

Understanding the variations in strength and extent of regional Hadley circulations

विद्या वाचस्पति की
उपाधि की अपेक्षाओं की आंशिक पूर्ति में प्रस्तुत शोध प्रबंध

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2026

To my beloved Maa-Deuta

CERTIFICATE

Certified that the work incorporated in the thesis entitled “*Understanding the variations in strength and extent of regional Hadley circulations*”, submitted by *Pratiksha Priyam Baruah* was carried out by the candidate, under my supervision. The work presented here or any part of it has not been included in any other thesis submitted previously for the award of any degree or diploma from any other University or institution.



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I declare that this written submission represents my idea in my own words and where others' ideas have been included; I have adequately cited and referenced the original sources. I declare that I have acknowledged collaborative work and discussions wherever such work has been included. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed. The work reported in this thesis is the original work done by me under the guidance of Dr. Neena J. Mani.



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Thesis abstract

The zonal-mean representation of the Hadley circulation provides a simple and effective framework for describing the global tropical circulation. However, such zonal averaging may obscure important regional meridional circulation characteristics. Therefore, the overarching goal of this thesis is to advance the understanding of regional Hadley circulations, with particular emphasis on how their structure, seasonal variability, and long-term evolution differ across longitudinal sectors, and on identifying the region-specific mechanisms that govern these differences.

The first objective of the thesis, addressed in Chapter 2 is to provide a comprehensive characterization of regional Hadley circulations across six major longitudinal sectors—Africa, Indian Ocean, Western Pacific, Eastern Pacific, South America, and Atlantic. The analysis reveals that strength and structure of regional HCs are closely tied to the spatial distribution of deep convection. Strong overturning cells such as the West Pacific HC and Indian HC are anchored by vigorous convective heating and exhibit deep vertical structures extending into the upper troposphere. In contrast, oceanic sectors like the East Pacific HC and Atlantic HC, situated over the “cold tongue” regions display weaker, shallower circulations. The intensity of each cell follows the seasonal cycle of ITCZ convection, peaking during hemispheric winters or active monsoon phases. East Pacific HC exhibits a strong correspondence with the zonal-mean Hadley circulation, suggesting that variability in the East Pacific HC has likely contributed substantially to the trends and variability of the zonal-mean HC reported in previous studies.

The second objective, addressed in Chapter 3, is to examine the role of sea surface temperature (SST) in governing the strength of regional Hadley circulations. Despite the widespread increase in SST across the Pacific, the East Pacific HC underwent a pronounced intensification post-1980, while the West Pacific HC remained nearly unchanged. This contrast points to basin-specific physical mechanisms controlling the regional Pacific HCs. It is found that Over the West Pacific HC, in the post-1980 period, enhanced upper-tropospheric warming relative to surface temperatures increases static stability, which is a manifestation of moist adiabatic lapse rate (MALR) adjustment. This stabilization raised the SST threshold for

convection and inhibited intensification of the West Pacific HC although the underlying SST was rising. Over the East Pacific HC, however, comparable warming throughout the troposphere maintained near-neutral stability, allowing SST-induced convection to increase and strengthening the East Pacific HC in the post-1980 period.

Chapter 4 examines how tropical transient disturbances influence the regional HC variability, focusing specifically on the East Pacific HC. The choice of the east Pacific domain is motivated by the distinctive prominence of synoptic-scale disturbances over the region, unlike other regions such as the western Pacific or Indian Ocean, where a wide range of scales, including intra-seasonal and quasi-biweekly oscillations, are also prevalent. Apart from the SST driven thermal convection and the convection driven by convergence induced by SST gradients, the study addresses a less explored aspect of how atmospheric wave induced convergence may be critical in determining the strength of regional meridional cells. The analysis identifies Mixed Rossby–Gravity (MRG) waves as the primary agents providing this dynamical support for deep convection over the East Pacific, thereby contributing significantly to the strengthening of the regional Hadley circulation in this region

Chapter 1

Introduction

The Earth's atmospheric circulation has intrigued scientists for more than three centuries, with early efforts primarily aimed at explaining the persistent easterly trade winds. In 1686, renowned astronomer Edmund Halley proposed one of the first scientific explanations for the trade winds. He envisioned a large meridional overturning circulation driven by differential solar heating, with warm air rising in the equatorial region and descending toward the poles. Halley was likely the first to recognize that the Earth's spherical geometry and the resulting uneven distribution of solar heating fundamentally shapes this circulation. However, Halley's model could not explain the persistent easterly component of the trade winds, as it did not account for Earth's rotation. Nearly half a century later, George Hadley (1735) reintroduced and refined the concept in his work "*Concerning the Cause of the General Trade Winds*." He provided the first physically grounded explanation for tropical atmospheric circulation, laying the foundation for what is now known as the Hadley circulation. Although Hadley's model incorrectly assumed conservation of linear momentum rather than angular momentum, it represented a major advance in understanding tropical air motion. Later, in the 19th century, scientists such as Gaspard Gustave Coriolis (1835), William Ferrel (1856) and Hermann von Helmholtz (1888) expanded Hadley's ideas by incorporating a more complete understanding of rotational dynamics and momentum conservation. Their contributions ultimately shaped the three-cell circulation model comprising the Hadley, Ferrel, and Polar cells—that is widely used today to describe the structure of zonal-mean circulation patterns. A detailed account of the historical progress in this area can be found in Lorenz (1967).

The Hadley circulation (HC) is a thermally direct meridional circulation, which is a major component of the general circulation of Earth's atmosphere consisting of narrow upward motion of moist air over the equatorial region and wider descending motion of air in the subtropical region (Lorenz, 1967; Held and Hou, 1980; Schneider, 2006; Held, 2019). The HC exhibits a pronounced seasonal cycle, as shown in Fig. 1.1(a–d), which compares the climatological HC represented by the zonal mean meridional mass streamfunction (Oort & Yienger, 1996) during

December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). During the equinox seasons (MAM and SON), the HC consists of two relatively symmetric cells straddling the equator, with ascent confined to near-equatorial latitudes and upper-tropospheric outflow directed poleward in both hemispheres. In contrast, during the solstitial seasons (DJF and JJA), the circulation transitions into a single dominant cross-equatorial cell, featuring strong ascent in the summer hemisphere and broad subsidence in the winter hemisphere. The HCs contribution to the poleward transport of energy and angular momentum and equatorward transport of moisture is crucial for maintaining the general circulation of the atmosphere. It plays a critical role in influencing the intensity of precipitation over the ITCZ and the descending branch of HC marks the location of the subtropical dry zones and contains many of the world’s largest deserts. The intensity and location of subtropical highs, subtropical jet streams and storm tracks are also dependent on the HC strength and it plays a significant role in modulating the extratropical and tropical weather patterns (Hou, 1998; Trenberth and Stepaniak, 2003; Diaz and Bradley, 2004; Quan et al., 2004). By the 20th century, advances in thermodynamics and fluid dynamics allowed a more quantitative treatment of the Hadley circulation. A modern theoretical framework of the Hadley cell was formalized by Held and Hou (1980). In the Held and Hou (1980) framework, the Hadley circulation is depicted as a set of thermally driven, laminar, and axisymmetric cells that respond directly to changes in thermal forcing. The model remains a cornerstone of atmospheric dynamics and is still used to interpret the response of the tropical circulation to climate change. However, this idealized representation is an oversimplification. In reality, a purely axisymmetric circulation cannot exist in Earth’s three-dimensional atmosphere, as the strong vertical shear of the zonal wind associated with such a regime would render it unstable to baroclinic instability (Held, 2000). Moreover, the influence of baroclinic waves exert eddy momentum fluxes that impact the zonal mean flow (Becker et al., 1997; Kim and Lee, 2001; Walker and Schneider, 2006) and contribute significantly to the meridional redistribution of heat and moisture away from the low-latitude regions (Trenberth et al., 2000).

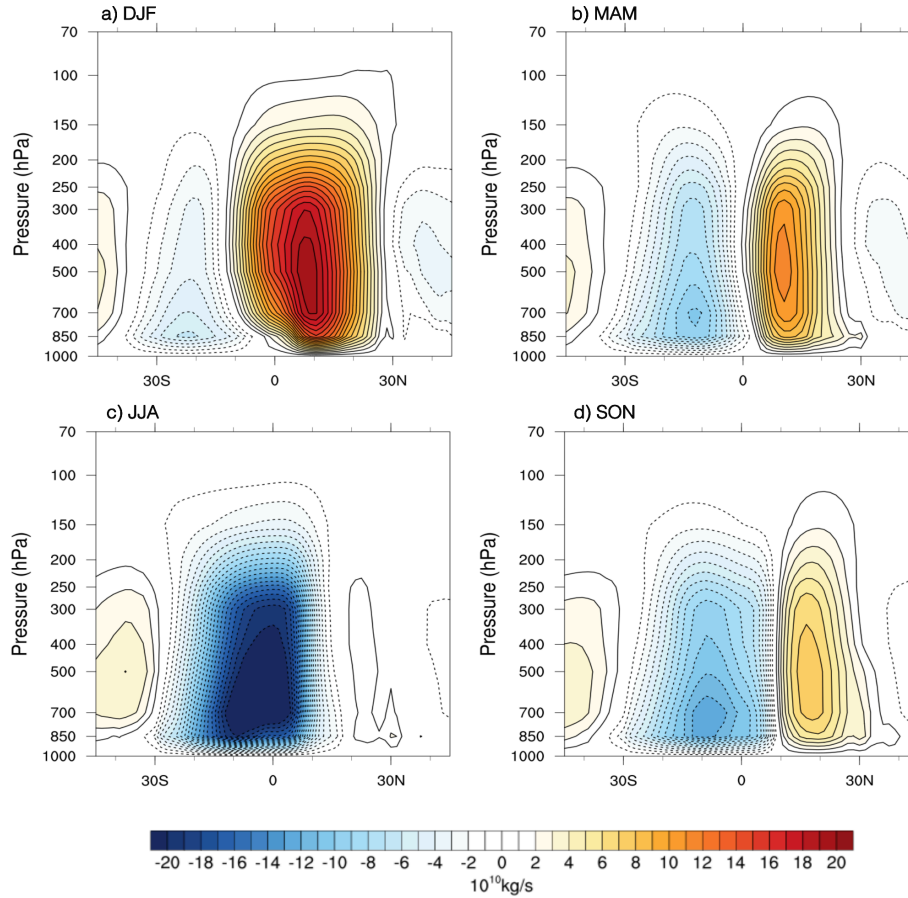


Fig.1.1. The zonal-mean meridional streamfunction representing the zonal-mean HC time-averaged during boreal a) winter (DJF), b) spring (MAM), c) summer (JJA) and d) autumn (SON) (Contours, Units : 10^{10} kg/s). Solid (dotted) contours denote clockwise(anti-clockwise) rotation. ERA5 monthly-mean fields were used from 1940-2021.

The late 20th century brought major observational advances with the advent of satellite data and global reanalyses. Using these datasets several new insights were gained on the variability and trends associated with the Hadley cell's width and intensity. Several studies have reported a systematic widening of the global Hadley circulation (Davis and Rosenlof, 2012; Hu and Fu, 2007; Rosenlof, 2002; Fu et al., 2006), attributing this expansion to factors such as global warming, stratospheric ozone depletion, and tropical sea surface temperature variability. Fu et al. (2006) identified a poleward displacement of the subtropical jet, suggesting an extension of the Hadley cell by approximately 2° latitude. Evidence from ozone observations also supports this expansion, with Hudson et al. (2006) reporting a poleward shift of the Northern Hemisphere Hadley cell edge at a rate of $1.1 \pm 0.2^\circ$ per decade. Seidel and Randel (2007) showed that the

tropical tropopause edge—often used as a proxy for the Hadley cell boundary—migrated poleward by roughly 5° – 8° latitude between 1979 and 2005. Climate model simulations also reproduce the poleward expansion of the Hadley circulation, although with a weaker magnitude compared to observations and reanalyses (Lu et al., 2007; Johanson and Fu, 2009; Hu et al., 2013; Ceppi and Hartmann, 2016; Davis and Birner, 2017). While there is a general consensus on Hadley cell expansion, the question of whether the HC is strengthening or weakening is still a matter of contention. Analyses based on subtropical outgoing longwave radiation trends suggest a strengthening of the Hadley circulation (Chen et al., 2002; Wielicki et al., 2002). Sohn and Park (2010) reported an intensification of the lower-branch of HC inferred from water vapor transport since 1979. In contrast, other studies found seasonally dependent trends, with strengthening during boreal winter but little to no increase during boreal summer (Quan et al., 2004; Ma and Li, 2008). Furthermore, future climate projections generally indicate a weakening of the Hadley circulation under continued global warming (Levine and Schneider, 2011; Seo et al., 2014).

Since the HC is conceptualized as an axially symmetric mean meridional circulation, it is defined as the longitudinally averaged meridional circulation. This form of representation of HC offers a simple and effective way to illustrate the global circulation. However, the heterogeneous distribution of land and ocean, along with the pronounced zonal asymmetry in winds and precipitation, limits the representativeness of this zonally averaged framework. While the global HC can be viewed as the cumulative outcome of multiple regional meridional circulations distributed across longitudes, this conventional definition may obscure important local features. For instance, competing or out-of-phase regional meridional circulations can cancel out in the zonal mean, thereby masking their individual characteristics and contributions. Recognizing these limitations, several recent studies have emphasized the need to examine regional Hadley circulations over longitudinally confined sectors, which provides a better perspective on the spatial variability and underlying drivers of the HC (Zhang & Wang, 2013; Schwendike et al., 2014; Nguyen et al., 2015). A few previous works have indicated the importance of regional HCs in modulating regional climate variability. For instance, Ambrizzi et al. (2005) demonstrated that variations in the regional HC significantly influence rainfall distribution over South America. Similarly, Huang et al. (2018a) reported that interannual fluctuations in the western Pacific HC

are closely associated with precipitation and temperature anomalies across Asia and Australia. Zeng et al. (2011) further showed that variability in the East Asian winter monsoon is strongly linked to changes in HC intensity over both the western and eastern Pacific sectors. In addition, several studies (Zhang and Wang, 2013, 2015; Guo and Tan, 2018) have documented that tropical cyclone activity across different ocean basins is strongly modulated by regional Hadley circulations.

The Hadley circulation is primarily driven by moist convective processes associated with the Intertropical Convergence Zone (ITCZ), where vertical heat transport occurs through deep convective structures often described as “hot towers” (Riehl, 1958). Warm equatorial SSTs favor deep convection by reducing the moist static stability of the atmospheric column and also the through the influence of meridional SST gradients which majorly control the convergence of moisture-rich boundary-layer winds (Lindzen & Nigam, 1987; Zhang, 1993; Xie, 2004; Back & Bretherton, 2009). As a result, both the strength and spatial extent of the Hadley circulation are highly sensitive to the distribution of tropical SSTs (Graham and Barnett, 1987; Waliser and Graham, 1993). A substantial body of literature has shown that variability in the equatorial warm pool, spanning the western Pacific and Indian Ocean plays a key role in modulating the zonal-mean Hadley circulation (Gadgil et al., 1984; McPhaden and Picaut, 1990; Wang, 2002a; Neale and Slingo, 2003; Huang and Mehta, 2004; Diaz and Bradley, 2004; Xiaoqing et al., 2015). The western Pacific warm pool, extending roughly from 110°E to 170°E, harbors some of the warmest ocean surface waters on Earth, with mean SSTs exceeding 28–30°C. This region serves as a major source of atmospheric heat and moisture, supporting persistent deep convection and heavy precipitation, and forming the ascending branch of the equatorial Walker circulation. In contrast, the eastern equatorial Pacific (approximately 180°–270°E) is characterized by substantially cooler SSTs, typically in the range of 22–26°C, and is commonly referred to as the Pacific “cold tongue”. These lower SSTs arise from a combination of cold-water upwelling and the dynamical influence of easterly trade winds. Consequently, this region is associated with suppressed convection, prevailing subsidence, and relatively clear-sky conditions, corresponding to the descending branch of the Walker circulation. While zonal asymmetries in SST and convection are present in other ocean basins, the Pacific Ocean’s vast spatial extent (covering nearly one-third of the planet’s surface), implies that the variability in the Pacific climate state would have large scale impacts on the global climate.

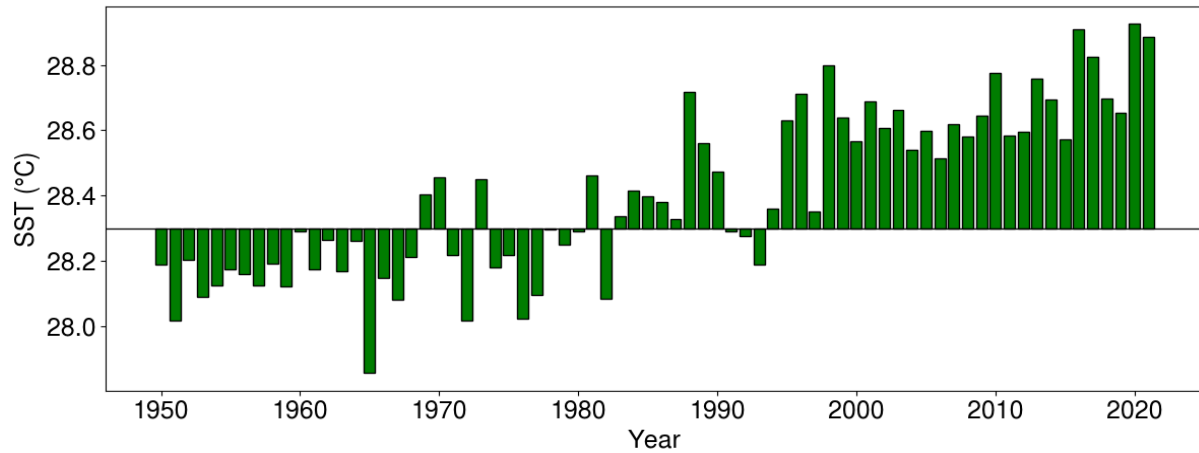


Fig. 1.2. Time series of area-averaged annual mean SSTs over the (a) Western Pacific Warm Pool (20°S–20°N, 110°E–170°E) for the period 1940–2021, derived from HadISST data.

Over recent decades, a growing body of research has documented a progressive intensification and an eastward expansion of the Pacific warm pool (Alory et al., 2007; Rao et al., 2012; Dong et al., 2014; Kidwell et al., 2017) (Fig. 1.2). This evolution has been attributed to a combination of internal climate variability and externally forced climate change (Hoyos and Webster, 2012; Dong et al., 2014; Roxy et al., 2014; Park et al., 2022). Several studies have reported an increase in both the frequency and intensity of El Niño events in recent decades and have linked these changes to the observed rise in warm pool sea surface temperatures, with contributions from both atmospheric and oceanic processes (Rao et al., 2012; Cai et al., 2014; Swapna et al., 2014). Roxy et al. (2014) further demonstrated that the warming of the tropical oceans has resulted in a nearly twofold expansion of the Pacific warm pool area—from approximately 2.2×10^7 km² during 1900–1980 to about 4×10^7 km² over the period 1981–2018. Consistent with these findings, climate model projections suggest that the warm pool will continue to expand eastward in the future, with the 29.2°C isotherm, commonly used to delineate the warm pool boundary projected to extend farther east by the end of the 21st century (Brown et al., 2015). Notably, the rapid expansion observed around 1980 coincides with a global sea surface temperature regime shift, indicating a major reorganization of the tropical climate system

(Levitus et al., 2009; Rhein et al., 2013; Reid et al., 2016). Correspondingly, several studies have identified an abrupt change in tropical atmospheric circulation during the late 1970s and early 1980s and have linked it to the warm pool regime transition (Chen et al., 2002; Ma and Li, 2008; Feng et al., 2011, 2013). In particular, enhanced warm pool conditions have been suggested to strengthen the Hadley circulation by amplifying convective heating and increasing moist static energy transport (Wang, 2002a; Feng et al., 2011). Consistent with this view, Quan et al., (2004); Wang and Mehta (2008) ; Feng et al. (2011) identified a regime shift in the strength of the zonal-mean Hadley circulation during the 1970s, characterized by an intensification of the northern overturning branch. This change was attributed to the overall warming of the tropical oceans, together with the increased amplitude and frequency of El Niño events following the mid-1970s climate shift. Collectively, these studies point to a climate regime shift around 1980 that not only transformed the thermal structure of the Pacific Warm Pool but also reorganized the large-scale Hadley circulation. While the warming trends have been linked to the modifications in tropical convection and the Walker circulation, only few studies have explicitly examined how the change in Pacific SST patterns can influence the regional Hadley cells in the sector, underscoring the need for a more detailed investigation into how SST variations modulate regional Hadley cell behavior.

Apart from boundary-forced convection driven by SSTs, numerous studies emphasize that interactions between the mean flow and transient eddies play a critical role in regulating the strength of the Hadley circulation. Much of the early work focused on the role of midlatitude baroclinic eddies in influencing the strength and structure of the HC (Becker et al., 1997; Caballero, 2007; Caballero & Anderson, 2009; Dickinson, 1971; Kim & Lee, 2001; Kuo, 1956; Pfeffer, 1981; Walker & Schneider, 2005). Walker and Schneider (2006) demonstrated that the strength of the equinoctial HC is linearly related to the divergence of extratropical eddy momentum fluxes. Similarly, Davis and Birner (2019) showed through numerical simulations that, in the absence of these extratropical eddy fluxes, the HC cannot effectively extend to the subtropical surface nor efficiently transport momentum poleward. In addition to midlatitude influences, tropical eddies embedded within the convective zone of the HC also can play an important role in modulating its strength (Dima et al., 2005; Zurita-Gotor, 2019). The Intertropical Convergence Zone (ITCZ)—the preferred location of HC ascent, may be viewed not as a steady feature but rather an ensemble of disturbances spanning a range of temporal and

spatial scales (Chang, 1970; Wallace & Chang, 1972; Reed & Recker, 1971; Yanai & Murakami, 1970a, 1970b). Recent studies propose that fluctuations in tropical moist convection over days to months may substantially modulate the HC intensity (Hoskins et al., 2020; Hoskins & Yang, 2021). Circulations associated with equatorial waves can generate low-level convergence, initiating deep convection and producing diabatic heating anomalies that feed back onto the mean meridional circulation (Tomassini & Yang, 2022). Such eddy–mean flow interactions provide a physically plausible pathway through which tropical disturbances can shape the strength and vertical structure of the HC. Despite these advances, the role of tropical transient disturbances in regulating regional meridional circulation variability remains underexplored, and demands further investigation.

Building on the above context, the overarching aim of this thesis is to develop a comprehensive understanding of the variability in strength and spatial extent of regional Hadley circulations across distinct geographic sectors, and to identify the underlying forcing mechanisms responsible for these variations. Given the identified gaps in previous research, the current thesis sets forth three primary objectives. The subsequent chapters are organized around these objectives, with each chapter focusing on a specific aspect of regional Hadley circulation variability and the underlying physical mechanisms that influence its variability. The *second chapter* presents a detailed analysis of regional Hadley circulations across six distinct geographic domains, highlighting their spatial diversity along with their seasonal and interannual variability in strength and extent. The *third chapter* investigates how the rapid increase in the warm pool SSTs since 1980 has influenced the two regional Hadley circulations over the Pacific. The SST threshold for convection and column destabilization over the western and eastern Pacific domains are studied during the two climate states corresponding to the pre-1980 and post 1980 periods. The study aims to provide a critical understanding of the co-evolution of tropical ocean warming, convective intensity, and tropical atmospheric overturning circulations. The *fourth chapter* examines how tropical transient disturbances influence the regional HC variability, focusing on the East Pacific HC. The choice of the east Pacific domain is motivated by the distinctive prominence of synoptic-scale disturbances over the region, unlike other regions such as the western Pacific or Indian Ocean, where a wide range of scales, including intra-seasonal and quasi-biweekly oscillations, are also prevalent. Apart from the SST driven thermal convection and the convection driven by convergence induced by SST gradients, the study

addresses a less explored aspect of how atmospheric wave induced convergence may be critical in determining the strength of regional meridional cells. Finally, the *fifth chapter* summarizes the key findings of the thesis and discusses future research directions.

