Chapter 7

Changes in the Atmospheric Circulation as Indicator of Climate Change

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1. INTRODUCTION

The strength, direction, and steadiness of the prevailing winds are crucial for climate. Winds associated with the atmospheric circulation lead to transports of heat and moisture from remote areas and thereby modify the local characteristics of climate in important ways. Specific names, such as extratropical Westerlies, tropical Trades, and equatorial Doldrums remind us of the significance of winds for the climate of a region and for the human societies living in it.

The purpose of this chapter is to discuss changes in the structure of the atmospheric circulation and its associated winds that have taken place during recent decades. These changes are best described as poleward displacements of major wind and pressure systems throughout the global three-dimensional

atmosphere. The associated trends are important indicators of climate change and are likely to have profound influences on ecosystems and societies.

This review is focused on two important examples of such change: first, tropical circulation change related to a poleward expansion of the Hadley cell (HC) and second, extratropical circulation change, as manifested by a poleward shift of the zone of high westerly winds in the midlatitudes, also known as an enhanced positive phase of the annular modes (AMs). Although both changes are associated with similar poleward displacements, it still remains to be seen whether the two phenomena are directly connected.

As with most aspects of climate change, the circulation changes that occurred over the past are still relatively subtle, making it difficult to distinguish them from naturally occurring variations. The difficulty of reliably monitoring the global circulation is an additional complication. Long-term records of the atmosphere exist at few locations only, and most regions of the Earth are not observed. The problem of sparse observations can be partly overcome by utilizing meteorological reanalyses, which represent a combination of numerical weather predictions and available observations. In the present context, however, reanalyses are only of limited use, since changes in the mix of used observations over time create spurious trends in the data [1].

Because of the difficulty in observing the atmospheric circulation and its long-term trends, this review will not only rely on observation-based evidence but also include findings from general circulation models (GCMs). GCMs are certainly not perfect representations of the real system, but they are extremely valuable in situations where observations alone are not giving sufficient information. For example, they allow producing consistent time series of virtually any length, location, and quantity. GCMs can be used to perform actual experiments of the Earth's climate system in its full complexity, an undertaking that would be impossible in a laboratory setting. This makes GCMs indispensable research tools, in particular for the search for human influences on climate.

The most intriguing challenges regarding the atmospheric circulation and climate change are to understand what the nature of this change is, what the consequences for surface climate are, and what the underlying causes and mechanisms are. At the beginning of this review, we will develop some basic understanding of the nature of the atmospheric circulation to provide necessary information for the remainder of this chapter. Next, I will give an overview of observation and model-based evidence of past circulation change. This discussion will primarily focus on the tropical widening phenomenon. I will continue by presenting some of the mechanisms that have been put forward in the literature to explain the widening. Later, I will clarify the relationship to other important forms of climate change and in particular to extratropical circulation change. I will conclude by summarizing some outstanding research questions and by highlighting possible impacts of atmospheric circulation change on other components of the global climate system.

2. THE GENERAL CIRCULATION OF THE ATMOSPHERE

The general circulation of the atmosphere describes the global three-dimensional structure of atmospheric winds. Halley [2] was probably the first to realize that the sphericity of the Earth and the resulting spatially non-uniform distribution of solar heating are the basic drivers behind this circulation. The tropics absorb about twice the solar energy that the higher latitudes absorb, creating a meridional gradient in temperature and potential energy. Some of the potential energy is converted into kinetic energy [3], which is manifested as wind. The winds are then deflected under the influence of the rotating Earth, creating the complicated flow patterns of the general circulation.

Atmospheric flow leads to systematic transports and conversions of energy within the Earth climate system. The different forms of energy involved are sensible heat, latent heat, potential energy, and kinetic energy. Typically, the energy transports are directed against spatial gradients, thus reducing the contrasts between geographical regions. For example, the winds transport warm air from the tropics to the extratropics and cold air in the opposite direction, decreasing the temperature contrasts between low and high latitudes. Similarly, the general circulation redistributes water from the oceans to the continents and supplies land surfaces with life-bringing precipitation. In other words, the atmospheric circulation exerts a moderating influence on climate and reduces the extremes in weather elements. The atmospheric winds also help drive the oceans, which in turn redistribute heat from low to high latitudes, nutrients from the ocean interior to the surface, and carbon from the atmosphere to the ocean. Because of its important role in redistributing properties within the climate system the general circulation has also been dubbed the "great communicator" [4].

