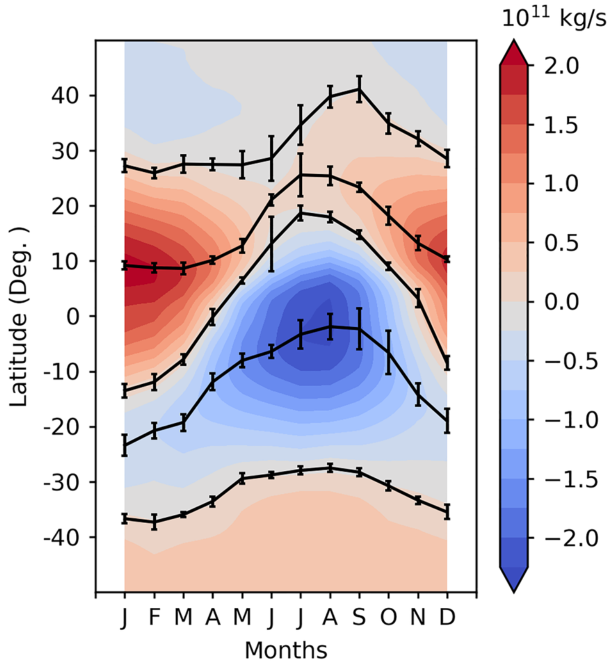

Fig. 3 Mean annual cycle of zonal mean HC parameters (five lines represent NH descending region edge, NH ascending region edge, HC center, SH ascending region edge and SH descending region edge, respectively) derived from of nine years (2007–2015) of ERA5 reanalysis using MSF metric. The background color map depicts the MSF at 500 hPa. Vertical bars indicate the standard deviation depicting the interannual variability

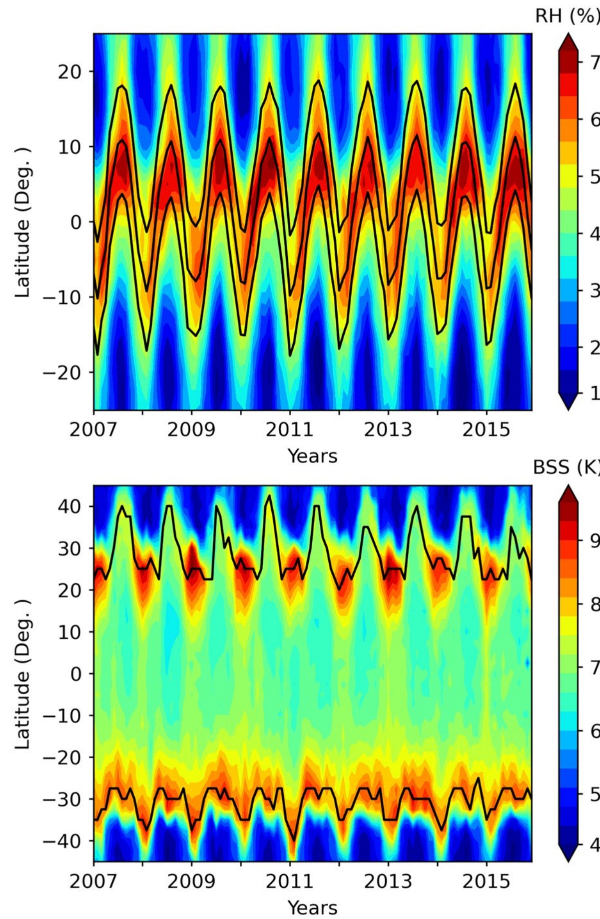

Fig. 4 *Top panel*: latitudinal distribution of monthly mean RH during 2007–2015 derived from COSMIC measurements. Three blacklines represent ascending region edges of the HC in NH and SH and its center. The background color map depicts the monthly mean RH at 5 km altitude. *Bottom panel*: latitudinal distribution of monthly mean BSS during 2007–2015 derived from COSMIC measurements. Two black lines represent descending region edges of the HC in NH and SH. The background color map depicts the monthly mean BSS

mass transport, respectively. The annual cycle in Northern hemisphere (NH) HC edges is more pronounced as compared to Southern hemisphere (SH). This is attributed to the abundance of landmasses in NH as compared to SH. The interannual variability as indicated by the standard deviations is relatively large in NH. Further, the ascending region edges in both hemispheres show the well-known annual migration of ITCZ.