Chapter 2

Understanding the characteristics and seasonal variability of the regional Hadley cells

2.1. Introduction :

The Hadley circulation (HC) is conventionally conceptualized as axially symmetric mean meridional circulation, with one branch extending towards the northern and another towards the southern subtropics. This form of representation of HC offers a simple and effective way to illustrate the global circulation. However, the heterogeneous distribution of land and ocean, and the observed zonal asymmetry in the wind distributions imply a limited utility of the conventional definition of global mean HC. Although the global HC can be viewed as a resultant of the cumulative effect of the meridional circulations across the longitudinal belt, it mostly will not capture the meridional circulation characteristics in the regional scale. Recognizing the importance of regional meridional circulations, many recent studies defined the HCs over longitudinally confined sectors and such HCs are termed as regional Hadley Circulations (Zhang & Wang, 2013; Schwendike et al., 2014; Nguyen 2015). These regional HCs have been shown to exert a strong influence on regional climate variability. For instance, Guo and Tan (2018) demonstrated that the regional Hadley circulation associated with the Indo-Pacific warm pool plays a key role in modulating tropical cyclone activity over the western North Pacific. Similarly, precipitation and temperature anomalies across Asia and Australia have been found to be closely linked to variations in the regional Hadley circulation over the western Pacific (Huang et al., 2018). In the Atlantic and northeastern Pacific sectors, regional Hadley circulations have also been shown to significantly influence tropical cyclone activity within their respective basins (Zhang and Wang, 2013, 2015). Furthermore, changes in regional Hadley circulation have been associated with declining trends in Sahel summer rainfall, reduced summer

precipitation over northern China, and decreased snow accumulation at Dasuopu in the Himalayas (Zhao and Moore, 2008).

However, a comprehensive understanding of the regional HC characteristics and variability across different regional domains remains lacking. In a recent study, Li et al. (2022) examined the variability of regional HCs using various reanalysis datasets. However, they defined the regional HCs based on the horizontal distribution of the mass stream function, which may overlook the influence of geographical factors. As the land ocean-distribution and SST patterns are critical factors that determine the meridional circulation strength and extent, in this study the regional HCs are identified by careful consideration of these factors. Several key questions related to the diversity in characteristics of various regional HCs, their seasonal variability and the role of ITCZ convection in determining the strength of different regional HCs are addressed in this chapter. It also examines whether the observed variations among regional HCs are interconnected or independent, and whether the regional HCs exhibit long-term variability similar to that of the zonal-mean Hadley circulation. Since regional HCs can play a crucial role in modulating the regional weather and climate variability, addressing the regional HC variability is highly relevant to better understand the weather and climate patterns over different regions.

2.2. Data and methodology:

The primary datasets used in this study are the monthly averaged zonal, meridional, and vertical pressure wind velocity data obtained from ERA5 reanalysis (Hersbach et al., 2020), with a horizontal resolution of $1.5^\circ \times 1.5^\circ$ at 11 pressure levels ranging from 1000 hPa to 50 hPa for the period from 1979 to 2021. For the same time period, NOAA interpolated daily outgoing long-wave radiation (OLR) data (Liebmann & Smith, 1996) with a horizontal resolution of $2.5^\circ \times 2.5^\circ$, is used as a proxy for tropical deep convection.

The HC is usually described using the global meridional stream function (Oort & Yienger, 1996).

$$\psi = \frac{2\pi R \cos\phi}{g} \int_0^p v(\phi, p) dp \text{ ----- (2.1)}$$

where R is the radius of Earth, g is the gravitational acceleration. ϕ is the latitude, p is the atmospheric pressure, v is the zonally averaged meridional velocity.

In this approach, the meridional circulation is assumed to be non-divergent, so there is no net mass flux in the zonal direction. But over the regional domains the net zonal mass transport is not negligible and this assumption is not valid. Therefore, an alternate method has been proposed to define the regional meridional stream function characterizing the regional HC based on the divergent component of the meridional wind (Zhang & Wang, 2013; Schwendike, 2014; Li et al., 2022). The regional MSF Ψ_R representing regional HC is defined as:

$$\Psi_R = \frac{\Delta\lambda_R R \cos\phi}{g} \int_0^p [v_d] dp \text{ ----- (2.2)}$$

where v_d is the regional zonal average of divergent meridional wind, and $\Delta\lambda_R$ is the longitudinal angular extent of the regional HC. The divergent meridional wind v_d at each pressure level is obtained by decomposing the horizontal wind into divergent and non-divergent wind and the divergent wind is further decomposed into zonal and meridional components.

Although the edge of the global HC is generally defined as the latitude where the stream function goes to zero (Oort and Yienger, 1996), the stream function for the regional HCs does not necessarily reach a zero value at its poleward edge. Therefore, we define the edge of the regional HC as the location where the stream function reduces to a 25% of the maximum stream function value in the tropics between 700–400 hPa pressure levels. The intensity of the northern (southern) branch of the regional HC is calculated as the maximum (minimum) of the stream function value in the tropics.

The HC branch extending poleward in the northern (southern) hemisphere is referred to as the NH (SH) branch. Over regions of large seasonal displacement of ITCZ like the Indian Ocean domain, the HC branch with rising motion in the summer hemisphere and descending motion in the winter hemisphere is referred as the winter HC, and the branch with ascending and descending motion both in the summer hemisphere is referred as the summer HC.

2.3. Results :

To examine the characteristics of each of the regional HC during different seasons, their long-term variability and how they are different from the global HC, in this study, the regional HCs over six geographical domains are considered: Africa (AFHC; 10°E–40°E), the Indian Ocean (IOHC; 60°E–100°E), the western Pacific (WPHC; 110°E–170°E), the eastern Pacific (EPHC; 150°W–110°W), South America (SAHC; 80°W–45°W), and the Atlantic (ATHC; 40°W–10°W). The choice of these sectors is made based on the diversity of geography and nature of convective activity over the domain (Chen et al., 2014; Cheng et al., 2019) (Fig. 2.1). For example, the AFHC and SAHC sectors cover only land regions, while the EPHC and ATHC sectors are entirely oceanic. The IOHC and WPHC sectors encompass both land and oceanic regions. Climatologically, the East Pacific and Atlantic are characterized by cold SSTs called ‘cold tongue’ and the West Pacific with warmer SST is recognized as a ‘warm pool’ (Philander, 1990). Therefore, understanding the disparity in regional HC dynamics between these sectors is of considerable significance. Additionally, with studies suggesting that regional monsoon is likely a manifestation of HC (Joseph, 1978; Webster & Yang, 1992; Goswami et al., 1999), investigating the regional HCs over major monsoon regions, like- Indian Ocean, West Pacific etc. will shed more light on the HC-monsoon relationship. Also, discussing the African and South American HCs will pave the way towards the understanding of how prominent geographical features, like- Saharan desert, or Amazon basin can have an impact on regional HC variations.

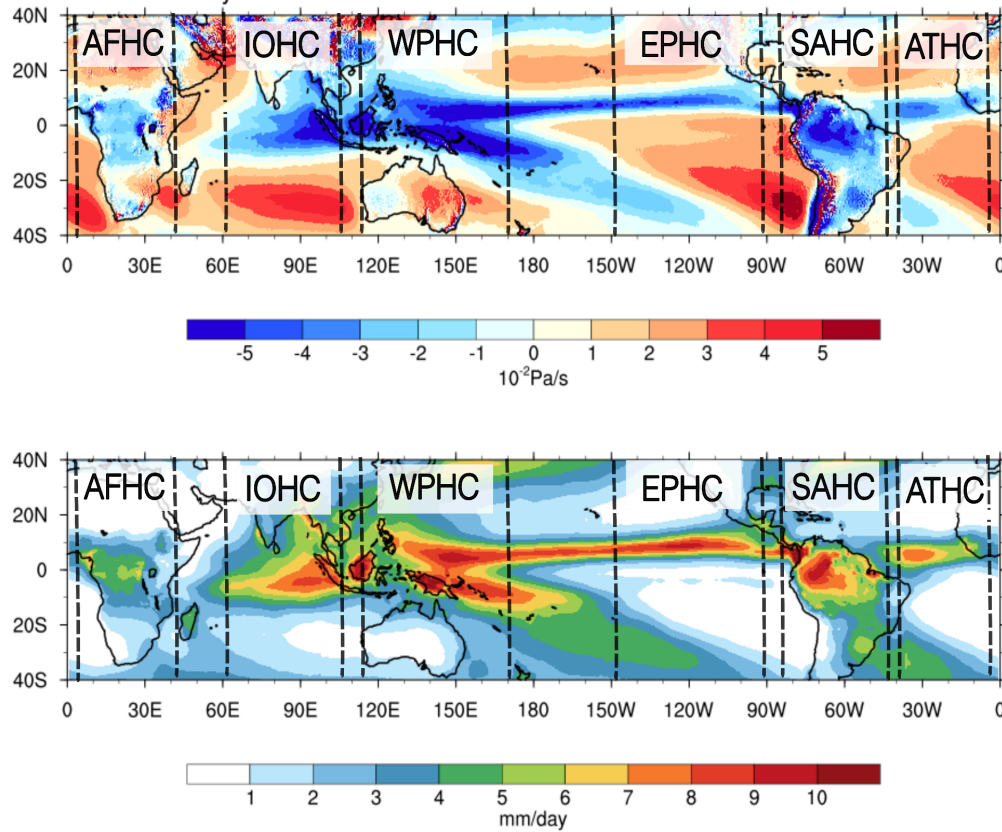


Fig.2.1. Annual mean climatology of (a) vertical velocity at 500 hPa, units : 10^{-2} Pa/s and (b) precipitation, units : mm/day. Black boxes show the six selected regions : Africa (10°E – 40°E , AFHC), the Indian Ocean (60°E – 100°E , IOHC), the western Pacific (110°E – 170°E , WPHC), the eastern Pacific (150°W – 110°W , EPHC), South America (80°W – 45°W , SAHC), and the Atlantic (40°W – 10°W , ATHC).

The meridional stream function fields manifesting the six regional HCs are shown for the four seasons (December-February (DJF), March-May (MAM), June-August (JJA), September-November (SON)) in Figures 2.2, 2.3, 2.4 and 2.5, respectively. Two meridional overturning circulations are observed in both the hemispheres over all the regional sectors. The stream function takes positive values (denoting clockwise motion) in the NH branch of HC and negative values (denoting anti-clockwise motion) in the SH branch. The zero contour of the mass stream function marks the region of convective ascent associated with the HC.

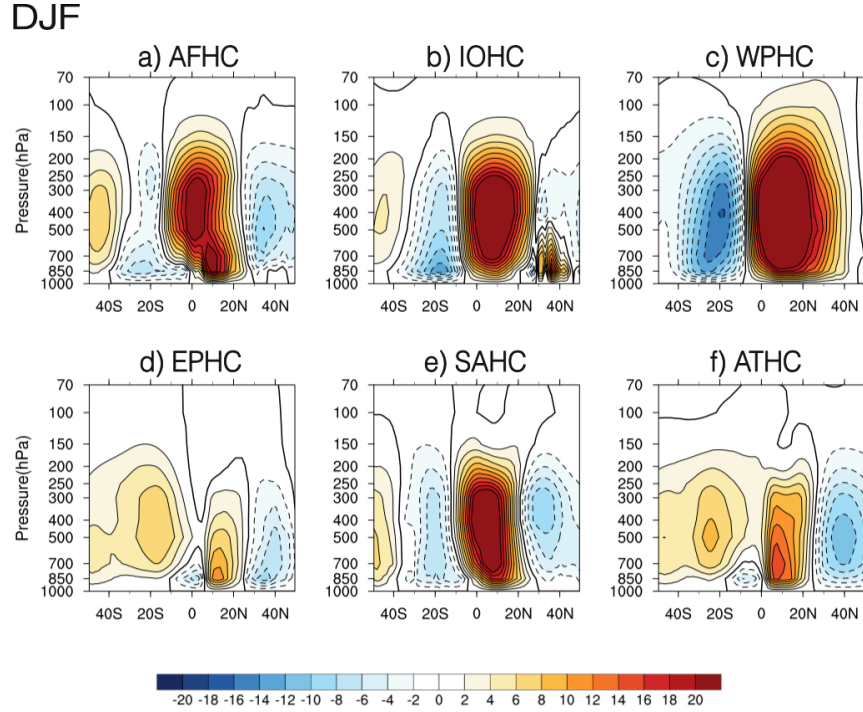


Fig.2.2. Boreal winter (DJF) climatology of the regional HC mass streamfunction (Contours, Units : 10^{10} kg/s) over the 6 sectors. Solid (dotted) contours denote clockwise (anti-clockwise) rotation.

During DJF, the Northern hemispheric HC is observed to be stronger than the Southern hemispheric HC across all the regional sectors (Fig.2.2). The West Pacific HC (WPHC) is found to have the largest intensity and meridional and vertical extent, followed by the Indian Ocean (IOHC), African (AFHC) and South American HC (SAHC). The regional HCs over the all-ocean domains East Pacific (EPHC) and Atlantic HC (ATHC) are observed to be the weakest as compared to the regions where the land-ocean contrast is strong. This is in agreement with AGCM modelling experiments (Cook, 2004), which showed that stronger HCs developed in simulations with continents as compared to those with no continents. As opposed to the other sectors, where the HC ascent is observed to the south of the equator; over the east Pacific and the Atlantic, the HC ascent is found to the north of the equator, around 5° - 10° N. While the NH HC over these two regions is moderately strong extending from around 0° - 5° N to 25° N meridionally and to about 200hPa in the vertical, the SH HC is almost absent.

As the season progresses to MAM, the equinoctial period, the difference in strength of

the Northern hemispheric and Southern hemispheric HCs get reduced and two equally strong overturning cells are observed in all the sectors including the Eastern Pacific (EPHC) and the Atlantic (ATHC) (Fig. 2.3). Ascending locations of all the HCs are found to be around the equator, and Northern hemispheric HC edges are found around 25°-30° N, except for West Pacific (WPHC), which extends beyond 40°N and 40°S in both hemispheres. Compared to other HCs, the Southern hemispheric branch of East Pacific HC (EPHC) and Atlantic HC (ATHC) has the smallest meridional extent and is restricted to around 15°-20° S in latitude. All the HCs extend to almost 200-100 hPa during this season.

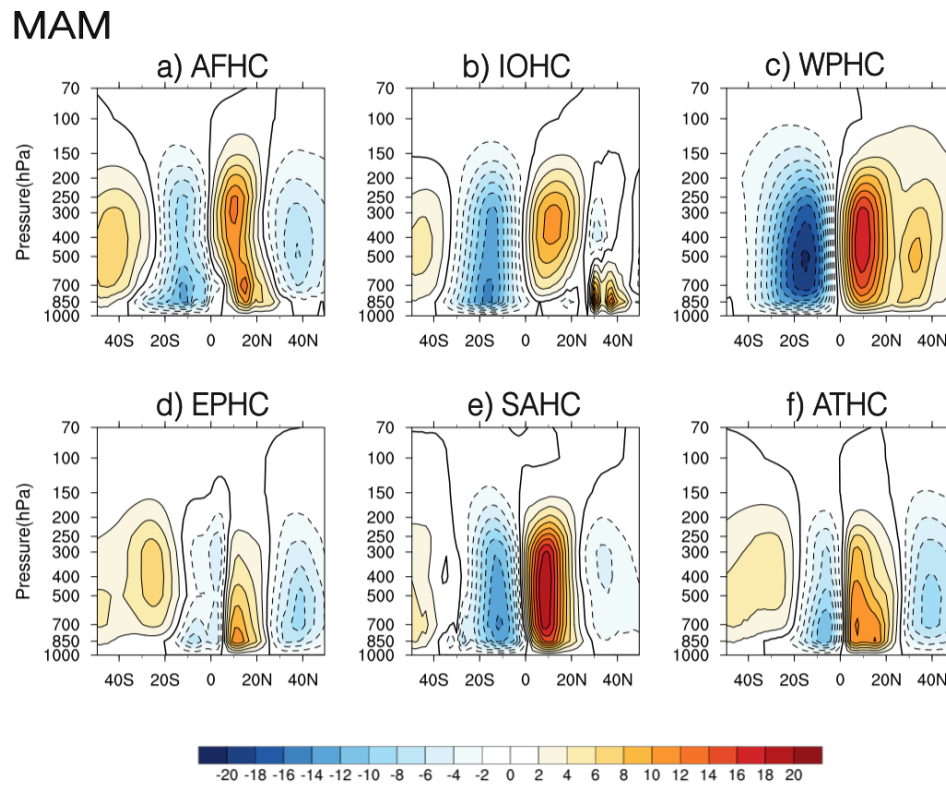


Fig.2.3. Boreal spring (MAM) climatology of the regional HC mass streamfunction (Contours, Units : 10^{10} kg/s) over 6 sectors. Solid(dotted) contours denote clockwise (anti-clockwise) rotation.

During JJA, a northward migration of the ascending locations of HCs are observed in all the sectors (Fig. 2.4). The most pronounced displacement is observed over the Indian Ocean (IOHC) and West Pacific (WPHC) domains, with the HC ascent shifting to around 15°-25° N. In contrast, over the East Pacific (EPHC), Atlantic (ATHC), South American (SAHC) and African (AFHC) sectors the ascending region is located mostly around 10° N. The Southern hemispheric

HC is stronger than the Northern hemispheric HC and extends from 35°-40°S to 20°-25°N over WP and IO domains and from 20°-25° S to 10°N over the other domains. Although the Southern hemispheric branch of the EPHC, SAHC and ATHC is well developed, extending up to about 150 hPa, the Northern hemispheric branch is observed to be very weak.

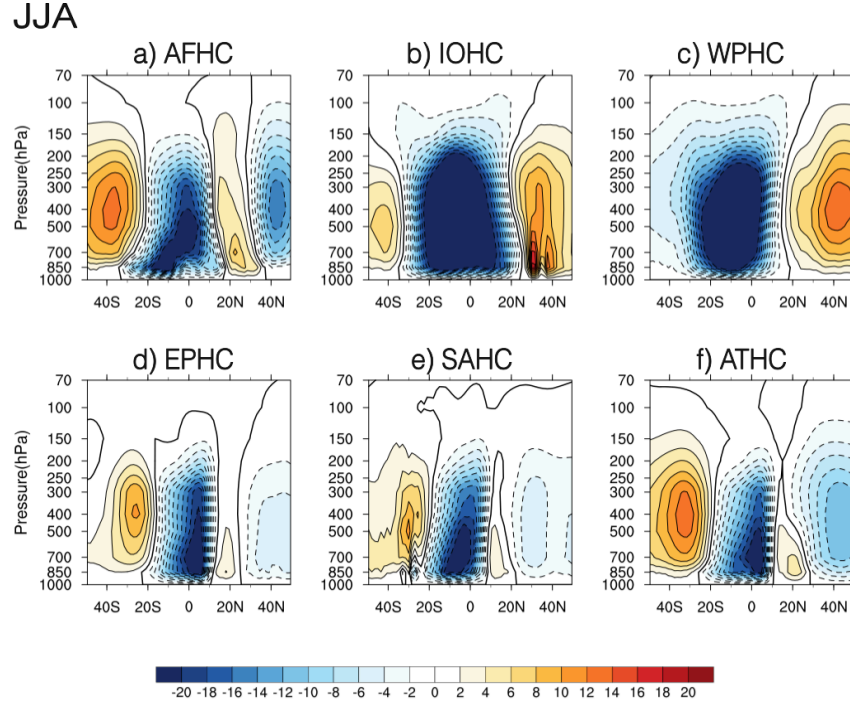


Fig.2.4. Boreal summer (JJA) climatology of the regional HC mass streamfunction (Contours, Units : 10^{10} kg/s) over 6 sectors. Solid (dotted) contours denote clockwise(anti-clockwise) rotation.

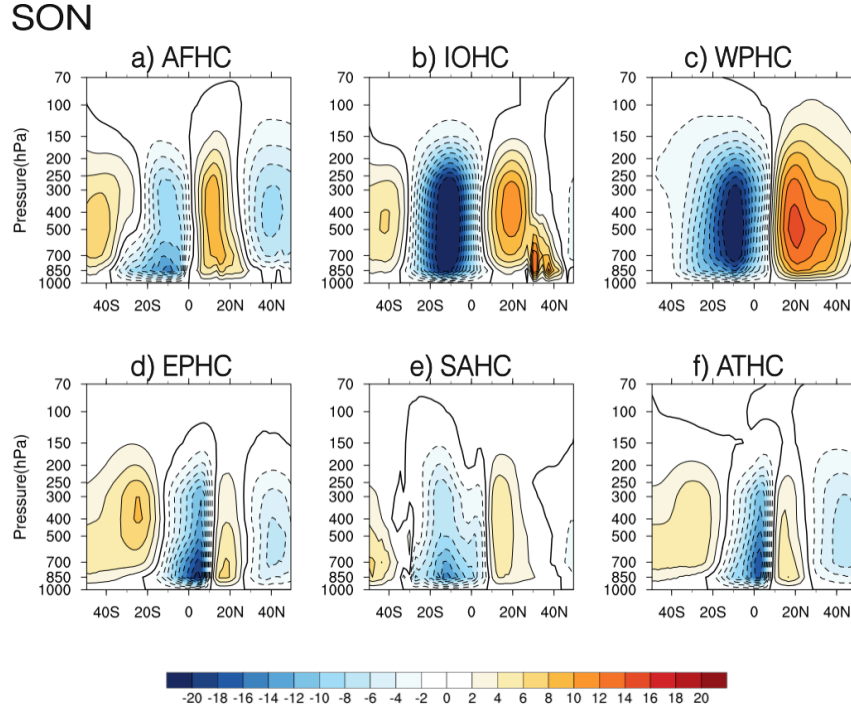


Fig.2.5. Boreal autumn (SON) climatology of the regional HC mass streamfunction (Contours, Units : 10^{10} kg/s) over 6 sectors. Solid (dotted) contours denote clockwise rotation.

During SON, the Indian Ocean (IOHC), West Pacific (WPHC), East Pacific (EPHC), South American (SAHC), Atlantic HC (ATHC) ascent over 10°N , while the African HC (AFHC) convective ascent is observed close to the equator (Fig. 2.5). Over most domains the Northern hemispheric and Southern hemispheric HCs have comparable strength. It is noteworthy that the two cells of HC over the Atlantic and East Pacific domains are well developed and have comparable strength only during the equinoctial seasons, while during the solstices, the summer hemisphere cell is observed to be weak and underdeveloped. The EPHC and ATHC extend to about 15° - 20° latitude, whereas the WPHC exhibit a larger meridional extent, extending to about 40° latitude. Similar to MAM, in this season also, both branches of the HCs extend vertically to about 150-100 hPa. Detailed analysis of the characteristics of the regional HCs are discussed in the remaining sections.

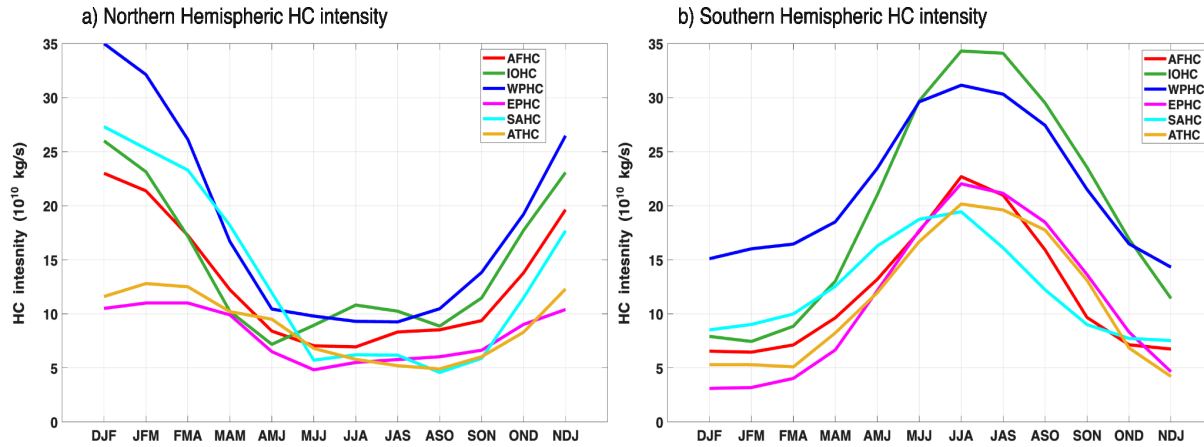


Fig.2.6. Seasonal cycle of intensity of the (a) Northern and (b) Southern Hemispheric branches of the six regional Hadley cells calculated as the amplitude maxima of the mass stream function over the latitudes extending from the ascending to the descending regions of HC in the respective hemispheres.