The distinction into tropical and extratropical regimes is fundamental for the Earth atmosphere. In the extratropics, large-scale motions are governed by quasi-geostrophic theory, a simple framework related to the near perfect balance between the pressure gradient force and the Coriolis force. The extratropical circulation is dominated by cyclones, which are also called storms, eddies, or simply waves. These cyclones are the product of baroclinic instability, which develops particularly strongly during winter as a consequence of the intense pole-to-equator temperature gradient during that season. The storm-track regions over the western parts of the Pacific and Atlantic oceans are the preferred locations for the development of such systems.

In the tropics, the Coriolis force is weak, and other effects such as friction, and diabatic and latent heating become important [5]. The resulting tropical circulation is very distinct from the extratropics. The HC [6] is the most prominent tropical circulation feature. It extends through the entire depth of the troposphere from the equator to the subtropics (ca. 30° latitude) over both hemispheres (Fig. 1). The cell develops in response to intense solar heating in the Inter Tropical Convergence Zone (ITCZ) near the equator. The moist tropical

Zonal mean zonal wind

Meridional mass streamfunction
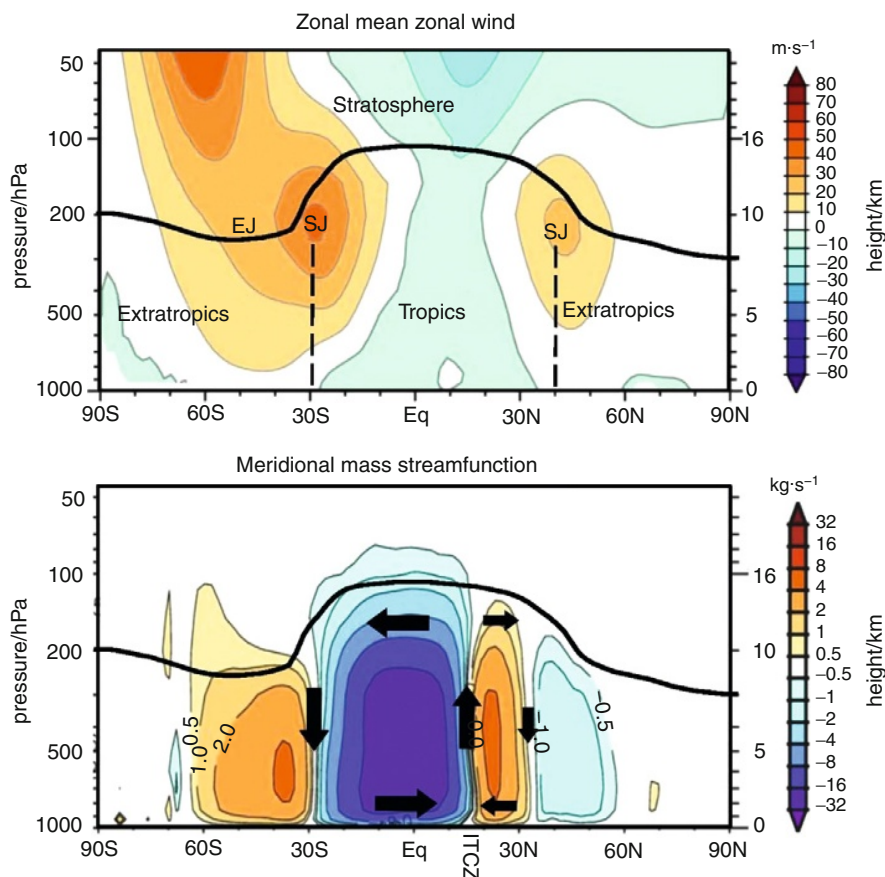
FIGURE 1   Climatological mean circulation in the height–latitude plane during boreal summer (June, July, August) (JJA). Vertical axis is atmospheric pressure (in hPa) and height (in km) and horizontal axis is latitude (in degrees). The continuous black line denotes the thermally defined tropopause. (Top) Zonal mean zonal winds (in m·s^{-1}) derived from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. The approximate position of the subtropical jet and the eddy driven jet is denoted by SJ and EJ, respectively. (Bottom) Mean meridional mass streamfunction (in kg·s^{-1}), with arrows indicating the direction and strength of the zonal mean overturning associated with the Hadley cell, with a strong winter cell in the SH and a weak summer cell in the NH.