In order to delineate the edges and center of the HC ascending region, the month-latitude cross section of RH at 5 km (about 500 hPa) is constructed. Top panel of Fig. 4 shows the monthly mean RH as a function of latitude at 5 km altitude obtained using the COSMIC measurements during 2007–2015. The boundaries of ascending region of the HC along with its center are also depicted in this figure. The monthly mean BSS estimated from COSMIC measurements is depicted in the bottom panel of Fig. 4. A detailed description of this method and its validation is given in Mathew and Kumar (2018). From this figure, it is evident that the BSS peaks around the region, which separates tropics and subtropics. This region corresponds to the edges of the descending region of the HC marked by the solid black lines.

The results depicted in Fig. 4 are consistent with the reported features of the HC edges. However, one needs to evaluate these from the HC parameters retrieved from well-established methods like MSF. Figure 5 depicts the zonal mean boundaries of the HC retrieved from COSMIC and MSF metric from ERA5. From this figure, it is evident that the zonal mean HC parameters from both show similar annual cycles. However, there are some subtle differences in magnitudes, especially in the NH edges. The NH edge of descending region boundaries in MSF shows a shift in peak with that from COSMIC during the boreal summer. The following are the potential reasons for observed discrepancies (i) the differences in grid sizes of ERA5 and COSMIC also play a role in the observed discrepancies. It is also noted that the identified peak in RH is broader rather than a sharp peak; hence, the latitude on either side of the detected peak can also be the center of the ascending region. It is noted that by adding one grid to the detected peak, the MSF and