The seasonal variability of the strength of the Northern hemispheric and Southern hemispheric branches of the regional HCs are shown in Figure 2.6 a & b. The regional HC intensity is defined as the amplitude maximum of mass streamfunction (MSF) over the latitudes extending from the ascending to the descending regions of HC in the respective hemispheres. The regional HC intensity was estimated for every three-months using a moving window approach. It is well-known that the global HC is stronger in the winter hemisphere as compared to that in the summer hemisphere (Lindzen & Hou, 1988; Webster, 2004; Cook, 2004). In general, the regional HCs demonstrate a similar seasonality as the global HC documented in earlier studies, but some differences are observed in the seasonal variation of the Northern and Southern hemispheric branches of the regional HCs. The Southern hemispheric branch of the regional HCs exhibit the highest amplitude during the Southern hemispheric winter months from April to November and the lowest intensity during Southern hemispheric summer (DJF). The peak intensity of the Southern hemispheric HC over the Indian Ocean (IOHC) and West Pacific (WPHC) sectors is more than 1.5 times that over the other regions. As for the Northern hemispheric branch of the regional HCs, excluding those over the Atlantic (ATHC) and East Pacific (EPHC) Ocean sectors, the highest intensity observed during Northern hemispheric winter months from November to April and lowest intensity observed during Northern hemispheric summer (JJA). The HC intensity is particularly more pronounced over the West

Pacific (WPHC) sector, and the Northern hemispheric branch of the regional HCs over the East Pacific and Atlantic do not exhibit much of a seasonal variation.

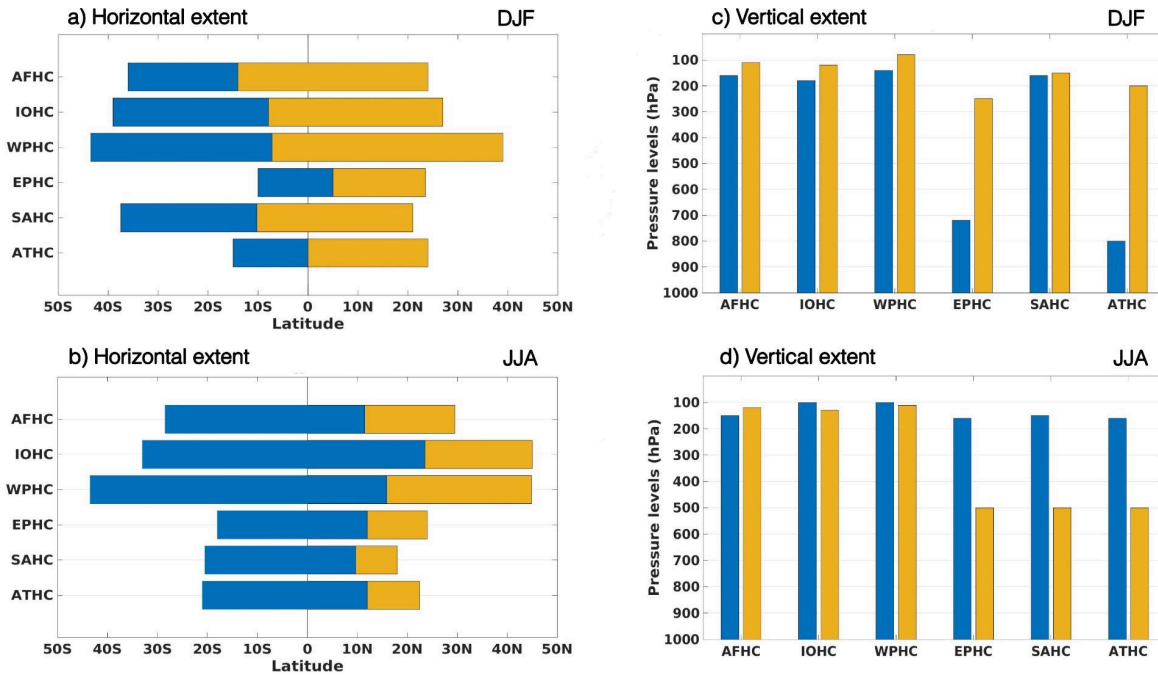


Fig.2.7. (a,b) Horizontal and (c,d) Vertical extent of the six regional Hadley cells during boreal winter (DJF, top panel) and boreal summer (JJA, bottom panel). Blue bars denote Southern hemispheric branch of HCs and Yellow bars denote the Northern hemispheric branch of HCs.

The meridional and vertical extent of the regional HCs for the boreal winter (DJF) and summer (JJA) months are summarized in Fig. 2.7(a, b). Convection of moist air over the Intertropical Convergence Zone (ITCZ) marks the region of HC ascent. The latitude of HC ascent is identified as the region where the mass stream function averaged between 700–400 hPa pressure levels tends to zero. While it is known that the ITCZ and the HC ascending region shifts seasonally towards the summer hemisphere (Mitchell and Wallace, 1992; Quan 2004; Nguyen, 2013), it is observed that the latitudinal migration differs significantly from region to region (Fig. 2.7(a)). The most pronounced seasonal displacement of ITCZ is observed over the Indian Ocean (IOHC) domain during JJA, when the convective ascent is observed at around 25° N while the least latitudinal displacement is observed over the East Pacific (EPHC), Atlantic (ATHC) and South American (SAHC) sectors. Over the East-Pacific and Atlantic, the HC ascent is observed to the north of the equator to around 5–10° N throughout the year (Hasternath, 1991; Xie & Philander, 1994; Webster, 2004). The latitude of HC descent in the two hemispheres, which

marks the northern and southern edges of the regional HCs is identified as the region where the mass stream function reduces to 25% percentage of the maximum amplitude of stream function value in the respective hemisphere. During DJF, the Northern hemispheric branch of Western Pacific HC (WPHC) extends beyond 40° N while all other HCs extend till 20°-25°N, while the Southern hemispheric branch extends to around 40° S in all sectors except the East Pacific and Atlantic, where, as noted before, the summer HC cell is not well developed (Fig. 2.2). The West Pacific HC (WPHC) exhibits the largest width among all the other regional cells, followed by the Indian Ocean (IOHC), South American (SAHC) and African HC (AFHC). During JJA, the edge of the northern hemispheric HC is shifted northward to 30° N over the African sector and to around 45° N over the Indian Ocean and West Pacific. As noted before, the summer HC is underdeveloped over the Atlantic, East Pacific and South America during this season, and hence the limited horizontal extent. Meanwhile the southern hemispheric HC extends to around 20° S latitude over these sectors and to around 30-45° S latitude over the African, Indian Ocean and West Pacific sectors. The broadest meridional overturning circulation is observed in the winter hemisphere over the West Pacific and Indian Ocean domains during both the seasons. The vertical extent of the regional HCs in both the Northern and Southern Hemisphere branches was quantified by identifying the pressure level at which the mass streamfunction drops to 25% of its maximum amplitude in the respective hemisphere. The winter HCs in all the sectors are found to extend vertically upto the tropopause level (100-200 hPa) during both seasons. While the HC branch in the summer hemisphere, extends vertically to 100-200hPa pressure levels only over the West Pacific, Indian Ocean, South America and African sectors, over the East Pacific and Atlantic sectors, the HCs in the summer hemisphere are not well developed and exhibit a limited vertical extent (only up to 700-500 hPa).

Moist convection within the ITCZ plays a pivotal role in maintaining the Hadley circulation (Riehl, 1958), and under the influence of the seasonal changes in background convection, the region of maximum convection and the ITCZ exhibit pronounced seasonal variations (Waliser & Graham, 1993). To verify whether the regional HC characteristics identified in the previous sections are consistent with the ITCZ convective activity over the respective regional domains, the seasonal variations of OLR is examined over the respective regional domains (Figure 2.8). The OLR values are longitudinally averaged over the respective regional HC sectors and the seasonal evolution of the HC ascent region (identified in the

preceding section) are also indicated along with it for the ease of comparison. A very strong association is observed between the latitudes of HC ascent and the OLR minima over the different regional sectors. Over the Atlantic and East Pacific oceanic domains, the convective maximum is observed to the north of the Equator, throughout the year and consistently the region of HC ascent is collocated with the OLR minima values (Fig. 2.8 a & b). As described by previous studies, the ITCZ is perennially located to the north of the equator over these basins (Xie & Philander, 1994; Xie, 2004; Webster, 2004). The convective signal is very weak over these domains, particularly during the boreal winter season. On the other hand, a very strong convective signal and a pronounced seasonal migration of the ITCZ is observed over the Indian Ocean and Western Pacific sectors (Fig. 2.8 c and d). During DJF, the ITCZ is centered over the equatorial warm pool and over the South Pacific convergence zone (SPCZ) and during JJA, following the northward migration of ITCZ over the South Asian land mass, the convective maximum shifts northward, leading to a corresponding northward displacement of the regional HC. These regions witness the largest poleward excursion among all regional HCs. The low OLR values observed to the north of 10° N is associated with the deep convection developing of the monsoon domain. A more limited north-south migration of the ITCZ convective maxima is observed over the South American and African sectors (Fig. 2.8 e and f). Over the African continent convective maximum is symmetrically displaced northward and southward by about 10° latitude during JJA and DJF respectively and a corresponding displacement of the HC ascent zone is observed over the region. A stronger convective amplitude is observed during DJF when the ITCZ is in the southward displaced location over the Congo basin. Over the South American sector, the continental land mass is to the south of the equator and hence the convective maximum exhibits a much stronger southward displacement during DJF, the Southern hemispheric summer season and the lower OLR values are indicative of stronger convection over land. Collectively, these patterns indicate that the seasonal migration of the ITCZ convection largely governs the latitudinal displacement of regional HC, with the largest seasonal excursions over the Indian Ocean and Western Pacific, and the smallest shifts over the East Pacific and the Atlantic.

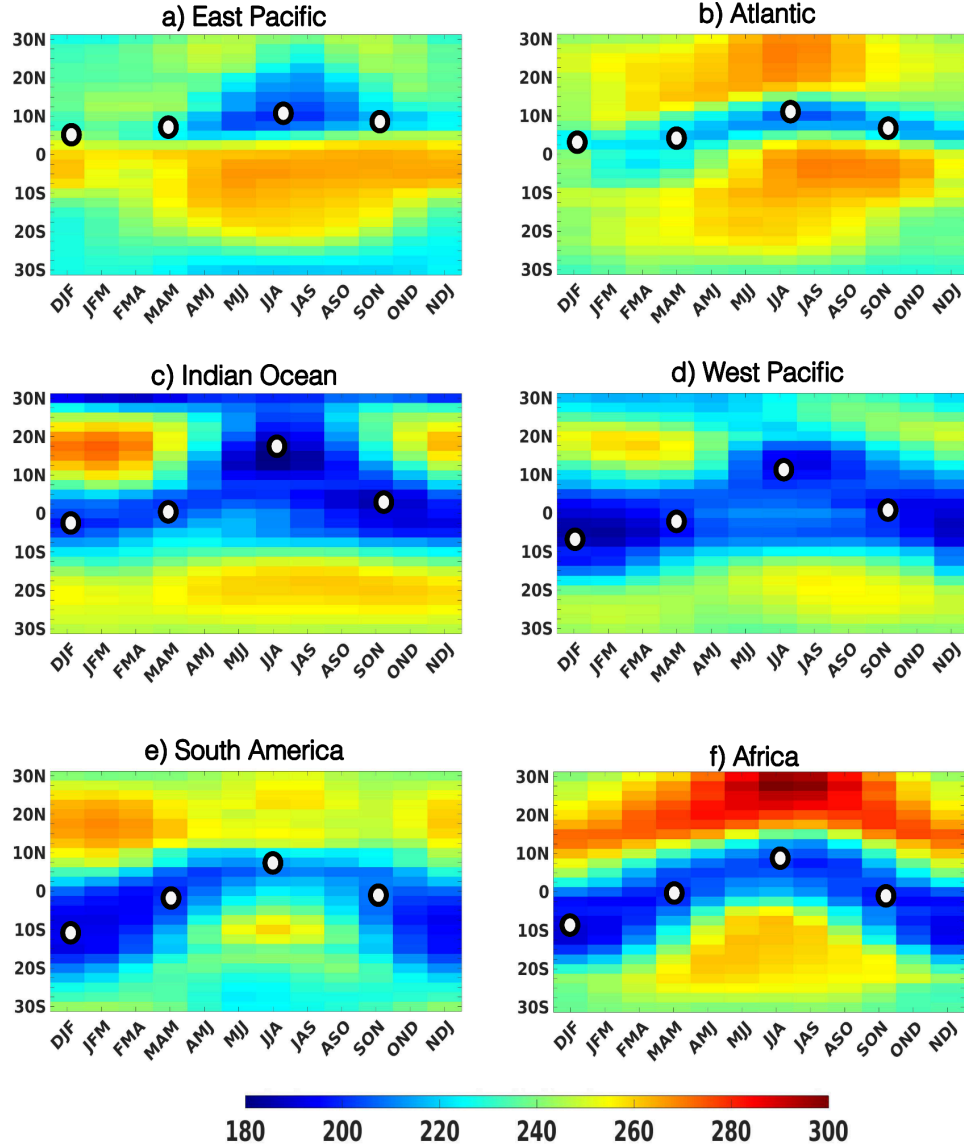


Fig.2.8. Seasonal evolution of OLR over each of the six regions. For each region, the OLR values are averaged longitudinally over the six sectors defined in Fig.1 (units : W/m^2). The white dots outlined by black line represent the respective regional HC ascending locations.

Further, the association between the strength of convection over the ITCZ, and the strength of the regional HCs were examined. Figure 2.9 shows a scatterplot of the intensity of the winter cell of the regional HCs plotted against the OLR values averaged over the ascending domains of each regional HC during DJF and JJA. The maximum (minimum) value of MSF over each region is taken as the NH (SH) HC intensity metric and the winter cell is chosen as it is more well developed compared to the summer cell and would be better suited to understand the

association between convection and HC strength. The OLR values were averaged over a $\pm 5^\circ$ latitude band centered over the location of the OLR minima over the ascending domains of each regional HC. A clear positive association is observed between the convective strength and HC intensity during both seasons. Highest convective strength is observed over the Indian Ocean (IOHC) and West Pacific (WPHC) during JJA, when the enhanced convection over the Asian monsoon domain drives a very strong Southern hemispheric HC, which extends from about 25°N to about 30°S over the IO and from about 20°N to about 45°S over the WP (Fig 2.4). Relatively lower convective strength is observed over the other regions and all the other regional HCs exhibit similar intensity during JJA. During DJF, strongest convection is observed over the West Pacific, followed by South America, following the Southward migration of the ITCZ to the SPCZ and the Amazon region and correspondingly the Northern hemispheric HC branches over these regions exhibit the highest intensity, extending from about 10°S to about 40°N over the West Pacific and from about 10°S to about 20°N over South America (Fig.2.2). IO is one of the domains where a significant difference is observed in the convective amplitude and HC intensity during the two seasons. While the strong monsoon convective activity drives an intense Indian Ocean HC (IOHC) during JJA, much weaker convection is observed during DJF, which also corresponds to a weaker IOHC strength. Meanwhile, over the WP domain, a stronger convective signal is observed during DJF as compared to JJA, which is accompanied by a stronger WPHC intensity in DJF compared to JJA over the western Pacific. As noted before, weak and shallow convective activity prevails over the East Pacific and Atlantic domains, which is even weaker during DJF, and correspondingly the regional HC intensity during DJF is much lower over these regions as compared to JJA. Overall, these seasonal contrasts demonstrate that regional HC intensity closely follows the seasonal and spatial variability of convection, with monsoonal forcing and ITCZ migration serving as the principal drivers. The strongest HCs correspond to regions and seasons of maximum convective activity and latent heat release, while weaker HCs coincide with periods of weaker convective activity.

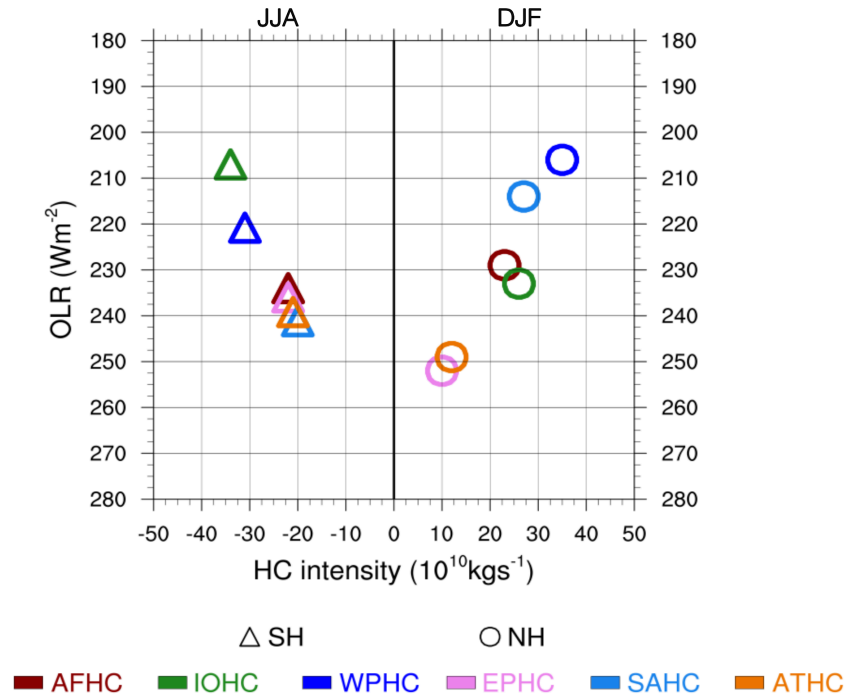


Fig.2.9. Scatter plot showing the relationship between regional winter HC intensity and OLR. OLR is averaged over the individual regional HC ascending domains (averaged within 5°N and 5°S from the location of OLR minima in each region). Only winter HCs of both seasons are considered. The triangles denote values of the southern hemisphere HCs during JJA, and circles denote values of northern hemisphere HCs during DJF.

Further, long-term variability of all regional HCs were examined for the period extending from 1979 to 2021 to assess whether the long-term variability of individual regional HCs is interdependent or whether they evolve independently (Fig.2.10). Additionally, the evolution of zonal-mean HC strength was also compared with the strength of each regional HC in order to understand whether the trends and variability of the zonal-mean HC reported in previous studies are influenced by specific regional HCs. For this analysis, the Southern Hemisphere branch during boreal summer was considered, as all the regional HCs are generally stronger and more well-defined in this season compared to boreal winter (Fig.2.4). The HC indices were computed using the mass streamfunction framework, with the strength of the southern branch of each regional HC quantified as the maximum amplitude of the streamfunction within the southern

hemispheric tropical latitudes. It was observed that most of the regional HCs fluctuate independently in the long-term, with very weak correlation (~ 0.2) among them (Fig.2.10). However, the South American (SAHC) and the Atlantic Hadley Cell (ATHC) show a close long-term covariability, with a correlation coefficient of approximately 0.5. Furthermore, the East Pacific Hadley Cell (EPHC) closely follows the temporal evolution of the zonal-mean HC, exhibiting strong correlations of about 0.8. This indicates that the variability of the East Pacific HC has likely played a dominant role in shaping the long-term trends and variability of the zonal-mean Hadley Cell reported in previous studies (Mitas and Clement, 2006; Stachnik & Schumacher, 2011; Zaplotnik et al., 2022). These results highlight the importance of considering regional HC contributions when interpreting global Hadley circulation features, rather than relying solely on global indices.

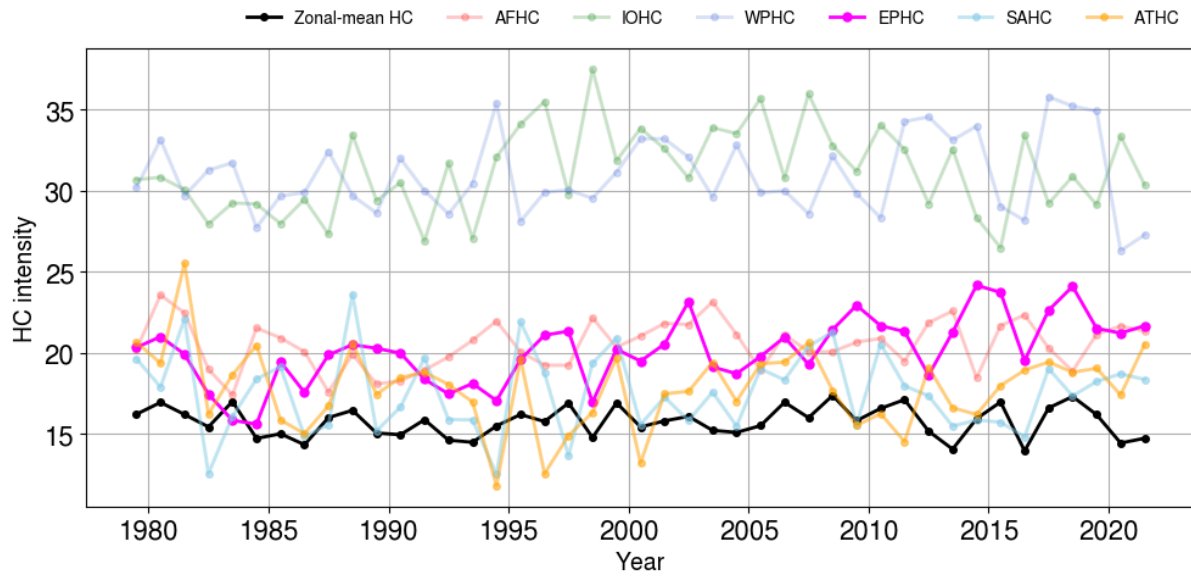


Fig.2.10. Time series of the MSF-based zonal-mean HC strength index and regional HC strength indices over Africa (AFHC), the Indian Ocean (IOHC), the western Pacific (WPHC), the eastern Pacific (EPHC), South America (SAHC), and the Atlantic (ATHC) for boreal summer (JJA) during the period 1979–2021 obtained using ERA5 reanalysis data. (Units: 10^{10} kg/s)

2.4. Summary and Conclusions:

This chapter provides a comprehensive analysis of the regional Hadley circulations across six major longitudinal sectors—Africa, the Indian Ocean, the western Pacific, the eastern Pacific, South America, and the Atlantic—aimed at understanding their seasonal as well as long-term variability, structural differences, and association with ITCZ convection. The division of these domains is motivated by contrasts in convective activity and geographic characteristics, which together shape the nature of the regional overturning circulations.

The climatological structure of the regional Hadley circulations exhibits distinct seasonality and clear variations among different regions. During boreal winter (DJF), the Northern Hemisphere branches dominate in most sectors, with the Western Pacific Hadley circulation displaying the greatest meridional and vertical extent due to its location within the deep convective warm pool. In contrast, the Eastern Pacific and Atlantic Hadley circulations, both situated over tropical cold-tongue regions, exhibit the weakest overturning. During the equinoctial seasons (MAM and SON), the two hemispheric branches become nearly symmetric in size and strength, with ascent near the equator. In boreal summer (JJA), the Hadley circulations shift northward following the seasonal migration of the ITCZ, with the Indian Ocean and Western Pacific Hadley circulations showing the largest poleward displacement of ascent (up to $\sim 25^\circ\text{N}$), primarily driven by strong monsoonal convection over South and East Asia. Meanwhile, the Eastern Pacific and Atlantic Hadley circulations maintain ascent near $\sim 10^\circ\text{N}$ throughout the year, reflecting the persistently northward position of the ITCZ in these regions, and both exhibit a strengthening during boreal summer. Additionally, the analysis demonstrates that the structural characteristics and intensity of regional Hadley circulations are strongly governed by the seasonal migration of the ITCZ, the distribution of deep convection, and the influence of monsoonal dynamics in specific regions. It is also observed that long-term variations of the regional Hadley circulations are largely independent. However, the Eastern Pacific Hadley circulation shows a remarkably similar temporal evolution to the zonal-mean Hadley circulation, suggesting that variability in the Eastern Pacific sector has likely contributed substantially to the trends and variability of the zonal-mean Hadley circulation reported in previous studies.

Thus, this chapter underscores the importance of adopting a regional perspective when

examining the Hadley circulation. Regional Hadley circulations exhibit distinct structural features, seasonal behavior, and long-term variability that are obscured in the zonally averaged global Hadley circulation, and can provide a clearer understanding of how localized processes collectively shape the variability and long-term evolution of the global overturning circulation.