air warms, becomes buoyant, and rises towards the upper troposphere. The rising air cools adiabatically, leading to condensation, release of latent heat, and production of clouds and intense precipitation. In the upper troposphere, the air then diverges towards the poles and descends in the subtropics. The air is now dry and warm since it lost its moisture but retained much of the latent heat gained while rising. Consequently, the climate under the descending branch of the HC is characterized by dry conditions and relatively high pressure. The

HC is closed by the trade winds at the surface, which take up moisture from the oceans before they converge into the ITCZ.

The Walker circulation [7,8] is another important tropical circulation system, representing east-west oriented overturning of air across the equatorial Pacific. It is driven by low pressure and convection in the west, and high pressure and subsidence in the east. The pressure differences across the Pacific are due to warm sea surface temperatures (SSTs) over the west and rather cool SSTs over the east. Variations in these SSTs and the Walker circulation are closely related to the El Niño Southern Oscillation (ENSO) phenomenon, a naturally occurring instability of the coupled atmosphere–ocean system that has worldwide climate impacts [9].

The meridional overturning associated with the HC is also important for the extratropical circulation. For example, the poleward moving air in the upper branch of the HC tends to conserve angular momentum, spinning up a region of high zonal winds over the subsiding branch of the HC. This is the subtropical jet (Fig. 1). The jet, however, is not entirely angular momentum conserving, mainly because of the stirring action of the midlatitudes storms [10]. The stirring creates net fluxes of zonal momentum out of the jet and into the midlatitudes, which are so-called divergences and convergences of eddy-momentum. The consequence of these fluxes is a slowing of the subtropical jet and the creation of another wind maximum poleward of the subtropical jet. This second zone of high-wind speeds is the eddy-driven or polar-front jet [11]. This jet is often merged with the subtropical jet, giving the appearance of only one tropospheric jet centered at ∼30° latitude [12]. Only over the southern hemisphere (SH) and during winter are the two jet systems fairly well separated.

How does climate change impact the atmospheric circulation? Alterations of the radiative balance of the Earth due to climate change modify regional temperature and humidity structures. The winds respond to the resulting gradients and change the intensity and structure of the circulation. In the following sections, I will present evidence that such change is already taking place, and discuss some of the underlying theoretical mechanisms.

3. THE POLEWARD EXPANSION OF THE TROPICAL CIRCULATION

The location of the poleward boundaries of the tropics are not defined in unique and commonly accepted ways. This is related to the lack of an easily identifiable boundary between the extratropics and tropics. Atmospheric features undergo a more or less gradual transition between the two zones. The poleward extent of the tropics, therefore, depends on the definition of specific indicators of tropical width. Indicators that have been used in the past can be roughly divided into two categories. The first includes dynamical indicators, which focus on characteristic features in the atmospheric circulation at the

outer edges of the tropics. Examples are the poleward boundary of the HC, the position of the subtropical jet cores, or the latitude where the surface winds change from westerly to easterly. The second consists of physical indicators, which utilize other aspects of the atmosphere that exhibit relatively sharp gradients at the tropical edge. These include the amount of outgoing longwave radiation, the concentration in stratospheric ozone, the height of the thermally defined tropopause, the relative humidity of the air, or the difference between precipitation and evaporation at the surface.