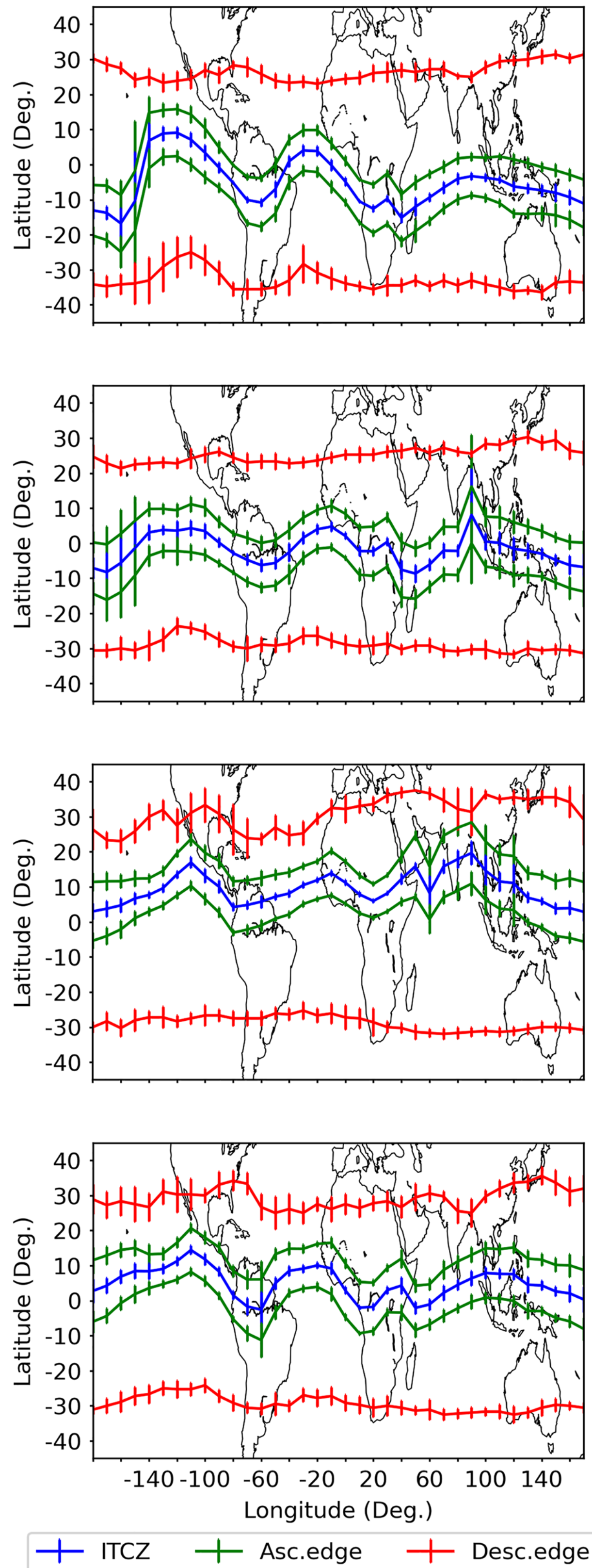

Fig. 7 Longitudinally resolved boundaries of ascending and descending regions of the HC derived from COSMIC GPS-RO measurements for DJF (first panel), MAM (second panel), JJA (third panel) and SON (fourth panel). The green lines represent the boundaries of ascending regions, red lines indicate the boundaries of the descending region and the blue line represents the HC center. Vertical bars represent interannual variability over a period of nine years

by Mathew and Kumar (2019). Fourth panel of Fig. 9 shows the precipitation trends during SON, which also show more are less similar features with increasing trends in the ascending region and decreasing trends around descending regions with few exceptions. Overall, it can be noted that most of the observed decreasing trends are in and around the flanks of the HC descending boundaries and increasing trends are around the ascending boundaries. This observation seems to be consistent with the reported poleward expansion of the HC. The zonally resolved boundaries of HC thus aid in understanding the role of large-scale circulations in the precipitation distribution and their long-term variability over the tropics and subtropics. The present study thus proposed a method to identify the zonally resolved boundaries of both ascending and descending regions of HC using COSMIC measurements alone and demonstrated its applicability in understanding the role of large-scale circulation in observed changes in global precipitation over tropics and subtropics.

Summary and concluding remarks

The present study focused on the retrieval of boundaries of both ascending and descending regions of HC at regional scales using COSMIC measurements during 2007-2015. The BSS metric derived from COSMIC is employed for the descending region boundaries whereas RH distribution is used for ascending region boundaries and center. The zonal mean latitudinal distribution of RH is fitted with a Gaussian curve, and the standard deviation of this distribution is taken as the width of the ascending region of the HC and the latitude where RH shows its peak is identified as the center of the HC. The zonal mean HC boundaries retrieved from COSMIC GPS-RO observations are validated using those derived using MSF from ERA-5 reanalysis. The HC boundaries retrieved from two entirely different techniques showed reasonably good agreement.

Further, COSMIC measurements are employed to retrieve the longitudinally resolved HC boundaries. The migration of the ascending region of the HC with seasons is captured by the present retrievals, which confirms the suitability of the procedure adopted in the study. The results showed that there are regional asymmetries in the HC ascending and descending boundaries, especially in the summer hemisphere. The width of the descending region was narrower in the NH as compared to SH in all seasons except boreal winter. Overall, zonally resolved HC boundaries derived from COSMIC observations for the first time were consistent with the present understanding.

To demonstrate the importance of HC boundaries in interpreting the long-term changes in climate variables, the precipitation distribution obtained from GPCP during 1980-2020 are analyzed. The results showed that the HC boundaries retrieved in the study suitably identifies the wet and dry regions thus demonstrating the robustness of the RH and BSS metrics employed in the study. Further, the time series of precipitation from GPCP are analyzed to estimate the trends and the same is discussed with respect to HC boundaries at regional scales. In general, it is noted that over majority of longitude sectors, decreasing trends are found near the edges of the descending regions in both the hemisphere whereas increasing trends are found near the edges of ascending region. These observations are consistent with the HC expansion detected in recent decades. As the regional perspective of the HC expansion and its consequences are increasingly becoming important, it is envisaged that the present study will be handy in demarcating the zonally resolved HC.

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Data availability The COSMIC measurements of temperature and water vapor are obtained from https://cdaac-www.cosmic.ucar.edu/cdaac/products.html, ERA-5 reanalysis datasets are downloaded from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 and GPCP data are obtained from https://psl.noaa.gov/data/gridded/data.gpcp.html

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