Chapter 3

Impact of the Indo Pacific warm pool intensification and expansion on the strength of Regional Hadley Circulations over the Pacific Ocean

3.1. Introduction:

Analysis of the characteristics of the regional Hadley Cells in the previous chapter reveals contrasting features in the strength and extent of the HCs and how the strength of convection over the ITCZ which modulates the HC intensity, varies regionally and seasonally. Two regional HCs over the same basin are particularly interesting as they exhibit very different characteristics, viz., the Western and Eastern Pacific HCs. Western Pacific HC exhibits the strongest intensity as well as largest meridional and vertical extent among all the regional HCs. In contrast, the Eastern Pacific HC exhibits the weakest and shallowest overturning. The observed differences in these regional HCs may be primarily attributed to the zonal distribution of SST over the Pacific. The strength and extent of the regional HCs are highly sensitive to the underlying tropical SST distribution, since warm surface temperature is a requisite condition for destabilizing the tropospheric column and instigating convection (Graham & Barnett, 1987; Waliser & Graham, 1993). A distinctive feature over the tropical Pacific is the zonal asymmetry in the SST distribution. The equatorial western Pacific, commonly referred to as the *warm pool*, exhibits the highest SSTs on the planet, often exceeding 28°C. In contrast, the equatorial eastern Pacific, known as the *cold tongue*, remains several degrees cooler despite lying at the same latitude. This persistent temperature difference primarily results from the influence of easterly trade winds and equatorial upwelling over the east Pacific. As noted in the previous chapter, the western Pacific warm pool, characterized by vigorous and persistent deep convective activity (Yan et al., 1992; Oberhuber, 1988; De Deckker, 2016; Kerns & Chen, 2016), supports a strong and deep regional Hadley circulation; whereas the eastern Pacific cold tongue, marked by lower SSTs and shallow convection features a comparatively weaker and shallower HC. Along with the meridional overturning circulations, the pronounced east-west thermal contrast in the basin also

gives rise to a zonal overturning atmospheric circulation, known as the Walker circulation (Walker, 1924; Bjerknes, 1969). Overall, these large scale circulations mainly define the tropical Pacific climate state and through the associated heat and moisture transport, the equatorial Pacific plays a fundamental role in regulating the global climate variability. Multiple studies have demonstrated that variations in warm Pool SSTs can exert a significant influence on the zonal-mean Hadley circulation through convective heating and moist static energy fluxes (Gadgil et al., 1984; Huang and Mehta, 2004; Diaz and Bradley, 2004; Xiaoqing et al., 2015; Feng et al., 2011). Observational evidence from recent decades indicates that the warm pool has undergone pronounced intensification and spatial expansion (Alory et al., 2007; Rao et al., 2012; Dong et al., 2014; Kidwell et al., 2017), driven by a combination of anthropogenic forcing and natural climate variability (Hoyos and Webster, 2012; Dong et al., 2014; Roxy et al., 2014; Park et al., 2022). Concurrently, several studies have reported an increase in both the frequency and intensity of El Niño events, which has been linked to changes in warm pool structure and extent (Sun, 2003; Eisenman et al., 2005; Cai et al., 2014; Lee et al., 2020; Gu et al., 2025). Quantitative estimates by Roxy et al. (2014) suggest that warming of tropical SSTs has resulted in a near doubling of the Pacific warm pool area, expanding from approximately 2.2×10^7 km² during 1900–1980 to nearly 4×10^7 km² over the period 1981–2018. This rapid expansion around 1980 coincides with a documented global SST regime shift (Levitus et al., 2009; Rhein et al., 2013; Reid et al., 2016). Several studies have further identified abrupt changes in tropical atmospheric circulation during this period, attributing them to a large-scale reorganization of the tropical climate system associated with warm pool expansion (Chen et al., 2002; Ma and Li, 2008; Feng et al., 2011, 2013). Studies (Wang & Mehta, 2008; Feng et al., 2011) have also identified a transition in the zonal-mean Hadley Cell during the late 1970s, synchronous with the intensification of the Indo-Pacific warm pool.

Collectively, these studies point to a climate regime shift around 1980 that not only transformed the thermal structure of the Pacific Warm Pool but also reorganized large-scale Hadley circulation. Since the regional HCs over the Pacific, primarily owe their differences to the amplitude and distribution of SST over the Pacific, the responses of the western and eastern Pacific regional Hadley cells to the 1980s shift in Pacific climate presents an interesting problem which demands further investigation. In this chapter the regional HC variations over the Pacific are contrasted and studied for the pre-1980 and post-1980 period, focusing on the aspect of

SST-convection coupling which may be very critical for understanding the large-scale circulation responses to background SST changes.

3.2. Data and methodology:

The primary datasets used in this study include the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data (Rayner et al., 2003), obtained from the Met Office Hadley Centre, with a horizontal resolution of $1^\circ \times 1^\circ$ for the period 1940–2021. Monthly mean temperature, zonal, meridional, and vertical wind velocities were taken from the ERA5 reanalysis (Hersbach et al., 2020), at $1^\circ \times 1^\circ$ horizontal resolution and at 11 pressure levels ranging from 1,000 hPa to 50 hPa over the same period. Additionally, the mean top-of-atmosphere net longwave radiation flux from ERA5 was used as a proxy for convection.

3.3.Results:

The climatological structures of the west Pacific Hadley cell (WPHC) and east Pacific Hadley cell (EPHC) during the boreal spring season (March–May) are shown in Fig. 3.1. The boreal spring season is considered for the analysis since during the season, the location of peak SSTs, intense convective activity, and Hadley cell ascent are stationed over the equatorial oceanic regions. Both the Northern and Southern Hemisphere branches of all the regional HCs are well developed and possess comparable strength, unlike in DJF or JJA, when the summer hemispheric HC branch is relatively weaker than the winter HC branch (Figs. 2.2 & 2.4). The regional HCs are identified by using the regional mass stream function (MSF) based on the divergent component of the meridional flow (Li et al., 2023; Schwendike, 2014; Zhang & Wang, 2013) (method described in Chapter 2), over the zonal domain ranging from 110° E to 170° E defining the WPHC and 170° W to 110° W defining the EPHC. The strength of the HCs is defined as the amplitude maximum of MSF over the latitudes extending from the ascending to the descending regions of HC. The WPHC is found to exhibit greater intensity and broader meridional and vertical extent than the EPHC. The WPHC shows a robust, deep overturning structure that extends well into the upper troposphere, while the EPHC is shallow, confined to the lower and middle troposphere. While the boreal spring WPHC is centered over equator and in both hemispheres it extends to around 40° latitudes, the EPHC ascent is observed at 5° N and both branches exhibit a width of about 20° , half of the HC width observed over the WP. This

contrast is attributed to the differences in the convective regimes prevalent over the two regions. The Western Pacific warm pool, harbors some of the warmest ocean waters on the planet, with the SST often exceeding 28°C , and is a region of deep convective activity. In contrast, the equatorial eastern Pacific, remains several degrees cooler, and the conditions are mostly not favorable for deep convection. The prevalence of stratocumulus clouds over the region are indicative of shallow convection and a shallow meridional circulation is observed in the climatology. Nevertheless, studies indicate that the east Pacific features a distinctive meridional overturning (Philander, 1990; Klein and Hartmann, 1992) circulation consisting of both shallow and deeper meridional return flow (Trenberth et al., 2000; Zhang et al., 2004, 2008; Huaman & Schumacher, 2018), as deep convection may develop over the region due to wave induced low-level convergence (Huaman et al., 2021, Yokoyama and Takayabu, 2012). This aspect of the EPHC is dealt with in more detail in Chapter 4 of the thesis.

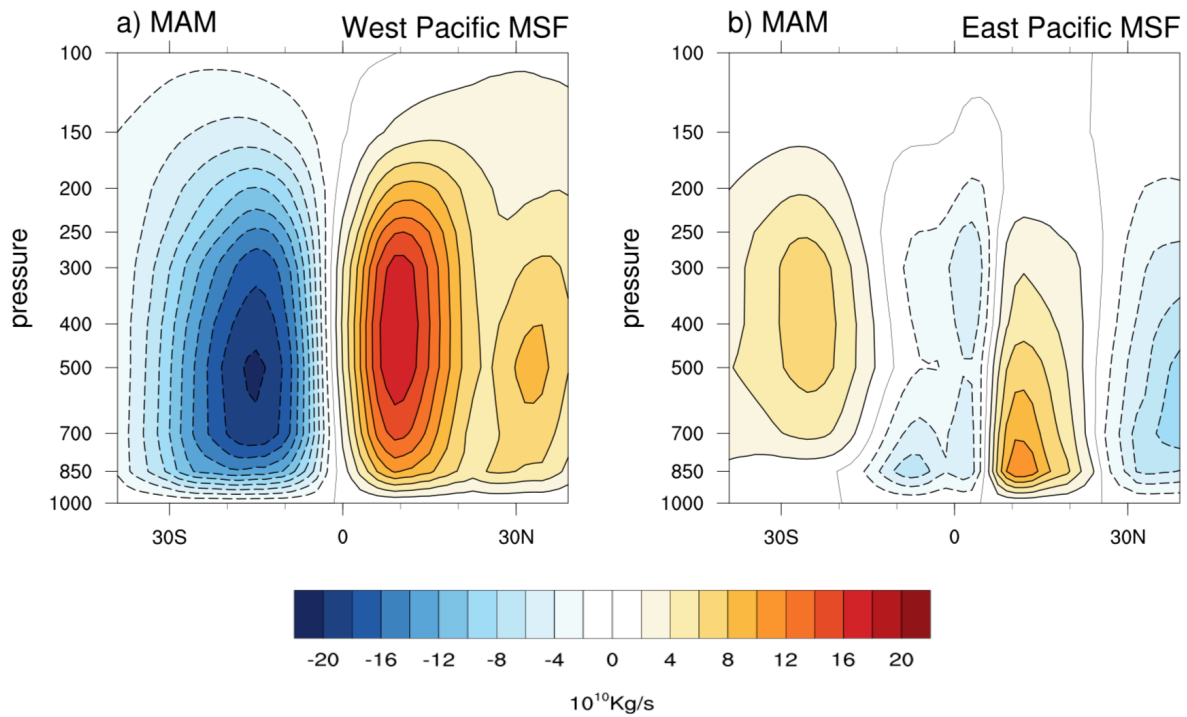


Fig.3.1. The climatological structures of the boreal spring (a) West Pacific HC and (b) East Pacific HC represented by mass streamfunction (MSF) averaged over the west Pacific longitudes (110°E – 170°E) and east Pacific longitudes (170°W – 110°W), respectively. (Units: 10^{10} kg/s). Solid (dotted) contours denote clockwise (anti-clockwise) rotation.

Before analyzing the long term changes in the two regional HCs, the variations in the SST conditions over the two domains are examined in Figure 3.2. Seasonal mean (March-May) SST values are area-averaged over the western (20°S – 20°N , 110°E – 170°E) and eastern (20°S – 20°N , 170°W to 110°W) Pacific sectors for the period from 1940–2021. It is interesting to note a distinct regime shift in the regional SSTs over the two domains around 1980 (Fig. 3.2), consistent with earlier studies which reported a large-scale reorganization of the Pacific SST pattern during that time (Rhein et al., 2013; Reid et al., 2016). Both regions show a pronounced warming trend, with substantially higher SSTs in the post-1980 period as compared to the pre-1980 period. The climatological mean distribution of SST over the Pacific during the pre-1980 and post 1980 period are shown in Figure 3.3 together with the difference in the two climatologies. Consistent with the reported studies, the warm pool intensification and eastward expansion is evident in the figure. The difference plot between the two mean fields (Figure 3.3c), highlights an enhancement of SSTs in the post 1980 period, is not restricted to just the Western Pacific warm pool, but is observed all throughout the Pacific basin. Positive SST anomalies are observed over a broad region of the eastern Pacific domain and the amplitude is comparable to the warm anomalies over the western Pacific. According to the Clausius–Clapeyron relation, saturation vapor pressure and hence the atmospheric moisture content, increases exponentially with temperature (Graham and Barnett, 1987; Waliser et al., 1993). Consequently, an increase in SST can contribute to destabilizing the tropospheric column and instigating more intense convective activity. Given the prominent role of tropical SSTs in driving the atmospheric convection which maintains the Hadley Circulation, the observed trends in the SSTs are also expected to reflect in the variations in the regional HC strength over the two domains. Long term evolution of the regional HC strength over the two domains for the period from 1940 to 2021 is shown in Figure 3.4. To capture the temporal evolution of ITCZ convective strength during the period, an OLR index calculated by averaging the OLR values over a $\pm 5^{\circ}$ latitude band centered over the location of the OLR minima over the ascending domains of each regional HC is also shown along with the MSF based HC strength index. Only the intensity of the NH branch of the regional HCs are shown as both the branches exhibit highly coherent variability and similar trends.

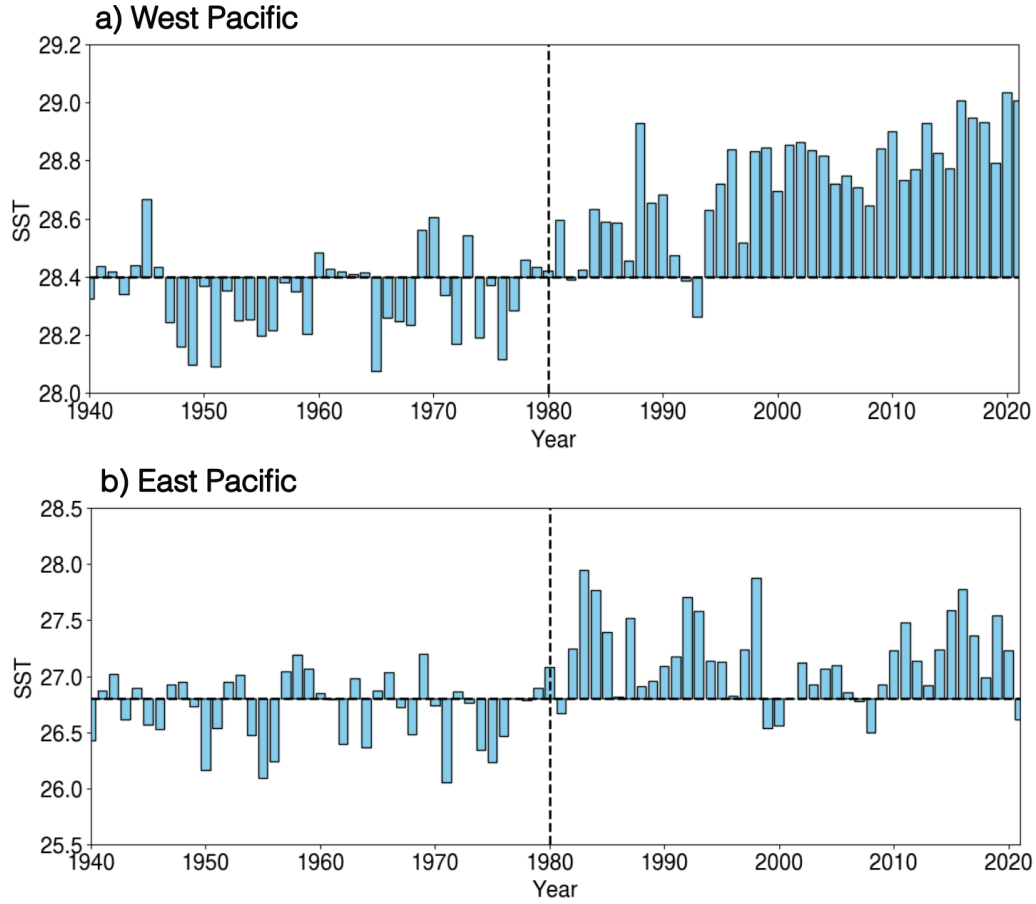


Fig.3.2. Time series of area-averaged SSTs over the (a) western (20°S – 20°N , 110°E – 170°E) and (b) eastern (20°S – 20°N , 170°W – 110°W) Pacific oceans for the period from 1940 to 2021 during boreal spring.

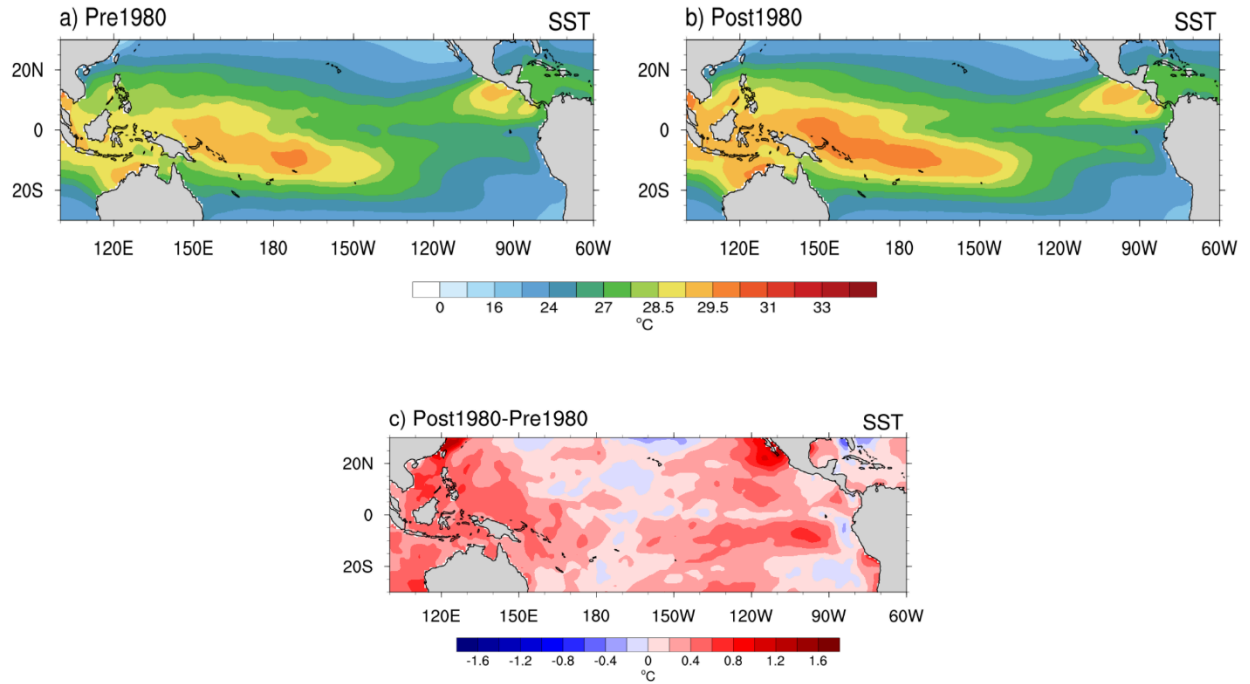


Fig.3.3. Sea surface temperature (SST) over the Pacific Ocean during (a) the pre-1980 and (b) post-1980 periods in boreal spring. Panel (c) shows the SST difference between the post-1980 and pre-1980 period

Long term evolution of the strength of the two regional HCs over the Pacific sector exhibits an interesting pattern (Figure 3.4). While the EPHC exhibits a systematic strengthening during the post-1980 period, no notable change is observed in the strength of the WPHC between the pre- and post-1980 periods. The increased EPHC strength in the post-1980 period is also consistent with the increased amplitude of the OLR index, as compared to the pre-1980 period, indicating stronger convection over the domain. The difference in HC strength during the two periods is further confirmed by analysing the differences in the regional mass stream function field (Figure 3.5 and 3.6). The climatological mean MSF at 500hPa over the Pacific domain, for the pre-1980 and post-1980 periods and their differences are shown in Figure 3.5. The difference field (Figure 3.5c) clearly brings out increased positive and negative amplitudes of MSF over the Eastern Pacific on either side of the equator, indicative of a stronger meridional overturning over the region during the post-1980 period. Meanwhile, little or no change is observed over the West Pacific between the pre- and post-1980 periods. The latitude–height cross sections of regional meridional stream function field over the two domains (Fig. 3.6) further highlight these

contrasting responses. The regional HC over the West Pacific shows no appreciable change in either vertical extent or intensity during the two periods, while the East Pacific Hadley cell displays a pronounced amplification in both intensity and vertical extent during the post-1980 period. It is interesting to note that despite a significant warming trend observed over the western Pacific warm pool, the WPHC remains mostly unchanged, whereas the EPHC strengthens considerably, in tandem with the rising SSTs over the region. This asymmetry suggests that the EPHC is perhaps more sensitive to regional SST variations. This contrasting evolution in SST and HC strength highlights the influence of differing thermodynamic and dynamic processes and underscores the need to examine how the variations in SST patterns modulate the regional Hadley cell strength.

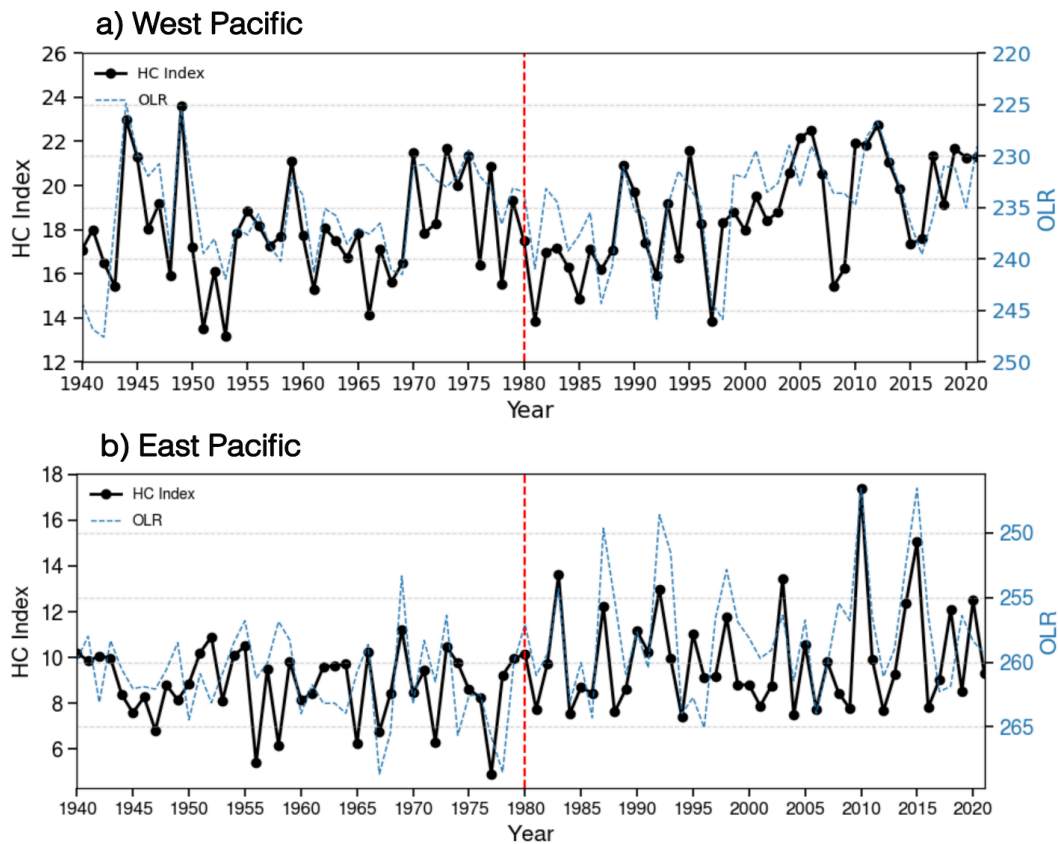


Fig.3.4. Time series of the MSF-based regional HC indices (black line) and OLR-index (blue dashed line) over a) West Pacific and b) East Pacific for the boreal spring season (MAM) from 1940 to 2021.