3.1. Observation-Based Evidence

Rosenlof [13] was probably the first to investigate long-term trends in the width of the tropics by studying the latitudinal extent of the upwelling branch of the Brewer–Dobson circulation in the lower stratosphere. This circulation represents a slow meridional overturning that extends through troposphere and stratosphere, with upwelling in the tropics and downwelling in higher latitudes. Rosenlof applied this indicator to reanalyses and found that the width of the tropics has increased by about 3° latitude per decade during the period 1992–2001. This rate is rather large and likely contains considerable observational uncertainty.

Continuing the pioneering work by Rosenlof, a subsequent study by Reichler and Held [14] focused on the structure of the global tropopause as another indicator of tropical width. This indictor is based on the well-known distinction between the tropics, where the tropopause is high, and the extratropics, where the tropopause is low (Fig. 1). The advantage of this method is that the tropopause is a relatively well observed atmospheric feature that can be easily derived from three-dimensional temperature fields. Using data from radiosondes (Fig. 2) and reanalyses (Fig. 3), it was found that the tropics have been expanding by about 0.4° latitude per decade since 1979. The same study arrived at very similar results by examining the separation distance between the two subtropical jets. Although the new widening figure was considerably smaller than what was found earlier [13], it confirmed the original result that the tropics were expanding.

The initial studies sparked a flurry of new research activity, aimed at better understanding the new phenomenon and its underlying cause. For instance, Fu et al. [15] examined long-term data (1979–2005) from the satellite-borne microwave sounding unit and found that the midtropospheric global warming signal was most pronounced in the subtropics (15–45°). It was argued that the enhanced warming was caused by a poleward shift of the subtropical jets. Hudson et al. [16] defined the location of the tropical edges from the characteristic distribution of total ozone between the tropics and the extratropics. They examined long-term records of total ozone from the Total Ozone Mapping Spectrometer instruments and found that the area over the northern hemisphere (NH) occupied by low ozone concentrations, which is indicative
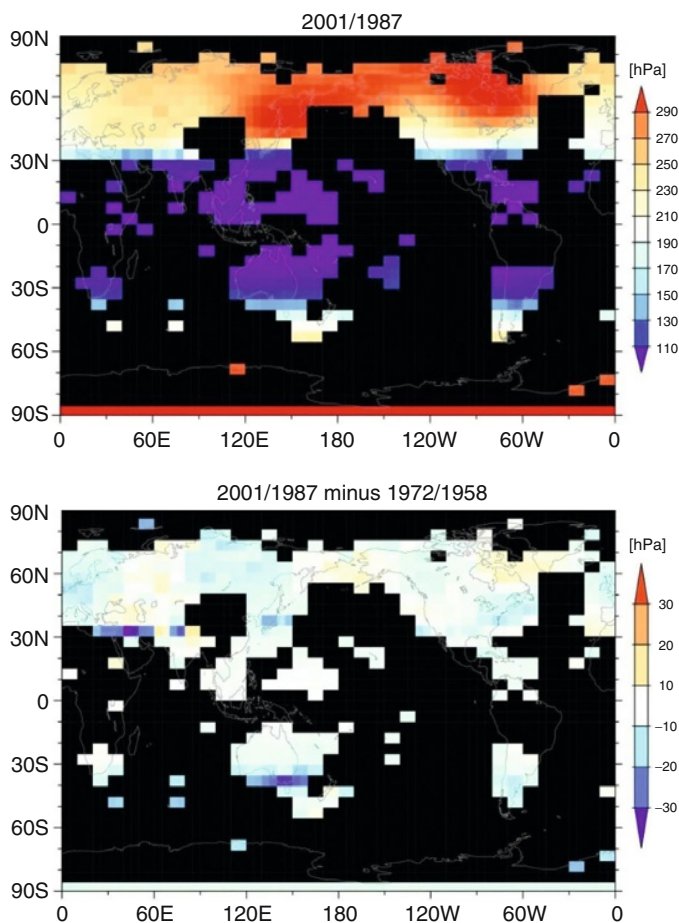
FIGURE 2   Changes in tropopause pressure during boreal winter (December, January, February) derived from gridded radiosonde data HADRT V2.1 [93]. (Top) Absolute tropopause pressure (in hPa) averaged over 1987–2001. (Bottom) Differences in tropopause pressure (in hPa) between the late period 1987–2001 and an early period 1958–1972. Bluish grid points indicate that tropopause pressure is decreasing and tropopause heights are increasing. The bluish banded structures over southern Australia and southern Europe indicate a trend toward tropical tropopause conditions and thus a widening of the tropics. Adapted from [14].