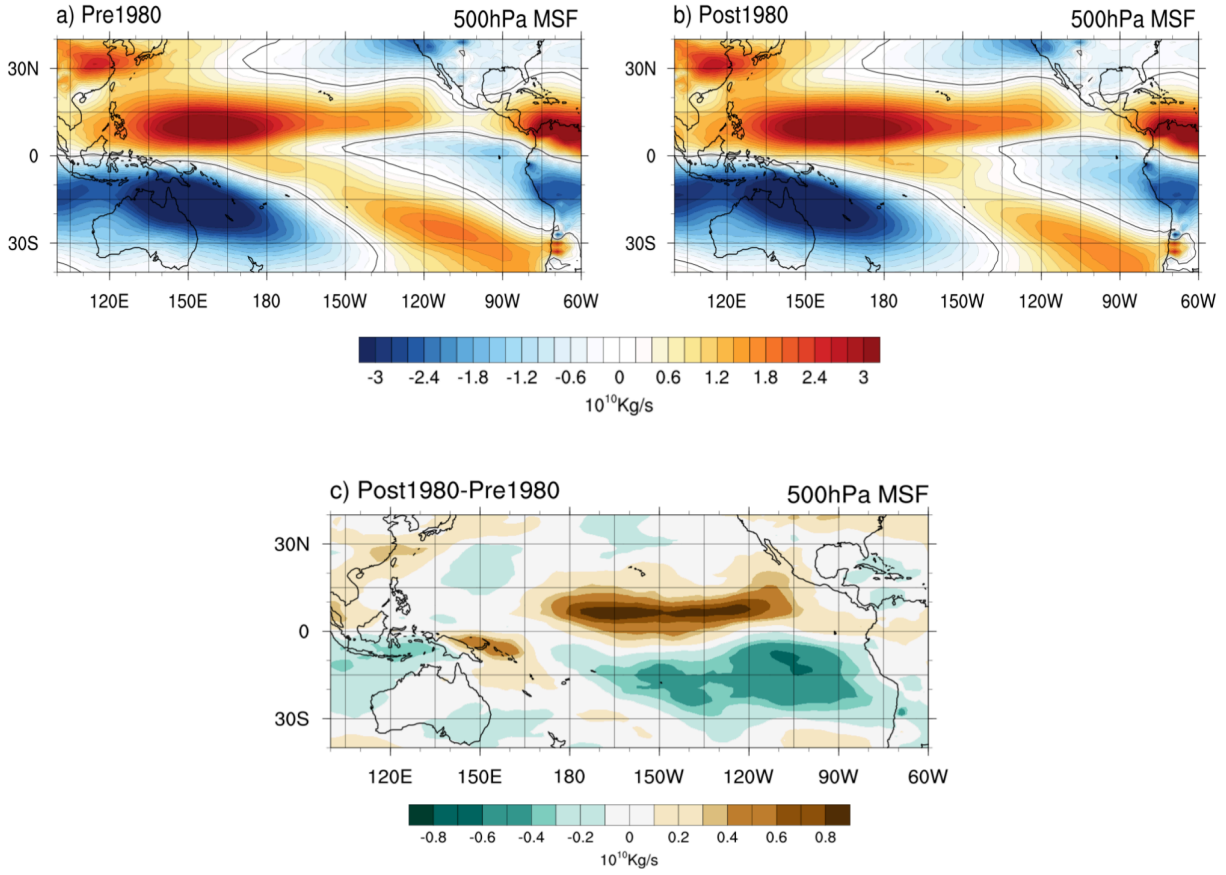


Fig.3.5. Horizontal distribution of the mass streamfunction (MSF) at the 500 hPa level during (a) the pre-1980 and (b) post-1980 periods for boreal spring. Positive and negative values represent the Northern and Southern Hemisphere branches, respectively, of the regional Hadley cells. (c) shows the difference between the post-1980 and pre-1980 periods. (units: 10^{10} kg/s)

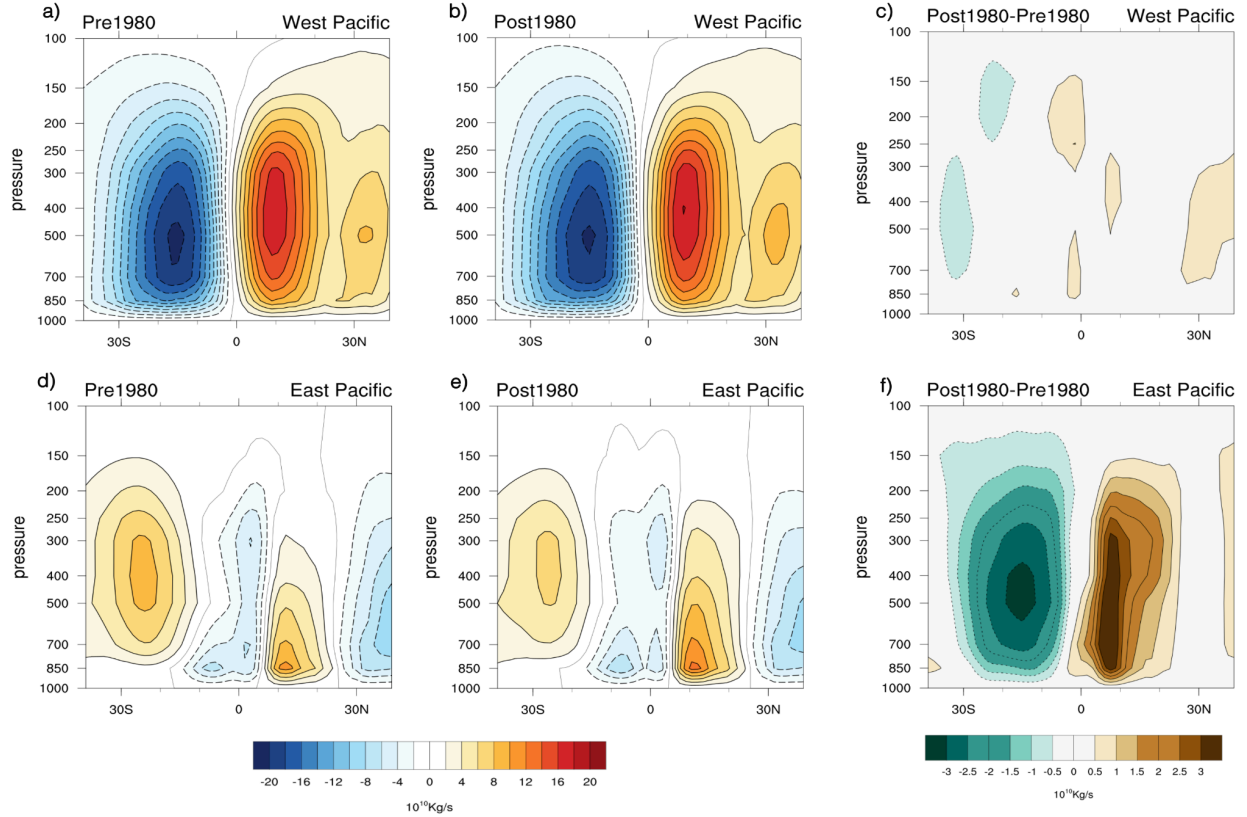


Fig.3.6. Latitude–height cross sections of the mass stream function for the West Pacific (a–c) and East Pacific (d–f) regions during (a, d) pre-1980 period, (b, e) post-1980 period, and (c, f) differences between the post-1980 and pre-1980 periods for boreal spring. Solid (dotted) contours denote clockwise (anticlockwise) circulation. (Units: 10^{10} kg/s)

As demonstrated in the previous Chapter, the strength of the regional HCs are majorly driven by ITCZ convection in the respective sectors, which in turn is strongly coupled to the SST background state. Beyond the direct thermodynamic influence of SST–convection coupling, the zonal and meridional gradients in SST plays a critical role in determining the moisture convergence in the boundary layer which is essential for instigating deep convection (Lindzen and Nigam, 1987, Back & Bretherton, 2009; Yokoyama & Takayabu, 2012). As the tropical atmosphere is conditionally unstable, warming and moistening of the air column over the tropical oceans can readily give way to the development of deep convection. Although it might seem that the convection strength would linearly increase with SST, that is not the case, and the SST–convection relationship is rather non linear. Waliser et al (1993), examined the SST–convection relationship in the global tropics using OLR data and identified an SST

threshold for deep convection as 26.5°C . For a range of temperature above the SST threshold, convection strength increased with increase in temperature. But for higher temperatures above 29°C , the strength of convection decreased with increase in temperature. In a follow up study, Sabin et al., 2013, examined the SST-convection relationship and their variations over different regional sectors in the tropics. They reported that while the non-linear SST-convection relationship is prevalent over the western Pacific warm pool, an almost linear relationship is observed over the Eastern Pacific. This difference stems from the widely different SST conditions that prevail over the western and eastern equatorial Pacific domains. While the SST over most of the warm pool region exceeds 28°C , the temperatures are on the lower side over the eastern Pacific and are mostly not favorable for deep convection. The observed increase in SST over both the domains during the post-1980 period, hence would have different implications on the SST-convection relationship over the regions. As the ITCZ deep convection strength has a strong bearing on the regional HC intensity, understanding the SST-convection relationship over the regional domains would provide critical insights for decoding the observed changes in the regional HCs.

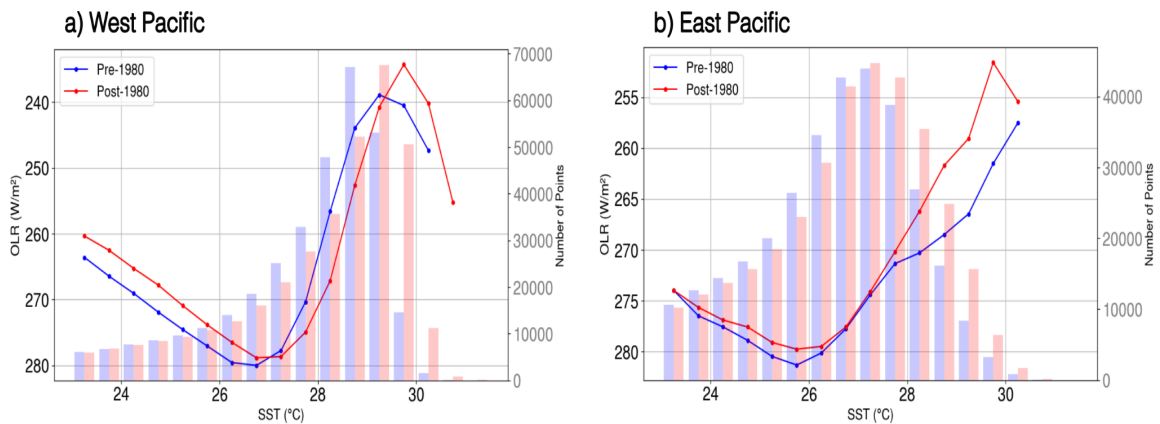


Fig.3.7. Relationship between SST and convection over the (a) West Pacific (20°S – 20°N , 110°E – 170°E) and (b) East Pacific (20°S – 20°N , 170°W – 110°W) for the pre-1980 (blue line) and post-1980 (red line) periods during boreal spring. Monthly mean OLR values are averaged for each 0.5°C SST bins and plotted as a function of SST. The number of data points contributing to each bin for the pre-1980 (blue bars) and post-1980 (red bars) periods is shown along the right vertical axis.

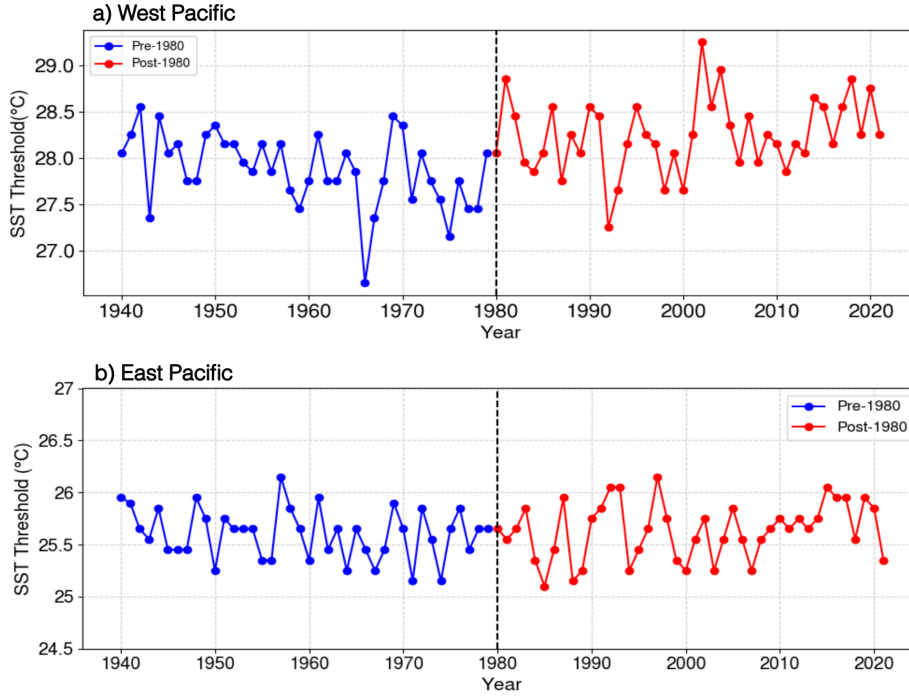


Fig.3.8. Time series of SST thresholds for the onset of deep convection over (a) the West Pacific and (b) the East Pacific during the period 1940–2021 for boreal spring. The threshold for each year is defined as the minimum SST at which the mean OLR falls below 280 W m^{-2} for at least three consecutive SST bins, representing the onset of deep convective activity.

The SST-convection relationship over the western and eastern Pacific domain during the pre-1980 and post-1980 periods are examined using monthly mean values of SST and OLR (Fig.3.7). The average OLR value corresponding to each 0.5°C SST bin was calculated over the domains 20°S – 20°N , 110°E – 170°E and 20°S – 20°N , 170°W – 110°W for the boreal spring seasons. The number of data points contributing to each bin are indicated by the bars. Consistent with previous studies (Waliser 1993; Sabin 2013), three distinct regimes of SST–convection relationship are evident over West Pacific: weak convection at low SSTs, a rapid intensification of convection beyond a critical SST threshold, and a saturation regime at higher SSTs, where convective strength decreases with increase in SST. (Fig.3.5(a)). The SST threshold for deep convection is found to increase from approximately 26.5 – 27°C during the pre-1980 period to 27 – 27.5°C during the post-1980 period. In contrast, no significant change is observed in the SST threshold for deep convection over the East Pacific (Fig.3.7b). The finding is further validated by examining the time series of SST threshold for deep convection over the two domains, during the

pre-1980 and post 1980 periods (Figure 3.8). For each year, the SST threshold for deep convection was identified as the lowest SST value corresponding to which, the mean OLR value is less than 280 W/m^2 . An additional requirement that the OLR remains below 280 W/m^2 for at least three consecutive SST bins was also imposed to ensure a robust identification of the SST threshold. The value of 280 W/m^2 is chosen as indicative of deep convection as it marks the beginning of the linear regime in the SST-convection relation over both domains (Figure 3.7). Over the West Pacific, a gradual upward shift in the convective threshold is observed in the post-1980 period, indicating that progressively higher SSTs are now required to trigger deep convection (Figure 3.8a), while over the East Pacific, the SST threshold does not exhibit any such trend (Figure 3.8b).

Another surprising and intriguing aspect in the SST- convection relationship over the western Pacific is the observation that for the SST range above the threshold, where convection increases with SST linearly, the same SST value is found to produce a higher OLR value (weaker convection) in the post-1980 period as compared to the pre-1980 period (Figure 3.7). It means that progressively higher SSTs are now required to initiate deep convection over the western Pacific in recent decades. This upward shift partly explains why the West Pacific Hadley Cell does not exhibit an intensification corresponding to the SST warming trend observed over the region in recent decades. In contrast, no significant change is observed in the SST threshold for deep convection over the East Pacific (Fig.3.7b). During the post-1980 period, a significant increase is noted in the number of data points corresponding to SST above 28°C , consistent with the warming observed over the region, and substantially stronger convection (lower OLR values) is observed in the SST range above the threshold. These findings point to a strengthening of the SST–convection coupling in the post-1980 period over the East Pacific, where warmer SSTs more efficiently promote deep convection. This enhanced convective response is consistent with the observed intensification of the East Pacific Hadley Cell, suggesting that increased convective efficiency under warmer conditions has contributed to its recent strengthening.

In short, the examination of the change in the SST-convection relationship over the western and eastern Pacific domains indicate that in the recent decades, while the West Pacific now requires higher SSTs to initiate deep convection, the East Pacific has become more conducive for deep convection. But the question remains, as to why the SST threshold for deep

convection has increased over the Western Pacific, while it has remained unchanged over the east Pacific. This can be understood in terms of the moist adiabatic lapse rate (MALR) adjustment framework Johnson and Xie (2010). According to the MALR adjustment framework, as surface temperatures rise, the upper troposphere also warms to preserve a moist-adiabatic temperature profile. This enhanced upper-tropospheric warming implies an increasingly stable tropical troposphere, leading to a gradual reduction in large-scale rising motion as the atmosphere approaches a more stable, moist-neutral state under sustained surface warming. Using high-resolution global climate model experiments, Johnson and Xie (2010) demonstrated that adjustments in the MALR can regulate the SST threshold for convection in tropical systems.

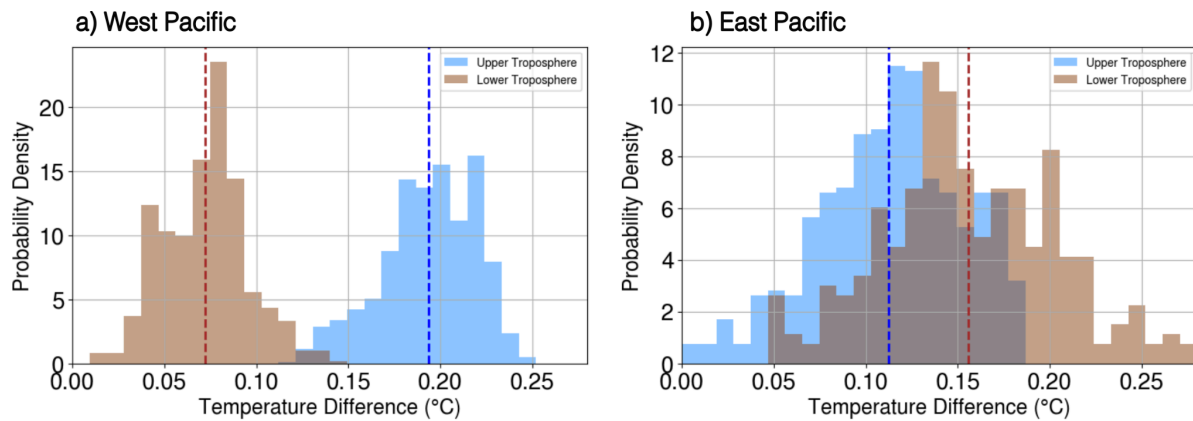


Fig.3.9. Differences in mean temperatures of the upper troposphere (blue bars; 200–400 hPa) and lower troposphere (brown bars; 850–700 hPa) between the post-1980 and pre-1980 periods during boreal spring over the ascending regions of (a) the West Pacific Hadley Cell and (b) the East Pacific Hadley Cell.

To verify whether MALR adjustment is the limiting factor which leads to the increase in SST threshold for deep convection over the Western Pacific, the upper-tropospheric (200–400 hPa) and lower-tropospheric (850–700 hPa) temperature changes between the post-1980 and pre-1980 periods, were examined over the ascending regions of the WPHC and EPHC (Figure 3.9). The analysis shows that, over the West Pacific, the upper troposphere has warmed more rapidly than the lower troposphere during the post-1980 period (Fig.3.9(a)). This disproportionate warming in the upper levels supposedly increases the static stability, swinging the atmospheric temperature profile toward a more stable configuration. Consequently, higher SSTs are now required to overcome the enhanced stability and initiate deep convection over the

region—consistent with the observed upward shift in the SST threshold for convection. The findings are in agreement with Kim et al. (2023) who analyzed historical data and future climate simulations and observed that upper-tropospheric temperatures are rising faster as compared to the surface temperatures, particularly over the Indo-Pacific Warm Pool. Over the East Pacific, on the other hand, the upper- and lower- troposphere has warmed by similar magnitude (Fig.3.9b). Since the MALR adjustment is not limiting the instability build up over the domain, the tropospheric column is driven more unstable by the SST warming in the recent decades leading to enhanced convective activity. In short, analysis of the SST-convection relationship over the western and eastern Pacific domains in the pre-1980 and post 1980 periods indicate, that while an SST warming is observed over both sectors, a much larger increase is observed in the upper tropospheric temperatures over the western Pacific, than over the eastern Pacific. The MALR adjustment has contributed to stabilizing the tropospheric column over the west Pacific which has led to an increase in the SST threshold for convection over the region. Thus, while the deep convection strength increases in response to the increase in SST over the eastern Pacific, a corresponding increase in convective strength is not observed over the warm pool. The results provide an explanation as to why the east Pacific Hadley Cell exhibit significant strengthening in the post-1980 period, while no such strengthening is observed in the case of the west Pacific Hadley Cell.

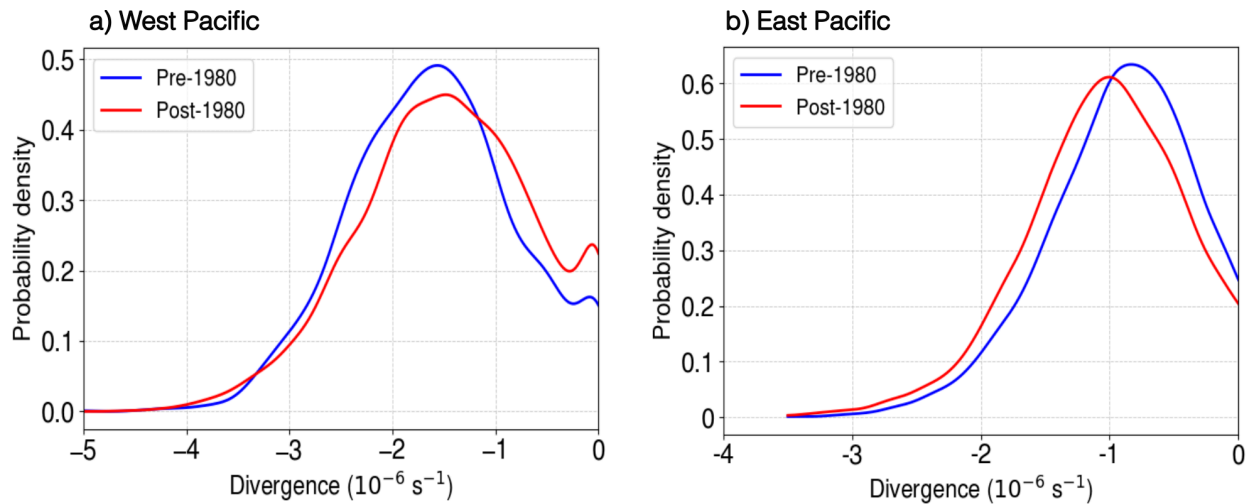


Fig.3.10. Probability distribution of low-level (850 hPa) convergence over the ascending regions of (a) the West Pacific and (b) the East Pacific Hadley Cells during the pre-1980 (blue line) and post-1980 (red line) periods for boreal spring. Units: 10^{-6} s^{-1}

Beyond the direct thermodynamic influence of SST–convection coupling, the zonal and meridional gradients in SST also play a critical role in determining the moisture convergence in the boundary layer, which is essential for instigating deep convection (Lindzen and Nigam, 1987, Back & Bretherton, 2009; Yokoyama & Takayabu, 2012). To understand the effect of such large changes in boundary layer convergence patterns in regulating the strengths of the regional HCs, the low-level convergence over the ascending regions of the WPHC and EPHC sectors during the pre-1980 and post-1980 periods are examined in Figure 3.10. The probability distribution of the convergence values over the two domains bring out a marked increase in the lower-tropospheric convergence over the East Pacific during the post-1980 period (Fig 3.10 b), indicating that large-scale dynamical convergence has also contributed to the enhancement of convection over the domain, complementing the SST-induced convection. In contrast, over the west Pacific, a noticeable reduction in low-level convergence is evident during the post-1980 period (Fig 3.10 a), implying that the boundary layer moisture convergence driven by SST gradients are in fact becoming less conducive for deep convection generation. This is also in line with the less efficient SST-convection coupling over the domain as seen in the previous analysis. Thus, the contrasting post-1980 evolution of the WPHC and EPHC appears to be a resultant of the combined influence of thermodynamic (SST–convection coupling) and dynamic (mass convergence) changes over the Pacific domain.