for tropical regions, has increased over time. Seidel and Randel [17] also used the tropopause criterion to distinguish between the tropics and extratropics and examined the bimodal distribution of tropopause heights in the subtropics. Applying this measure to radiosonde and reanalysis data they again concluded that the tropics have been expanding.

   Table 1 provides an overview of these and other relevant studies. Individual widening estimates range between 0.3° and 3° latitude per decade, with
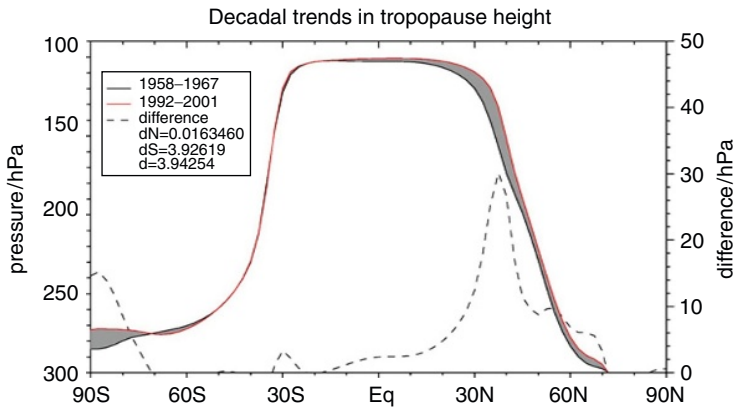
FIGURE 3 Zonal mean profile of the tropopause during boreal summer (JJA) derived from NCEP/NCAR reanalysis. Shown are the tropopause pressure (in hPa, left axis) averaged over the years (black) 1958–1967 and (dark grey) 1992–2001. Light grey shading indicates the differences in tropopause position between the two periods. The dashed curve shows the difference in tropopause pressure (in hPa, right axis). Horizontal axis shows latitude (in degrees). Adapted from [14].

TABLE 1 Estimates of tropical widening (in degrees latitude per decade) from observation-based studies

Study	Indicator	Data	Widening
Rosenlof [13]	Tropical upwelling (60 hPa)	Analyses	3.0
Reichler and Held [14]	Tropopause height	Radiosonde	0.4
	Tropopause height	Reanalyses	0.7
Fu et al. [15]	Tropospheric temperatures	MSU	0.7
Hudson et al. [16]	Total ozone	TOMS	1.0 (NH only)
Seidel and Randel [17]	Tropopause height	Radiosonde, reanalyses	1.8–3.1
Hu and Fu [59]	Outgoing longwave radiation	Various satellite sensors	1.5
	Mean meridional circulation	Reanalyses	1.0
Archer and Caldeira [92]	Jet stream separation	Reanalyses	0.3
Seidel et al. [23]	Jet stream separation	Reanalyses	1.0

a consensus widening of about 1.4°. The wide range of outcomes may be reconcilable in terms of observational uncertainties and methodological differences. However, some of the estimates are probably unrealistically large. For example, a sustained widening of 3° or more over the past three decades would have led to pronounced shifts in climate that have not been observed. Excluding some of the outliers, the most likely consensus estimate is, therefore, close to 1° latitude widening per decade over the recent decades.

Another important aspect of the observed tropical widening is its regional and seasonal structure. At least two studies suggest that the widening trend is strongest during summer of the respective hemisphere and that it is generally more pronounced over the SH than over the NH. In other words, the tropical expansion is largest over the SH during December, January, and February, and it is smallest over the NH during the same months.