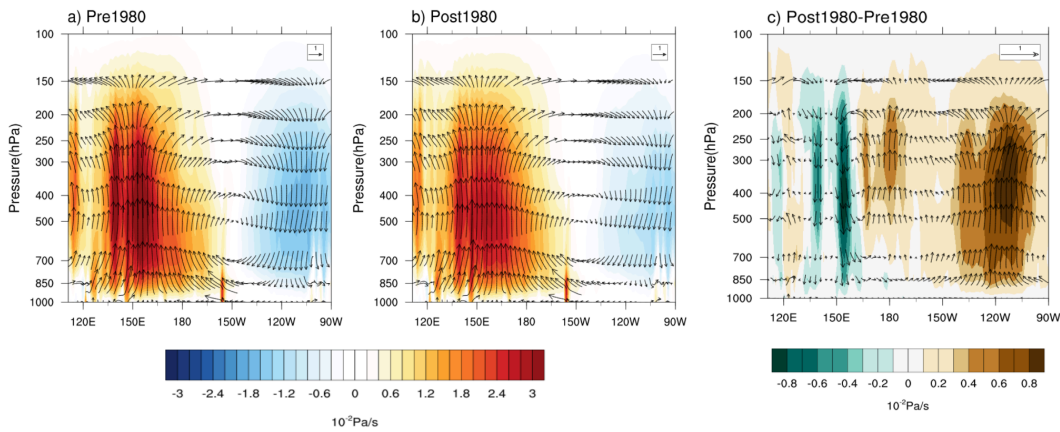


Fig.3.11. Changes in the Walker circulation illustrated using zonal–vertical cross-sections of the zonal-divergent and vertical velocity fields for (a) the pre-1980 period, (b) the post-1980 period, and (c) the difference between the post-1980 and pre-1980 periods. Vectors are the composite of vertical velocity (Pa s^{-1}) and zonal divergent wind (m s^{-1}). Shading represent pressure velocity (Pa s^{-1}) averaged between 5°S and 5°N

Since the low-level convergence over the tropical Pacific is strongly influenced by the Walker circulation, the Pacific zonal circulation is further contrasted for the two periods to understand the observed changes in low level convergences over the two regional HC domains (Fig. 3.11). The climatological mean state of the Pacific Ocean sustains a pronounced east–west SST gradient which drives the Walker circulation, which is characterized by low-level easterly winds, low level convergence and enhanced convective activity over the warm western Pacific, and subsidence and low over the cooler eastern Pacific. Changes in the Walker circulation over the tropical Pacific between the pre-1980 and post-1980 periods are examined in the zonal–vertical cross-sections of the zonal divergent wind field and the vertical velocity fields averaged between 5° N to 5° S (Fig. 3.11). The analysis reveals a weakening of the ascending motion over the western Pacific and a descending motion over the eastern Pacific during the post-1980 period, along with a weakening of the low level easterly winds. This suggests an overall weakening of the Walker circulation in the recent decades, consistent with earlier studies (Vecchi et al., 2007; Han et al., 2006; Yang & Wang, 2009; Tokinaga et al., 2012). Thus, the observed changes in the convergence fields over the two regional HC domains (Figure 3.10) may be largely attributed to the weakening of Walker circulation. And, as the Pacific regional Hadley cells are strongly coupled to the Walker circulation, changes in the moisture convergence associated with the changes in the Walker circulation would in turn reflect in the strength of the regional HCs. The convergence fields may also be modulated by the meridional SST gradients and atmospheric circulation responses associated with disturbances of different spatial and temporal scales. More detailed and region specific focused studies may be required to understand these modulations. An investigation in this direction is carried out in the fourth Chapter, focusing on the Eastern Pacific.

3.4. Summary and Conclusions:

This chapter examined the contrasting evolution of the West Pacific HC and the East Pacific HC in response to tropical ocean warming during 1940 to 2021. With the widespread SST increases across the Pacific, the East Pacific HC underwent a pronounced intensification post-1980, while the West Pacific HC remained nearly unchanged. As the ITCZ deep convection strength has a strong bearing on the regional HC intensity, the SST-convection relationship over the regional domains were examined to understand the observed changes in the regional HCs. The SST–convection relationship demonstrated distinctly different behaviors across the two regions. Over the West Pacific, the SST threshold for convection increased in the post-1980 period, implying that progressively higher SSTs are now required to initiate deep convection compared to pre-1980 period. In contrast, the East Pacific maintained a nearly constant SST threshold throughout the period, due to which warmer SSTs could more effectively promote convective activity. These results indicate that while SSTs over the West Pacific have become less efficient in inducing convection, they have become more efficient over the East Pacific, potentially leading to the observed intensification of the EPHC. The upward shift in the SST threshold for convection over the West Pacific can be understood in terms of the moist adiabatic lapse rate (MALR) adjustment framework. The MALR adjustment has contributed to stabilizing the tropospheric column over the west Pacific which has led to an increase in the SST threshold for convection over the region.

Beyond thermodynamic influences, large-scale dynamical factors are also found to play a key role in strengthening the EPHC. Strengthened low-level convergence in the east Pacific supported deep convection and rising motion in the post-1980 period, reinforcing the EPHC, whereas weakened convergence in the west inhibited convection and limited changes in the WPHC. These dynamical differences are further accompanied by a weakening of the Walker circulation, characterized by anomalous surface westerlies across the central Pacific and reduced subsidence over the eastern Pacific. The weakened Walker circulation facilitated enhanced ascent over the East Pacific and reduced upward motion over the West Pacific, providing an additional mechanism for the asymmetric response of the regional Hadley cells.

Overall, the findings of this chapter indicate that the contrasting evolution of the WPHC and EPHC since 1980 stems from the combined effects of thermodynamic stabilization and

changes in dynamic convergence. Over the western Pacific, atmospheric stabilization associated with moist adiabatic lapse rate adjustment has limited the intensification of convection, while over the eastern Pacific, stronger SST–convection coupling and enhanced dynamical convergence have led to a marked strengthening of the Hadley cell.

Chapter 4

The role of tropical synoptic-scale disturbances in modulating the strength of east Pacific Hadley circulation

4.1.Introduction:

The strength of the Hadley Circulation (HC) is governed by a combination of thermodynamic and dynamic factors that regulate tropical convection and large-scale momentum transport. From a thermodynamic perspective, moist convection plays a pivotal role in determining HC intensity, as emphasized by the “hot towers” hypothesis (Riehl, 1958), which proposes that vertical heat transport within the ascending branch of the HC occurs primarily through deep cumulus convection concentrated within their “protected” cores. Sea surface temperature (SST) and its meridional gradient further exert strong control on HC strength by influencing moist static stability and driving moisture-laden winds within the marine boundary layer (Waliser & Graham, 1993; Lindzen & Nigam, 1987; Back & Bretherton, 2009). Beyond these thermodynamic controls, dynamic processes via large-scale circulation also play a critical role in modulating HC strength. Several studies have demonstrated that momentum flux convergence by midlatitude baroclinic eddies substantially influences the intensity and vertical extent of the HC (Kuo, 1956; Dickinson, 1971; Pfeffer, 1981). Compared to axisymmetric simulations, eddy-permitting models produce significantly stronger circulations, with the HC being up to twice as intense (Becker et al., 1997; Kim & Lee, 2001; Walker & Schneider, 2005). Walker and Schneider (2006) showed that incorporating extratropical eddy momentum fluxes yields a nearly linear relationship between HC strength and the divergence of these fluxes, highlighting the dynamical coupling between tropical and extratropical circulations. Subsequent studies have identified similar eddy influences under solstitial conditions (Caballero, 2007, 2009), and more recent simulations by Davis and Birner (2019) demonstrated that in the absence of extratropical eddy momentum fluxes, the HC cannot efficiently extend to the surface or effectively transport momentum poleward. Eddies within the tropics can also modulate the

strength of the HC, particularly near its ascending branch. The Intertropical Convergence Zone (ITCZ)—the preferred region of HC ascent—is composed of an ensemble of convective disturbances spanning a broad range of spatial and temporal scales (Chang, 1970; Yanai & Murakami, 1970a,b; Wallace & Chang, 1972; Reed & Recker, 1971). For instance, Schwendike et al. (2021) demonstrated that the strength of local Hadley and Walker circulations varies with the phase of the Madden–Julian Oscillation (MJO), the dominant mode of tropical intraseasonal variability. Similarly, Hoskins et al. (2020) and Hoskins & Yang (2021) suggested that fluctuations in tropical moist convection, occurring on timescales from days to months, play an essential role in modulating the HC. A major subset of tropical eddies—convectively coupled equatorial waves—are well known to organize and modulate tropical convection (Kiladis et al., 2009). Since organized convection is fundamental in determining both the location of the ascending branch and the overall strength of the HC, these equatorial waves can exert a significant influence on HC variability. However, despite these insights, the role of tropical eddies in modulating the strength and structure of the HC remains underexplored and warrants detailed investigation.

Therefore, this chapter examines how tropical transient disturbances modulate the strength of East Pacific HC. The east Pacific domain is chosen due to the distinctive prominence of synoptic-scale disturbances in this region, in contrast to other regions such as the western Pacific or Indian Ocean, where a wider range of temporal scales including intra-seasonal and quasi-biweekly oscillations also contribute. Moreover, the East Pacific features a distinctive meridional overturning circulation consisting of both shallow and deeper meridional return flow (Huaman & Schumacher, 2018; Trenberth et al., 2000; C. Zhang et al., 2004, 2008). Although studies (Back & Bretherton, 2009; Lindzen & Nigam, 1987) attribute the shallow meridional flow over the EP to the meridional SST gradients. Yokoyama and Takayabu (2012) suggested that the low-level convergence associated with Mixed Rossby Gravity waves could be one of the important factors which induce deep convection over the East Pacific. Hence, it is worthwhile to investigate the role of tropical synoptic-scale disturbances in modulating the strength of East Pacific HC, as it will advance our understanding of the mean meridional circulation.

4.2.Data and methodology:

The primary datasets used in this study are six-hourly zonal, meridional and vertical pressure velocity data obtained from the ERA5 reanalysis (Hersbach et al., 2020), with a horizontal resolution of $1.5^\circ \times 1.5^\circ$ and 11 pressure levels ranging from 1000 hPa to 50 hPa for the duration 1979 to 2021. For the same time period, NOAA interpolated daily outgoing long-wave radiation (OLR) (Liebmann and Smith, 1996), is also used as a proxy for convection with a horizontal resolution of $2.5^\circ \times 2.5^\circ$. The SST data used in the study are the $1^\circ \times 1^\circ$ horizontal resolution Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data, obtained from the Met Office Hadley Centre (Rayner et al. 2003). For verification of results with satellite observations, cloud area fraction data from the H-series of International Satellite Cloud Climatology Project (ISCCP, <http://isccp.giss.nasa.gov>) also have been used, which is available for the period 1983 to 2017. Classifications of El Niño and La Niña years are based on the 3 month running mean of SST anomalies in the Niño 3.4 region (5°N - 5°S , 120° - 170°W), provided by NOAA's Climate Prediction Center (NOAA-CPC).

The HC is usually defined as the meridional-vertical mass stream function (MSF) all around the globe (Oort & Yienger, 1996). Several recent studies constructed the regional MSF of the HC (Zhang & Wang, 2013, Schwendike et al., 2014) to be used over specific longitude ranges, based on the divergent component of the meridional flow. Under this method the MSF of EPHC, denoted by ψ can be defined as :

$$\psi = \frac{2\pi R \cos\phi}{g} \int_{50 \text{ hPa}}^{1000 \text{ hPa}} [v_d] dp \quad (1)$$

where, R is the radius of Earth, g is the gravitational acceleration. ϕ is the latitude, p is the atmospheric pressure, v_d is the divergent meridional velocity and the square brackets denote zonal average over the east Pacific region, ranging from 170° W to 110° W. The branch of HC extending poleward in the northern (southern) hemisphere will be referred to as the NH (SH) branch. The strength of the NH (SH) branch is determined by the maximum(minimum) value of the MSF within tropical latitudes, extending from the ascending region to the poleward edge.

Given that the EPHC during boreal summer is more well-defined, stronger and deeper compared to boreal winter, the focus of this study will be on examining the factors modulating the strength of EPHC during boreal summer. We consider the strength of the SH branch of the EPHC to represent the overall strength of the EPHC during boreal summer, as the NH branch is nearly absent during this season. The strength of the SH branch is determined by the minimum value of the MSF within tropical latitudes, extending from the ascending region to subtropical latitudes. Further, an EPHC strength index is formulated by averaging the EPHC strength over each boreal summer season from 1979 to 2021. Utilizing the normalized, de-trended MSF-based EPHC strength index for this period, the five strongest and five weakest EPHC seasons were identified as when the EPHC index exceeded +1 and receded -1, respectively.

4.3. Results:

In this study we focus on understanding the factors causing the variability in strength of the EPHC during boreal summer, as the EPHC during this season is more well-defined and stronger compared to that during the boreal winter season. Thus, the variability in the strength of EPHC is examined for 43 boreal summer seasons from 1979 to 2021, using the MSF-based EPHC index (Figures 4.1a). Further, the association between EPHC strength and the strength of moist convection was examined using an OLR index averaged over the ascending region of EPHC (5° – 15° N, 170° – 110° W). A strong correlation (0.65) is observed between the MSF index and the OLR index, highlighting a strong coupling between moist convection and HC strength (Figure 2b). Five strongest (1997, 2002, 2014, 2015, 2018) and five weakest (1984, 1993, 1995, 1998, 2012) EPHC seasons are identified and the remaining analysis is carried out for these two categories of distinctly different EPHC strength (It should be noted that the five strong and five weak EPHC years are also consistent among the different reanalysis data sets (Figure 4.1b). It is expected that such a classification will help in bringing out the role of different factors that affect EPHC strength. Seasonal composites of MSF for the strong EPHC seasons reveal a broad and intense vertical ascent extending up to 150 hPa, and the SH MSF reaching amplitudes of about 25.4×10^{10} kg/s (Figure 4.1c). On the other hand, the weak seasons composite reveals a shallower and narrower ascent extending weakly till 200 hPa. and the amplitude of SH MSF reduced to about 13.6×10^{10} kg/s (Figure 4.1d). The poleward edge of the SH branch of EPHC can be defined as the latitude where the MSF reduces to 20% of the maximum amplitude of MSF

observed within the tropics between 700 and 400 hPa pressure levels. Although the ascent of EPHC occurs near 5° – 10° N in both cases, the poleward edge is located around 20° S during strong seasons and near 15° S during weak seasons. Moreover, the NH branch of EPHC is moderately developed during strong seasons, whereas it is nearly absent during weak seasons. These observations verify the robustness of classifying the EPHC strength based on the MSF-based index.

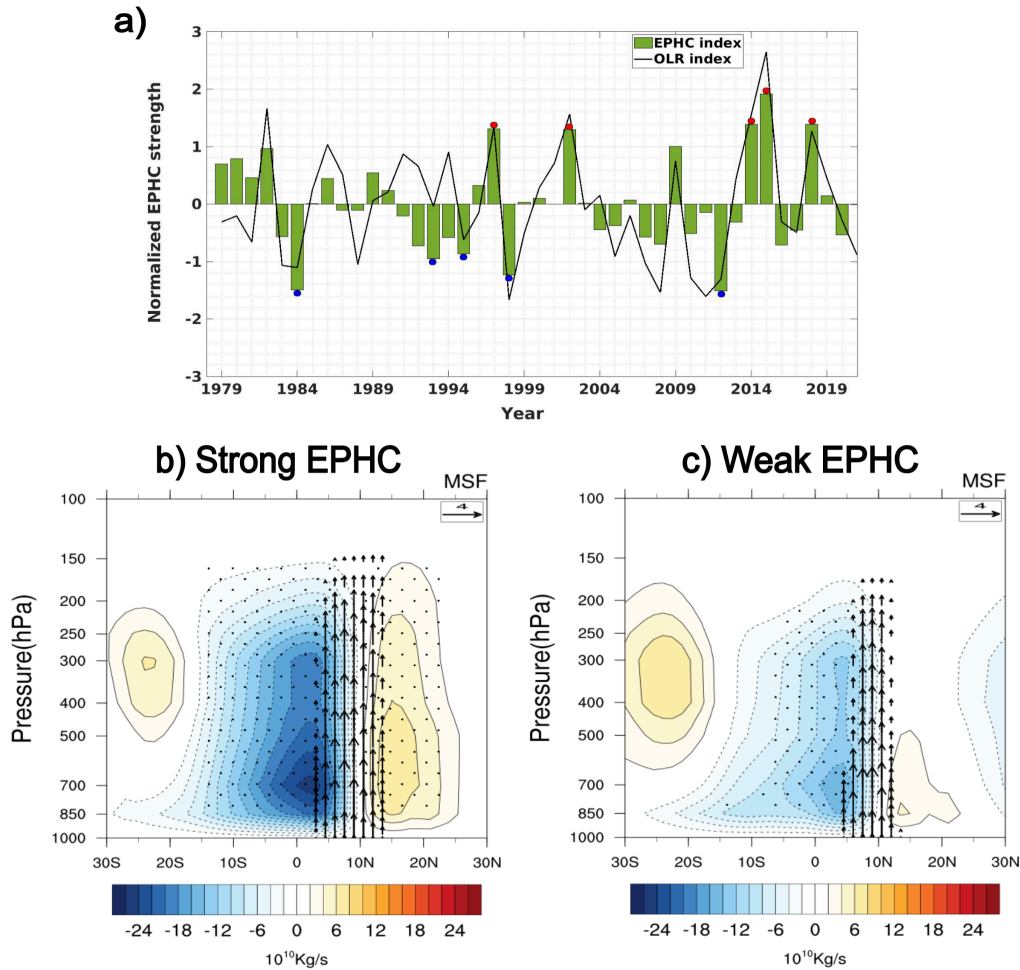


Fig.4.1.(a) Normalized, detrended time series of the MSF-based EPHC index for boreal summer seasons (JJA) from 1979 to 2021 (Green bars). Five strong (weak) EPHC seasons are marked by red (blue) dots. The black solid line denotes the normalized, detrended OLR index (multiplied by -1) averaged over the ascending region of EPHC (5° N– 15° N, 170° W– 110° W). Bottom panels show the composites of MSF (Units: 10^{10} kg/s) for the (b) five strong and (c) five weak EPHC seasons. Solid (dotted) contours denote clockwise (anti-clockwise) rotation. Black arrows indicate upward vertical pressure velocity (Units: 10^{-2} Pa/s). Stippled regions are statistically significant at the 95% confidence level.

However, several studies have noted the limitations of reanalysis data sets over the East Pacific, where the observations are sparse and the reanalysis is mainly reliant on the physical parameterizations in the models (Bretherton, 2007; Huaman et al., 2021). Hence, we use the cloud type and height data from the International Satellite Cloud Climatology Project (ISCCP) to validate the classification of strong and weak EPHC seasons. From the joint histograms of cloud top pressure and cloud optical thickness estimated over the EPHC ascending region (5° – 15° N, 170° – 110° W) (Figure 4.2), it is evident that although deep clouds (with cloud top pressure 440–50 hPa) represent a larger cloud fraction during strong EPHC years (Figure 4.2a), weak EPHC seasons exhibits more shallow clouds (with cloud top pressure 1,000–680 hPa) (Figure 4.2b). This is in accordance with the EPHC vertical ascent observed in the composite analysis (Figures 4.1c and 4.1d). Stronger and deeper vertical ascent during strong EPHC seasons results in the formation of deep clouds, whereas during weak EPHC seasons, the shallower ascent leads to the development of shallow clouds. The consistency between the satellite and reanalysis data based results further validates the separation of strong and weak EPHC seasons and supports the use of reanalysis data for further investigating the major factors which affect EPHC strength. Seasonal composites of OLR and 850 hPa meridional winds during strong and weak EPHC seasons (Figures 4.2c and 4.2d) further brings out a clear distinction in the large-scale convection and circulation patterns over the EP confirming the effectiveness of the classification. Although enhanced lower-level wind convergence and convection is observed over the EP during strong EPHC seasons, weak EPHC seasons are marked by reduced lower-level wind convergence and convection. Interestingly, the convective region is meridionally broader during strong seasons compared to weak seasons, aligning with the broader zone of vertical ascent observed in Figure 4.1.

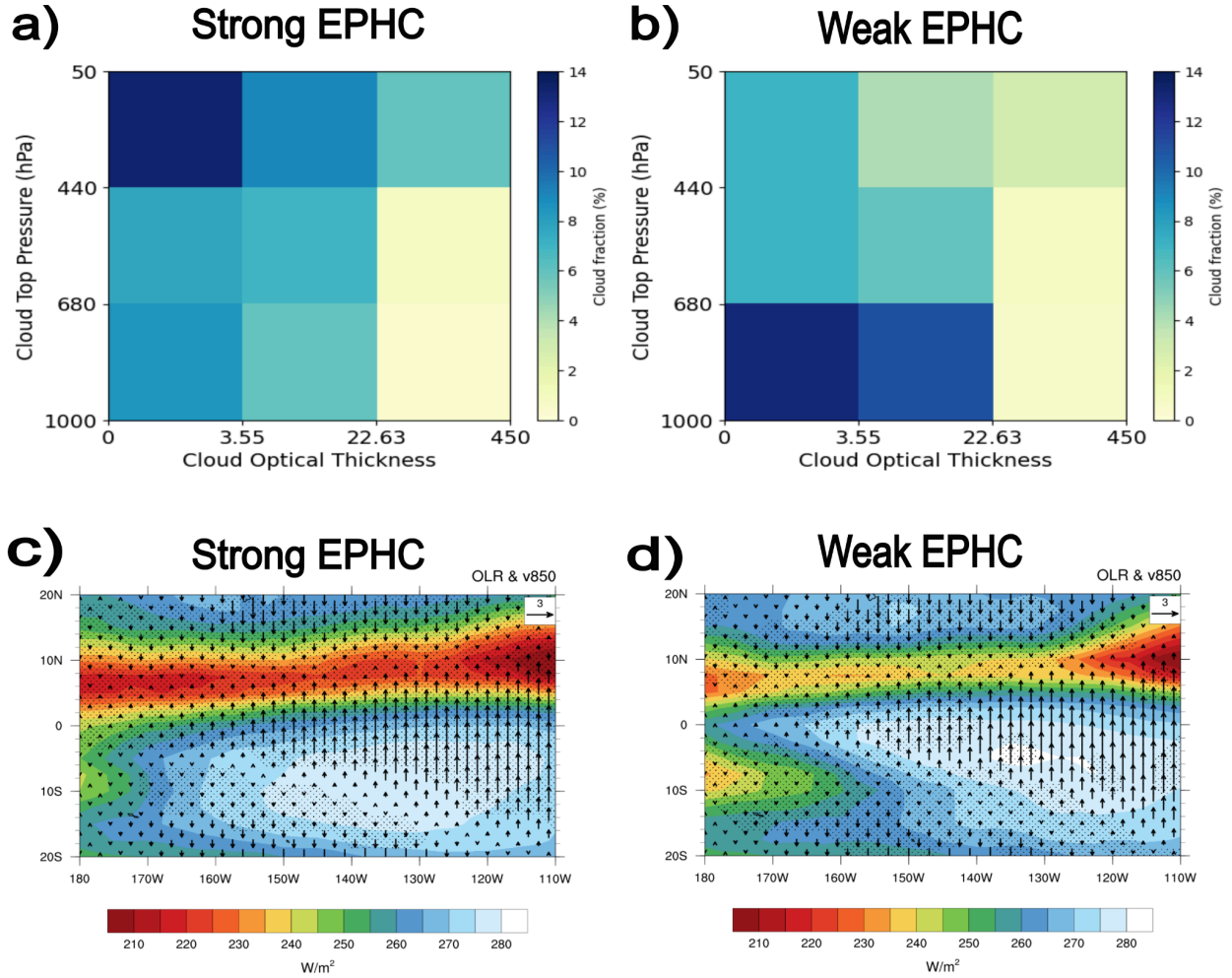


Fig.4.2. Joint histograms showing the cloud classification based on cloud top pressure and cloud optical thickness using ISCCP data during the (a) strong and (b) weak EPHC seasons. The bottom panel shows the composite fields of OLR (shading, Units: W/m^2) and 850hPa meridional winds (arrows, Units: m/s) over the east Pacific during (c) strong and (d) weak EPHC seasons. Stippled regions are statistically significant at the 95% confidence level.