3.2. Model-Based Evidence

The observed expansion is also reproduced by climate models that are driven with the observed history of forcings over the past decades. For example, most of the twentieth century scenario integrations of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4) [18] reproduce a widening of the tropopause [14]. The widening in the model with the largest expansion amounts to 0.7° latitude per decade over the last three decades, which is consistent with the observations. However, other models simulate much smaller rates, and some even negative ones. When the mean meridional circulation is used as indicator for the tropical edge, the same simulations averaged over all models show a widening of 0.2° latitude per decade over the period 1970–1999 [19].

Given the relatively small expansion seen in GCM simulations for the past one may ask how models respond to stronger greenhouse gas increase, which is expected to take place in the future. Kushner et al. [20] forced a fully coupled GCM with ~1% CO_2 increase per year and found over the SH a strong poleward shift of the westerly jet and of several related dynamical fields. The A2 scenario integrations of the IPCC-AR4 project, which correspond to a strong future increase in greenhouse gases, also reproduce robust poleward shifts of the jets [21], with an ensemble mean response of ~0.2° latitude per decade over the period 2000–2100 [19,22] (Fig. 4).

The aforementioned studies demonstrate that GCMs respond to anthropogenic forcings in expected ways, that is, the tropical edges and other aspects of the general circulation move poleward (Fig. 4). However, the model simulated trends seem to be smaller than in the observations. For example, the mean widening rate under the A2 scenario is about five times smaller than what was apparently observed during the past, despite the strong increase in greenhouse gas forcing under the A2 scenario. One might conclude that models have deficits in simulating the full extent of the widening. Seidel et al. [23],
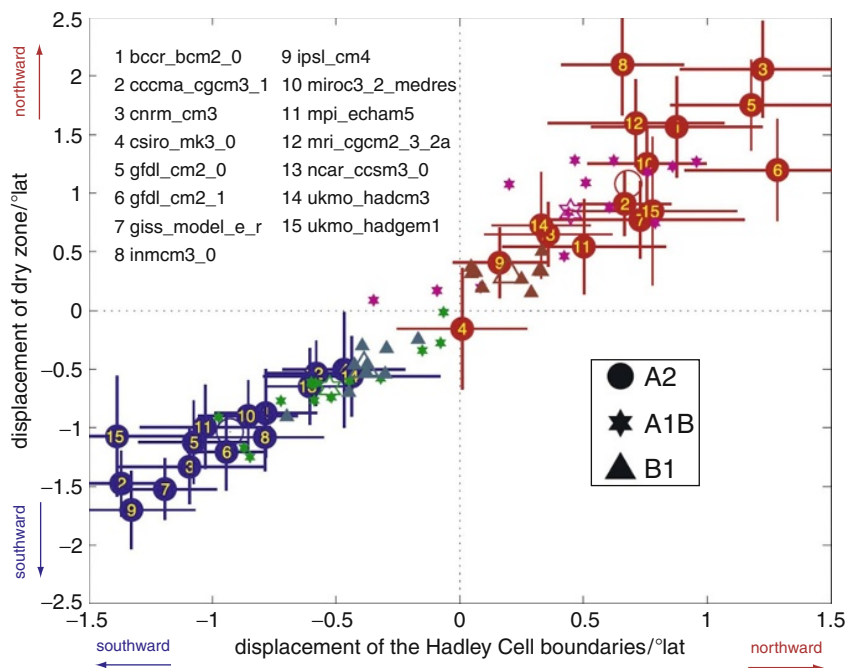
Model simulated widening of the tropics

FIGURE 4   Displacements of (*x*-axis) the poleward boundaries of the tropical HC and (*y*-axis) the subtropical dry zone for different GCMs and scenarios. Reddish colors are for the NH and bluish colors are for the SH. The circles, hexagrams, and triangles denote the changes (2081–2100 minus 2001–2020, in degrees latitude) estimated from the A2, A1B, and B1 scenarios of the IPCC-AR4 simulations. The open symbols denote the multimodel ensemble mean values. The crosses centered on each circle show the 95% confidence intervals using a Student's *t*-test. Adapted from Ref. [22].

for example, raised the possibility that the poor representation stratospheric processes in the IPCC-AR4 models [24,25] may be in part responsible.