Although the primary composite analysis indicates that convection plays a major role in determining the strength of EPHC, decoding the relationship between convection and mean meridional circulation is not so straightforward. Large-scale convection in the tropical atmosphere may manifest in the form of various tropical disturbances with different temporal and

spatial scales, which might have varying contributions to the HC strength. To assess the prominence and spatial distribution of such transient activity over the eastern Pacific, we analyzed the variance of OLR across different time scales, which provides insight into the dominant types of disturbances and their regions of activity. Figure 4.3 shows the climatological distribution of OLR variance in the synoptic (3–10 days), quasi-biweekly (10–20 days) and intra-seasonal (20–90 days) timescales during the boreal summer season. It is well known that the Indian Ocean and west Pacific domains experience an overlap of transient convective disturbances evolving over different time scales. These regions are marked by the presence of MJO (a dominant mode of tropical intraseasonal variability) (Madden & Julian, 1994) and QBWO, and hence, significant OLR variance is observed in the intraseasonal and quasi-biweekly timescales, in addition to the synoptic scale. Eastward propagation of MJO convection do not extend beyond the dateline and the influence of low frequency modes of tropical convection are hence minimal over the EP (Dunkerton & Baldwin, 1995; Krishnamurti & Arduinay, 1980; Straub & Kiladis, 2002, 2003; C. Zhang, 2005). It is evident from the distribution of OLR variance (Figure 4.4a) that the EP domain is predominantly affected by synoptic-scale disturbances (Gu & Zhang, 2002; Huaman et al., 2021; Serra et al., 2008; C. C. Wang & Magnusdottir, 2006). The clear scale separation in convective activity makes it an ideal region to explore the influence of synoptic scale convective activity on large scale circulation.

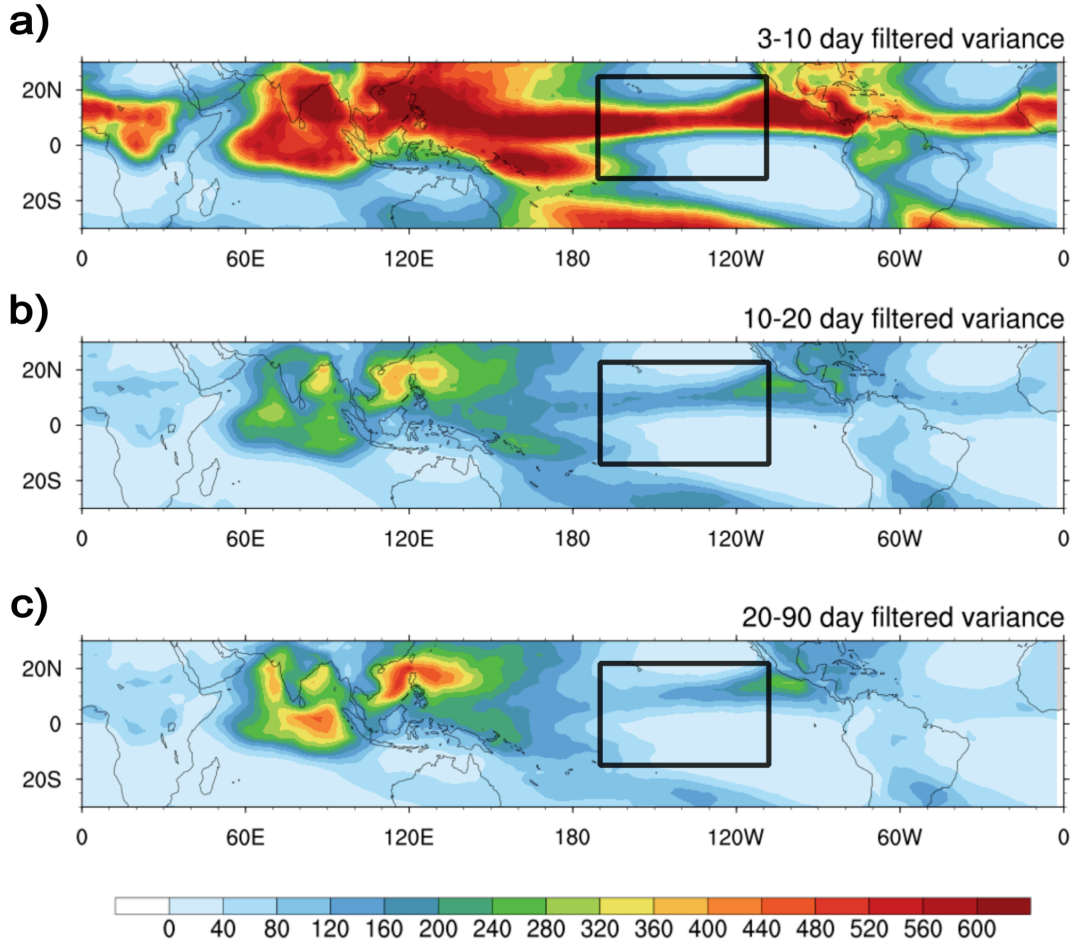


Fig.4.3. Climatological variance of (a) 3-10 day, (b) 10-20 day and (c) 20-90 day filtered OLR anomalies (W^2m^{-4}) during boreal summer (JJA) seasons from 1979-2021. The east Pacific domain is indicated by the black box (Longitudes, 170° W to 110° W).

The observed synoptic-scale convective variance, might be a resultant of both westward and eastward propagating modes prevalent in the tropical atmosphere (Kiladis et al., 2009; Suhas & Neena, 2025). To explore the presence of these modes over the EP, we further decomposed the synoptic-scale filtered OLR into westward and eastward propagating components. The seasonal cycle of OLR variance associated with westward (wavenumbers 2 to 40) and eastward (wavenumbers 2 to 40) propagating synoptic-scale disturbances averaged over the EP domain are shown in Figure 4.4a. A significantly larger variance is observed for the westward propagating synoptic modes as compared to the eastward propagating synoptic modes during boreal summer and fall seasons (Figure 4.4a). Furthermore, the seasonal cycle of the westward

modes is found to be synchronized with the seasonal cycle of the strength of the EPHC, with a minimum observed during boreal winter and a peak observed in boreal summer (Figure 4.4b). In contrast, the eastward propagating mode is relatively weaker and follows a seasonal cycle peaking in boreal spring, which do not align with the EPHC seasonal cycle. Looking at the seasonal cycle, it is likely that Kelvin waves might be the dominant eastward propagating mode, whereas easterly waves and MRG waves might together represent the westward propagating disturbances (Roundy & Frank,

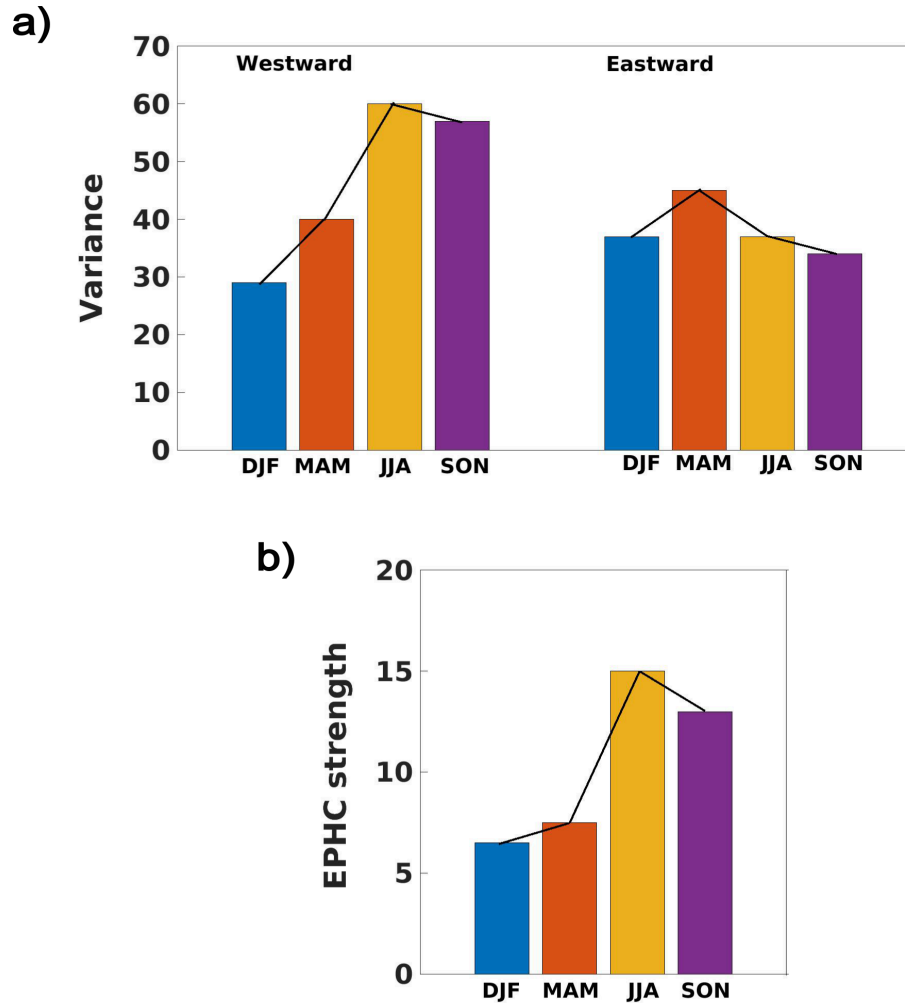


Fig.4.4. (a) Seasonal cycle of OLR variance (W^2m^{-4}) associated with the synoptic-scale westward (wavenumbers -2 to -40) and eastward (wavenumbers 2 to 40) propagating modes over the east Pacific domain (b) seasonal cycle of EPHC strength (Units: 10^{10} kg/s)

2004; Serra et al., 2008). Since a detailed analysis of Yokoyama and Takayabu (2012) suggests

that many of the convectively coupled disturbances including the easterly waves may actually be triggered by deep convection induced by MRG waves, the MRG waves may be considered as the major synoptic scale mode largely contributing toward the modulation of EPHC. The presence of MRG waves over the central-east Pacific during boreal summer has already been reported by several previous studies (Kiladis et al., 2016; Suhas et al., 2020; Zhou & Wang, 2007). These key observations prompt further exploration of the role of MRG waves in influencing the convective activity over the EP and modulation of the EPHC strength.

A recent study by Tomassini and Yang (2022) suggested that the MRG circulation can induce low-level convergence, facilitating deep convection, which in turn can modulate the strength of HC. However, this attribution was made based on a single boreal winter season over the Atlantic domain, and demands further affirmation. Hence, we focus on examining whether the circulation component of MRG waves can contribute to modulating convection over the EP and in turn modulate the strength of EPHC. Since the MRG waves exhibits a temporal scale of 3–10 days and wave numbers 10 to 2 (Kiladis et al., 2009), the MRG wave power in OLR and meridional wind fields are isolated by filtering daily anomalies in these spatial and temporal ranges. A reference index is created to represent the circulation component of MRG waves, by averaging MRG filtered 850 hPa meridional winds over the region of intense MRG wave activity over the equatorial EP (2.5°N – 2.5°S , 117° – 122°W). We refer to this index as the “circulation-index.” The purpose of employing the circulation-index is to examine whether the low-level convergence associated with MRG waves can drive deep convection over the EP, which can ultimately influence the strength of EPHC. The days when the normalized circulation-index exceeds +1 are identified as the reference days (DAY 0), when the MRG-associated low-level meridional winds are the strongest. Composites of 3–10 days filtered OLR and wind anomalies at 850 and 200 hPa levels for the reference days bring out the salient features of MRG waves in convection and circulation fields during strong and weak EPHC seasons (Figure 4.5). A baroclinic vertical structure is evident, with anticyclonic circulation in the lower levels and cyclonic circulation in the upper levels. During strong EPHC seasons, a prominent MRG wave structure is evident, characterized by pronounced MRG-wind convergence in the lower level (Figure 4.5c) and divergence in the upper level (Figure 4.5a). A significant off-equatorial enhanced convection is observed between 150° and 120°W with OLR

anomalies 10 to 12 W/m^2 . On the other hand, during weak EPHC seasons, the off-equatorial convection is limited to 4 W/m^2 , and the MRG-associated convergence and divergence are much weaker in the lower and upper levels respectively (Figures 4.5b and 4.5d). The differences between the composites basically indicates that deep convection triggered by MRG induced low level convergence is more prevalent during strong EPHC seasons.

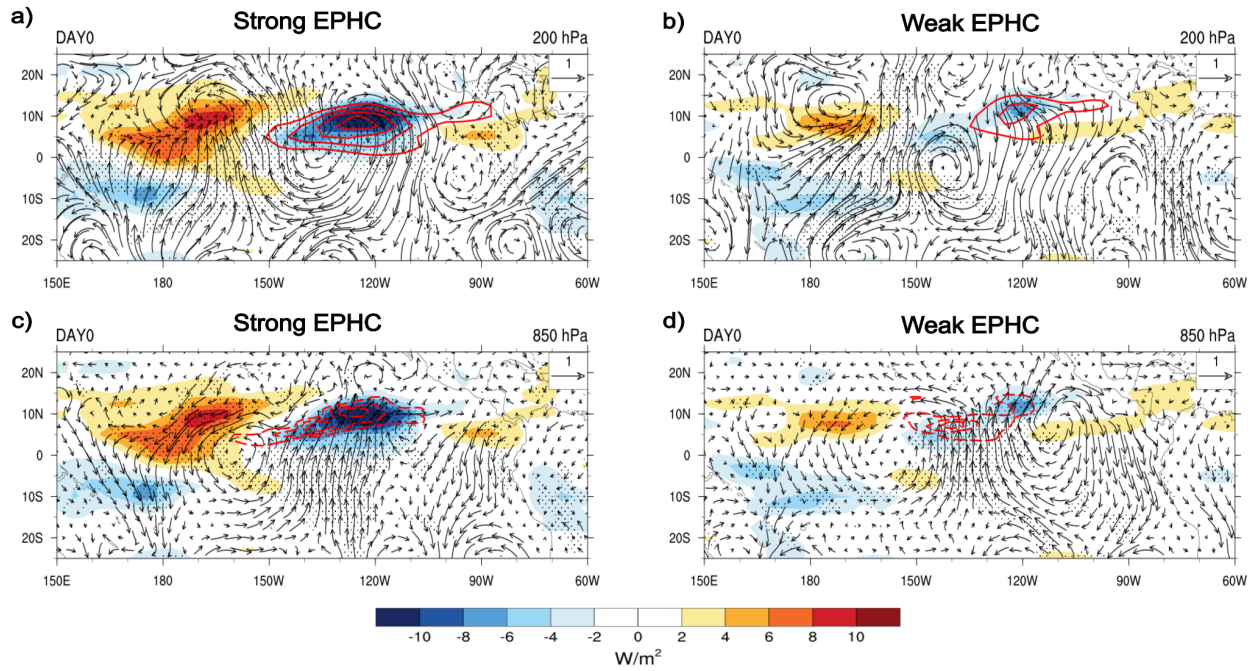


Fig.4.5. Composites of 3-10 day filtered OLR (shading, Units: W/m^2), and wind (vectors, Units: m/s) anomalies at 200 hPa (top panel) and 850 hPa (bottom panel) for the reference days (DAY0) of MRG activity identified based on the “circulation index” during (a,c) strong and (b,d) weak EPHC seasons. The solid (dotted) red contours represent MRG-associated divergence (convergence) in the upper (lower) levels (Units: 10^{-6} s^{-1}). Stippled regions are statistically significant at the 95% confidence level.

The spatial and temporal evolution of MRG waves is further brought out using lag composites of OLR and wind anomalies from day 1 to day +1 with respect to the reference day (Fig. 4.6 and 4.7). A clear westward propagation is observed from EP to central Pacific in convection as well as in the 850 hPa (Figures 4.6a–4.6c) and 200 hPa (Figures 4.7a–4.7c) circulation fields during strong EPHC seasons. In contrast, during weak EPHC seasons, the MRG wave structure is almost absent, with very weak convective activity over the EP (Figures

4.6d–4.6f and 4.7d–4.7f). Since the composites are derived based on the “circulation index” they emphasize the significance of the circulation component of MRG waves. Thus, the clear distinction between the composites indicates that during strong EPHC seasons, MRG-associated convergence might be responsible for triggering a large fraction of deep convection over the EP, in turn contributing to the intensification of EPHC. The absence of this mechanism, on the other hand, can lead to a weaker EPHC.

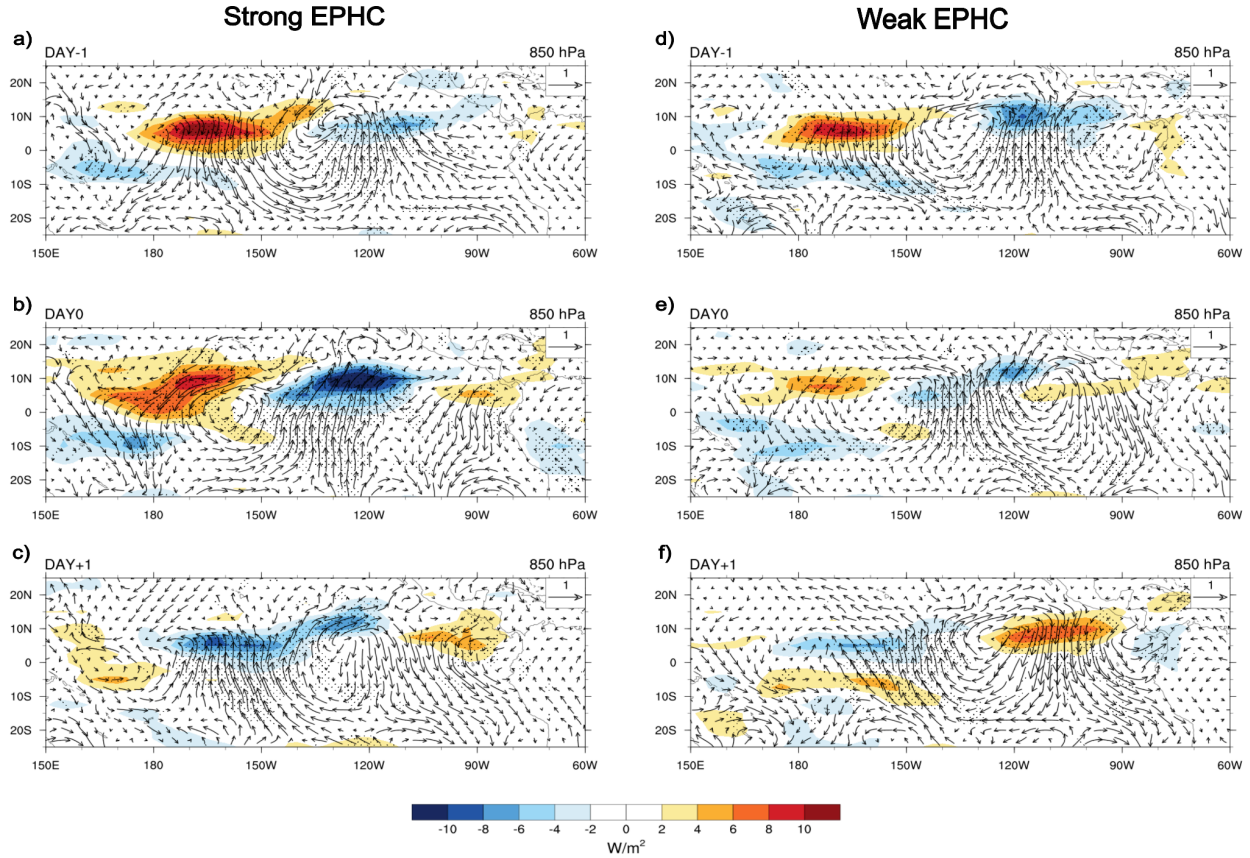


Fig.4.6. Composite evolution of 3-10 day filtered OLR (shading, Units: W/m^2), and wind (vectors, Units: m/s) anomalies at 850 hPa for DAY-1, DAY0 and DAY+1, during (a-c) strong and (d-f) weak EPHC seasons. Stippled regions are statistically significant at the 95% confidence level.

To measure the degree of association between convection and circulation in synoptic scales due to MRG waves over the east Pacific, a coherence-squared spectral analysis was conducted over the 3-10 day period between daily anomalies of OLR and meridional wind at 850 hPa and 200 hPa over the east Pacific for both strong and weak EPHC seasons. Because of the equatorially symmetric cross-equatorial meridional wind distribution and off-equatorial

anti-symmetric convection structure associated with the MRG waves, an OLR index was formulated by averaging OLR anomalies over the off-equatorial region (5°N to 15°N) over east Pacific where convection is most pronounced, while the meridional wind index was averaged over near-equatorial regions between 5°S to 5°N . The magnitude of coherence between the two indices reflects the strength of convection-circulation coupling over the east Pacific. The seasonal coherence spectra obtained for both strong and weak EPHC seasons reveal that

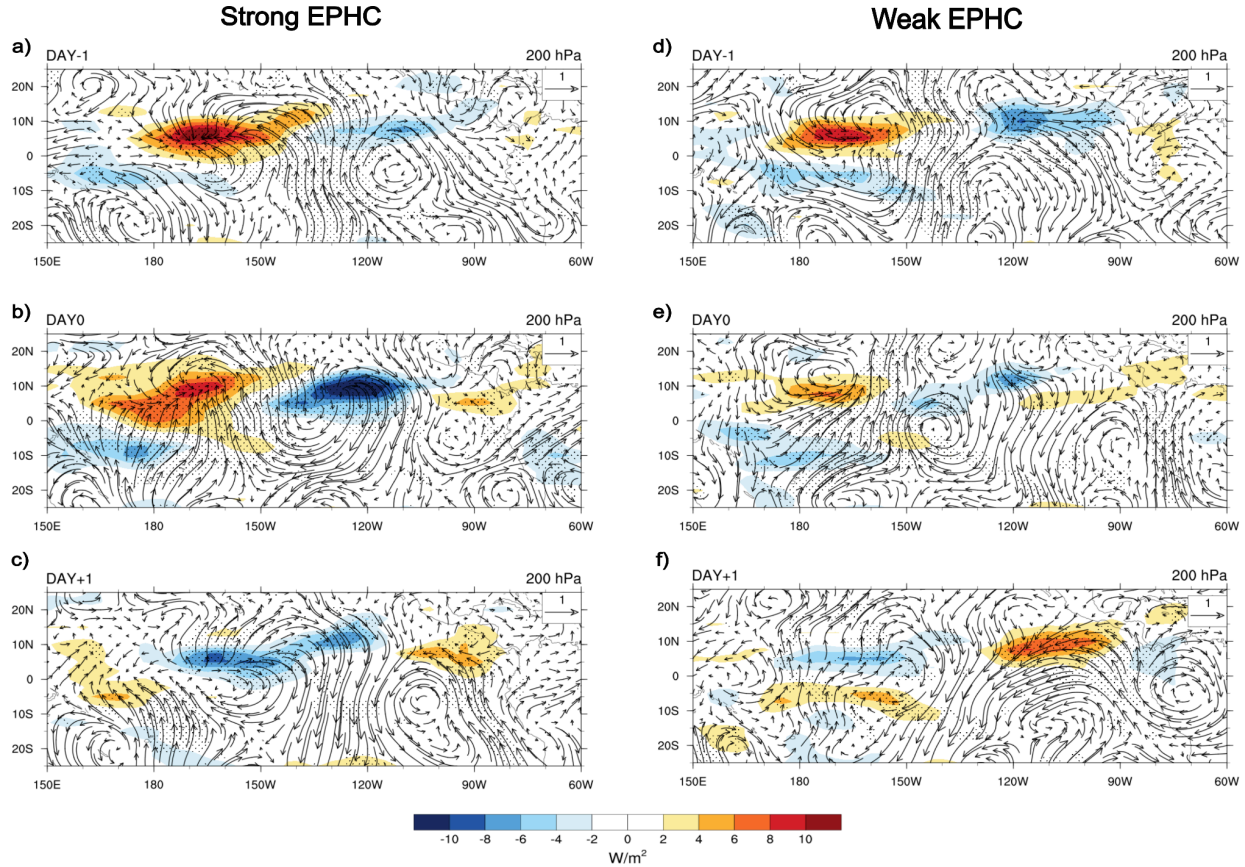


Fig.4.7. Same as Figure 4.6, but for 200 hPa

coherence is much higher during strong (Fig.4.8a,c) seasons compared to weak (Fig.4.8b,d) seasons at both upper and lower levels. This difference highlights a strong coupling between convection and circulation in the synoptic scales driven by MRG waves over east Pacific during strong EPHC seasons, supporting our findings.

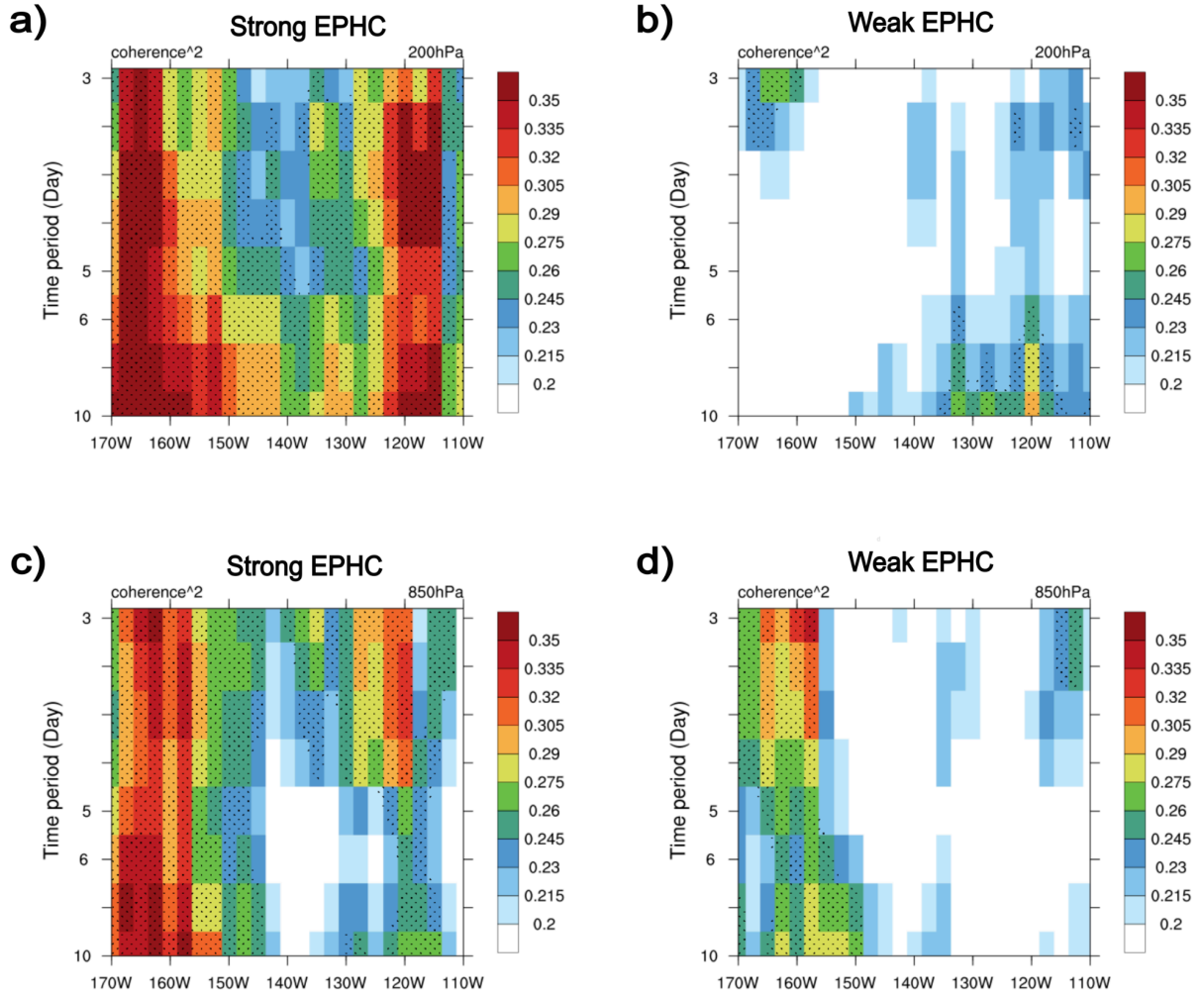


Fig.4.8. Coherence-squared spectra between daily anomalies of OLR (averaged over 5°N to 15°N) and meridional wind (averaged over 5°S to 5°N) at 200 hPa (top panel) and 850 hPa (bottom panel) for (a, c) strong and (b, d) weak EPHC seasons. Stippled regions are statistically significant at the 90% confidence level

Although it appears that MRG convection is triggered by low-level convergence induced by MRG circulation, it is also possible that the observed circulation features might be a response to MRG convection. Differentiating between these two scenarios is indeed challenging; however, their relative dominance can be evaluated. In order to do so, a “convective-index” is created to represent the convective field of MRG waves, using MRG filtered OLR averaged over the OLR minima over EP (5°–15°N, 133°–128°W). The days when the normalized convective-index fall less than 1 are identified as the reference days when the MRG-associated convection is the

strongest. Composites of 3–10 days filtered OLR anomalies are created for the reference days during strong and weak EPHC seasons. The difference in the composites for strong and weak seasons are shown in Figure 10b. Also shown alongside is the similar difference composite constructed using the “circulation index” (Figure 4.9a). The results indicate that the difference in convective activity during strong and weak EPHC seasons is less pronounced when the MRG activity days are identified based on the “convective index” in comparison to when the MRG activity is identified based on the “circulation index.” The results suggest that the “convective index” may be less effective in bringing out the MRG modulation of EPHC strength, which is better captured by the “circulation” index. MRG circulation hence plays the lead role in triggering MRG convection and not the other way around. This supports our hypothesis that MRG-associated convergence contributes significantly to driving deep convection over EP and intensifying the EPHC.

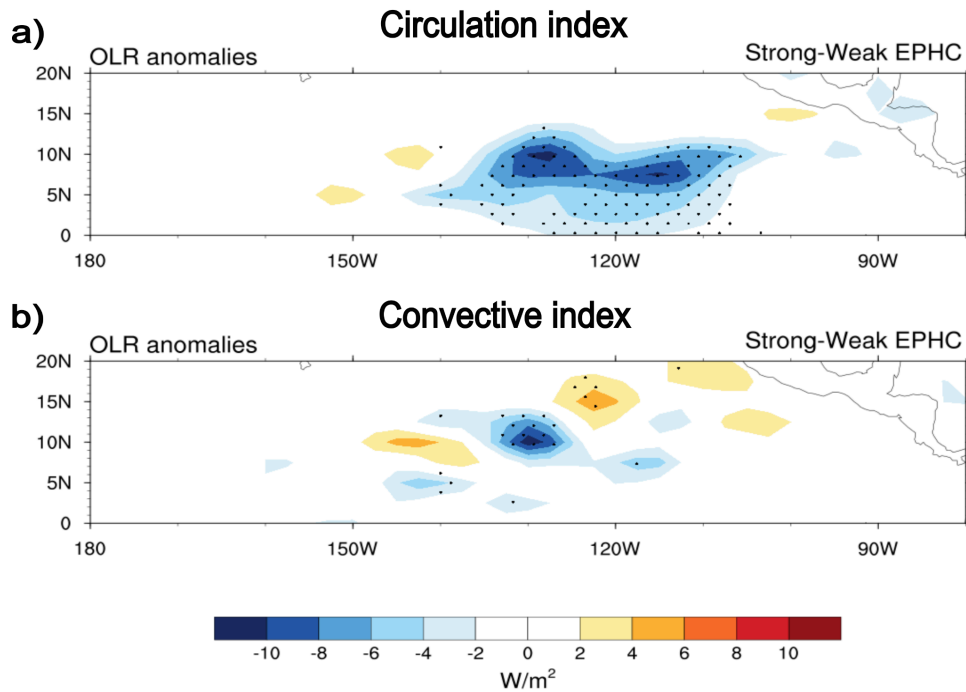


Fig.4.9. Difference between the composites of 3-10 day filtered OLR anomalies (shading, Units: W/m^2) for the reference day (DAY0) of MRG activity during strong and weak EPHC seasons, the reference day of MRG activity is identified using the (a) circulation index and (b) convective index. Stippled regions are statistically significant at the 95% confidence level.

Other than the low-level convergence induced by the large-scale circulation (including the MRG waves), meridional SST gradients over the EP might also induce surface convergence, instigate deep convection and thus influence the EPHC strength. So, to understand the relative importance of these two mechanisms—boundary-forced versus large-scale circulation driven convergence—over the East Pacific, we employ the atmospheric mixed-layer model (MLM) of Back and Bretherton (2009). The mixed layer model-sea surface temperature (MLM-SST), a version of the MLM, uses SST as the input to estimate the boundary forced contribution to surface wind convergence. Seasonal composites of surface winds and the boundary forced convergence obtained from the MLM-SST during strong and weak EPHC seasons are used to understand the role of SST gradients in modulating surface convergence (Figure 4.10). The model is able to well-simulate the off-equatorial (5° – 15° N) convergence zone over EP in both strong and weak EPHC seasons. However, the surface convergence driven by SST gradient is not found to be significantly different for the strong and weak EPHC seasons; in fact, it is slightly stronger during weak seasons (Figure 4.10b). The analysis underscores the dominance of low-level convergence driven by the large-scale circulation over those driven by SST gradients in modulating the EPHC strength. As noted by earlier studies (Back & Bretherton, 2009; Lindzen & Nigam, 1987) possibly meridional SST gradients only influence the shallow meridional circulation over the EP.

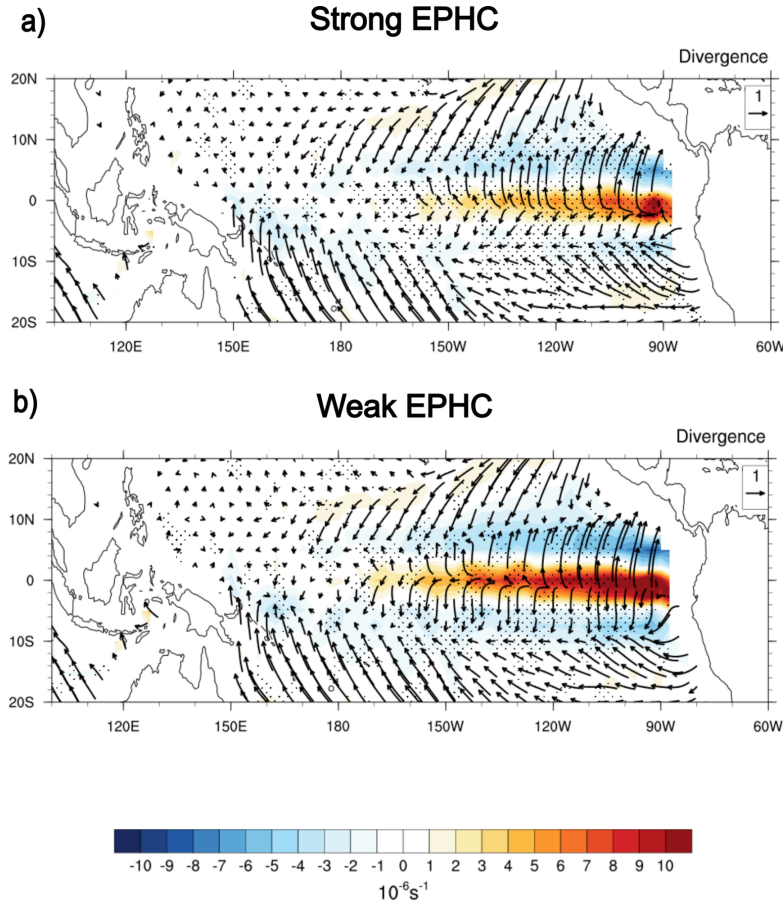


Fig.4.10. Results from MLM-SST showing surface winds (vectors, Units: m/s) and divergence (shading, Units: $10^{-6} s^{-1}$) induced by SST gradients during (a) strong and (b) weak EPHC seasons. Stippled regions are statistically significant at the 90% confidence level.

Previous studies have associated the strength of HC over the tropical Pacific with the different El Niño Southern Oscillation (ENSO) phases (Feng & Li, 2013; Oort & Yienger, 1996; C. Wang, 2004). In accordance with these findings, we also find a good correlation (correlation coefficient of 0.4) of the EPHC index with the Niño3.4 index, indicating the association between ENSO and EPHC. It is also observed that all five strong EPHC seasons (1997, 2002, 2014, 2015, and 2018) and three weak EPHC seasons (1984, 1995, and 1998) occurred during the El Niño and La Niña phases of ENSO, respectively. Figure 4.11 shows the composites of seasonal mean OLR, SST and 850 and 200 hPa wind anomalies during the strong and weak EPHC seasons. Strong EPHC composite fields exhibit a close similarity to an El Niño background state,

characterized by warm SST anomalies and dominant convective activity over the eastern Pacific, westerly wind anomalies in the lower troposphere, and easterly wind anomalies in the upper troposphere (Figures 4.11a and 4.11c). Conversely, weak EPHC composites are very close to the La Niña background state (Figures 4.11b and 4.11d). The inferences drawn in the previous sections may be used to bring out a possible new mechanism which can explain the association between ENSO phases and EPHC strength. Although the ENSO induced changes in mean circulation can modulate the low-level convergence and influence the strength of the mean meridional circulation, we suggest that the ENSO modulation of EPHC strength occurs via the MRG waves. The ENSO state modulates the seasonal mean background state, which modulates the spatial and temporal characteristics of MRG waves and associated low-level convergence over the region, which in turn affects the strength of the EPHC.

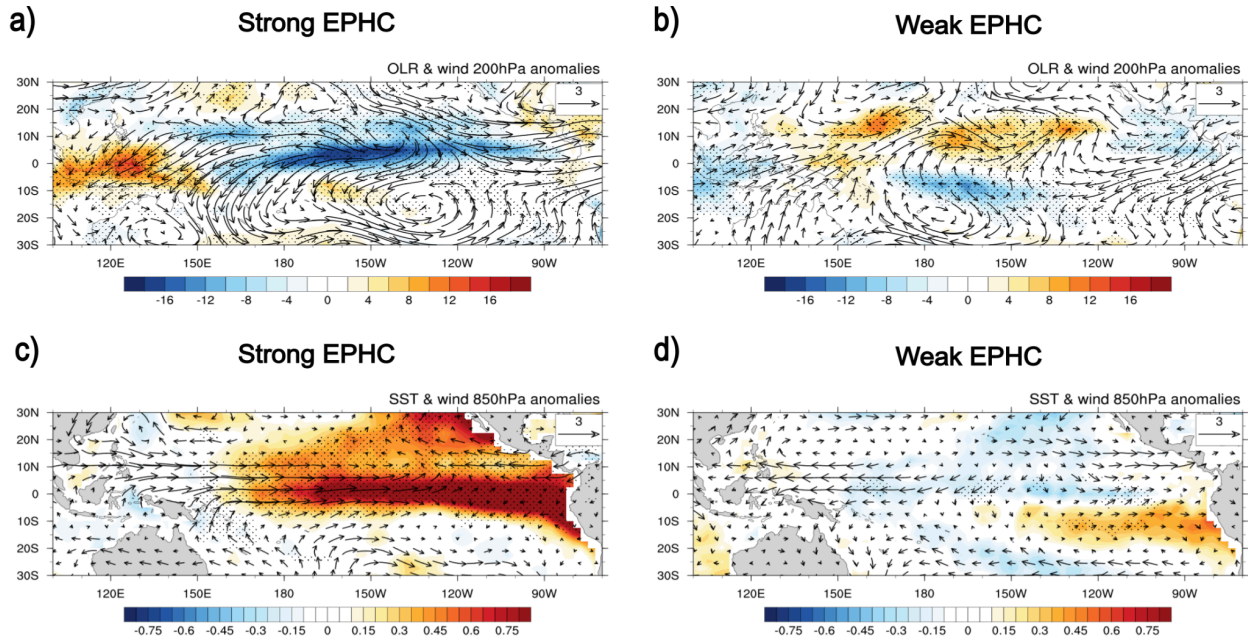


Fig.4.11. (a, b) Composites of seasonal mean OLR (W/m^2) and 200 hPa wind anomalies (m/s) for strong and weak EPHC seasons. (c), (d) Composites of seasonal mean SST ($^{\circ}C$), and 850 hPa wind anomalies (m/s) for strong and weak EPHC seasons. Stippled regions are statistically significant at the 95% confidence level.

4.4. Summary and Conclusions :

This chapter investigates the role of tropical synoptic-scale disturbances in modulating the strength of the East Pacific Hadley circulation (EPHC) during the boreal summer season. The focus on the eastern Pacific is motivated by the pronounced dominance of synoptic-scale variability in this region, in contrast to other tropical basins such as the western Pacific and the Indian Ocean, where convection is influenced by a broader range of timescales, including intraseasonal and quasi-biweekly oscillations. Beyond the well-established influences of SST-driven thermal convection and convergence arising from SST gradients, this study explores a comparatively less examined mechanism—the role of atmospheric wave-induced convergence in regulating the strength of a regional meridional overturning circulation.

The analysis identifies transient synoptic-scale disturbances, particularly mixed Rossby–gravity (MRG) waves, as key dynamical contributors to deep convection over the eastern Pacific. During years characterized by a strong EPHC, enhanced MRG-wave activity generates robust low-level convergence, creating favorable conditions for organized deep convection. This wave-induced convergence accounts for a substantial fraction of convective triggering in the region and acts to reinforce large-scale ascent associated with the EPHC. In contrast, during weak EPHC years, diminished MRG-wave activity disrupts this coupling between wave dynamics and convection. The resulting reduction in dynamical convergence and convective heating leads to a shallower and weaker meridional circulation. These results highlight the critical role of synoptic-scale disturbances in sustaining deep convection and facilitating large-scale mass transport over the eastern Pacific. In addition, a potential linkage between EPHC variability and ENSO is proposed, mediated through changes in MRG-wave activity. Composite analyses reveal that strong EPHC years closely resemble an El Niño–like background state, whereas weak EPHC years are more consistent with La Niña–like conditions. This suggests that ENSO may influence EPHC strength by altering the seasonal-mean background state, which in turn modulates the spatial structure, frequency, and intensity of MRG waves and their associated low-level convergence. Through this pathway, ENSO variability can indirectly regulate the strength of the East Pacific Hadley circulation.

Overall, the findings of this chapter present a framework that links transient tropical wave

activity, deep convective processes, and large-scale meridional circulation, emphasizing the importance of synoptic-scale dynamics in shaping regional Hadley cell variability.

Chapter 5

Thesis summary

The Hadley circulation is a prominent feature of the general circulation of the atmosphere, consisting of rising motion of moist air over the Intertropical Convergence Zone poleward diverging winds in the upper troposphere which eventually descend over the subtropical latitudes around 30°N and S, and winds converging toward the equator near the surface. This zonal-mean representation of the HC provides a simple and effective framework for describing the global tropical circulation. However, the heterogeneous distribution of land and ocean, along with the pronounced zonal asymmetry in winds and precipitation, limits the applicability of the conventionally defined, zonally averaged HC. Although the zonal-mean HC can be regarded as the cumulative outcome of variations in meridional circulations across different longitudinal sectors, such zonal averaging may obscure important regional meridional circulation characteristics. While the global HC has been extensively investigated, the individual regional Hadley circulations remain comparatively less understood. Therefore, the overarching goal of this thesis is to advance the understanding of regional Hadley circulations, with particular emphasis on how their structure, seasonal variability, and long-term evolution differ across longitudinal sectors, and on identifying the region-specific mechanisms that govern these differences.

Chapter 2 presents a comprehensive characterization of regional Hadley circulations across six major longitudinal sectors—Africa, Indian Ocean, Western Pacific, Eastern Pacific, South America, and the Atlantic—with the aim of highlighting their structural diversity, seasonal evolution, and mutual relationships. The analysis demonstrates that the strength and vertical

extent of regional HCs are closely governed by the spatial distribution and intensity of deep convection over ITCZ. Regions characterized by persistent and vigorous convective heating, such as the Western Pacific and Indian Ocean sectors, exhibit strong and deep overturning cells that extend well into the upper troposphere. In contrast, the Eastern Pacific and Atlantic sectors, located over climatological cold-tongue regions with suppressed convection, exhibit comparatively weaker and shallower circulations. The seasonal evolution of all regional HCs closely follows the migration of convective activity, with maximum intensities occurring during hemispheric winters or during active monsoon phases, underscoring the fundamental role of thermally driven ascent in shaping these circulations. An examination of the long-term variability further reveals that most regional HCs fluctuate largely independently, as indicated by weak correlations among their strength indices. Interestingly, the East Pacific HC exhibits a strong correspondence with the zonal-mean Hadley circulation, suggesting that variability in the East Pacific sector plays an important role in shaping the trends and variability of the zonal-mean HC reported in previous studies. This finding emphasizes the importance of regional contributions in interpreting changes in the global Hadley circulation, and highlights the limitations of relying solely on zonal-mean diagnostics to understand tropical overturning dynamics.

Chapter 3 addresses the role of sea surface temperature in governing the strength of regional Hadley circulations over the Pacific basin. The analysis investigates how the rapid increase in warm pool SSTs since the 1980s has influenced the regional Hadley circulations over the eastern and western Pacific. Despite the basin-wide warming of SSTs, a striking contrast emerges in the response of the two Pacific cells: the East Pacific Hadley Cell exhibits a pronounced intensification in the post-1980 period, whereas the West Pacific Hadley Cell shows little to no long-term strengthening. This contrasting behavior highlights the importance of basin-specific physical mechanisms in regulating regional Hadley circulations. Over the western Pacific, enhanced upper-tropospheric warming relative to surface warming in the post-1980 period leads to increased static stability, consistent with moist adiabatic lapse rate (MALR) adjustment. This stabilization raises the SST threshold required for deep convection, thereby suppressing further intensification of the West Pacific HC despite rising SSTs. In contrast, over the eastern Pacific, warming is distributed more uniformly throughout the troposphere, maintaining near-neutral static stability and allowing SST-driven convection to remain effective

in strengthening the East Pacific HC. In addition to thermodynamic controls, the analysis reveals a strengthening of low-level convergence over the eastern Pacific in the post-1980 period, likely associated with a weakening of the Walker circulation. This shift enhances ascent over the eastern Pacific while simultaneously reducing upward motion over the western Pacific, providing an additional dynamical pathway for the intensification of the East Pacific HC and the muted response of the West Pacific HC.

Chapter 4 investigates the role of tropical transient disturbances in modulating the strength of East Pacific Hadley circulation. The choice of the east Pacific domain is motivated by the distinctive prominence of synoptic-scale disturbances over the region, unlike other regions such as the western Pacific or Indian Ocean, where a wide range of scales, including intra-seasonal and quasi-biweekly oscillations, are also prevalent. Apart from the SST driven thermal convection and the convection driven by convergence induced by SST gradients, the study addresses a less explored aspect of how atmospheric wave induced convergence may be critical in determining the strength of regional meridional cells. The analysis identifies transient synoptic-scale disturbances, particularly Mixed Rossby–Gravity (MRG) waves, as the primary agents providing dynamical support for deep convection over the eastern Pacific. During strong East Pacific HC years, enhanced MRG-wave activity produces pronounced low-level convergence, which initiates a substantial fraction of deep convection over east Pacific and amplifies the large-scale ascent associated with the East Pacific HC. In contrast, weak East Pacific HC years are characterized by suppressed MRG-wave activity, leading to reduced wave-induced convergence, diminished convective heating, and the development of shallower and weaker overturning cells over east Pacific. Additionally, a linkage is found between East Pacific HC variability and ENSO, mediated by the MRG waves. ENSO-related changes in the seasonal-mean background state modulate the characteristics of MRG waves, thereby altering patterns of low-level convergence over the eastern Pacific and influencing the strength of the East Pacific HC. As a whole, these results highlight the crucial role of tropical synoptic-scale eddies in shaping mean meridional circulations. They emphasize the importance of accurately representing such transient disturbances in climate models to improve confidence in projections of future tropical circulation changes.

Collectively, this thesis sheds light on how the Hadley circulation varies regionally and the underlying physical processes that shape it. Rather than being a single uniform system, the Hadley circulation emerges as a collection of interconnected regional cells responding to local thermodynamic and dynamical conditions. Thus, the findings of this thesis emphasize the necessity of adopting a regional perspective to better understand the Hadley circulation. It also suggests that future research should explore how different influencing factors affect the regional Hadley circulations through carefully designed modeling experiments, which could strengthen the reliability of the conclusions. Using high-resolution models may further improve our understanding by capturing wave–mean flow interactions more clearly. In addition, since the present work has concentrated mainly on the effects of disturbances within the tropics, future studies could explore how disturbances originating in the extratropics interact with and influence the regional Hadley circulations.

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List of Publications

1. **Baruah, P. P.**, Neena, J. M., & Suhas, E. (2025). “*The role of tropical synoptic-scale disturbances in modulating the strength of east Pacific Hadley circulation*”. *Journal of Geophysical Research: Atmospheres*, 130, e2024JD042980. <https://doi.org/10.1029/2024JD042980>
2. **Baruah, P. P.**, Neena, J. M. “*Understanding the characteristics and seasonal variability of the regional Hadley cells*”. (in preparation)
3. **Baruah, P. P.**, Neena, J. M. “*Impact of the Indo Pacific warm pool intensification and expansion on the strength of Regional Hadley Circulations over the Pacific Ocean*”. (in preparation)