However, there are also reasons that may help to reconcile the discrepancies between observed and simulated trends. For example, the width of the tropics may undergo large natural swings on decadal and longer time scales; although model-derived estimates of this component of variability do not seem to support this explanation [19]. In addition, despite the increase in greenhouse gases, future trends may be smaller than past trends because of the expected recovery of stratospheric ozone [26]. And lastly, given the difficulty to make consistent long-term atmospheric observations, it is likely that the observed trends contain large uncertainties. Based on these limitations, it is currently impossible to say how realistic models simulate past and future widening trends.

4. THE DECREASING INTENSITY OF THE TROPICAL CIRCULATION

Another important aspect of the tropical overturning circulation is its strength. Theoretical considerations suggest that global warming weakens the strength of the mean tropical circulation [27,28]. This can be understood from the increasing moisture holding capacity of air in a warmer world, which is not followed along by an equivalent intensification of the hydrological cycle. A circulation slow-down is required to compensate for the difference.

Long-term observations of sea level pressure over the tropical Pacific reveal a weakening of the zonally asymmetric Walker circulation [29,30], which is consistent with the theoretical findings. Model simulations suggest that this downward trend is largely due to anthropogenic forcing and that this trend is going to continue in the future [28,31,32]. Warming of SSTs seems to be mostly responsible for the weakening [33].

For reasons yet to be understood, models also suggest that the weakening of the tropical circulation affects mostly the east–west oriented Walker circulation and not so much the zonal-mean HC [22,28]. This finding is also supported by the analysis of radiosonde data [34]. Atmospheric reanalyses give a somewhat mixed picture in this respect, with some indicating intensification and others showing no change [34,35]. This discrepancy may be related to well-known quality problems of the reanalysis [1]. Overall, the relative stability of the HC strength suggests that intensity changes in the tropical circulation are probably less important for the poleward movement of the HC and other elements of the general circulation.

5. EMERGING MECHANISMS

Understanding why the tropics are expanding under climate change is an area of active research. Several ideas have been put forward so far which, individually or together, may help to explain the phenomenon. Here, I will discuss three principal mechanisms that have been suggested in the literature: the changes in tropical tropopause heights, extratropical eddy activity, and static stability. In addition, I will explain what role recent and future SST changes have for the tropical width.

5.1. Tropical Tropopause Heights

Analysis of radiosonde [36] and reanalysis data [37,38] shows that the height of the global tropopause has increased over the past decades, and GCM experiments indicate that anthropogenic climate change is likely responsible for this increase [39]. This increase has been suggested as a possible reason for the poleward expansion of the tropical circulation. For example, nearly inviscid theory for axisymmetric circulations, proposed by Held and Hou [40],

suggests that the meridional extent of the Hadley circulation varies proportionally with the square root of its vertical depth. However, applying this scaling to the past observed tropopause height increase of about 200 m [39] leads to a tropical expansion of only 0.1° latitude per decade, which is less than what is suggested by the observations and by most models. Analyses of idealized [41,42] and more complex climate models [22,43] also demonstrated that the Held and Hou theory does not provide a good explanation for the full parameter dependence of the meridional extent of the HC.

Other studies have suggested that changes in tropopause heights poleward of the jet are key to the poleward shift of the jet and the tropical edges [21,44,45]. These modeling studies have in common that the height of the tropopause is controlled by externally imposed temperature changes above or below the tropopause. However, this not only affects the height of the tropopause but also the meridional temperature gradients, the zonal winds, and the vertical wind shear by way of the thermal wind relationship. The additional circulation changes make it difficult to unequivocally assign the cause for the tropical widening to the lifting of the tropopause. In addition, none of the above studies puts forward a convincing physical mechanism by which tropopause height changes impact the position of the jets and the tropical edges.

5.2. Extratropical Eddies

The aforementioned recent increase in global tropopause heights is closely associated with systematic temperature changes below and above the tropopause [46]. Temperatures have been warming in the troposphere and cooling in the stratosphere, both of which have shown to be related to anthropogenic activity [47–49]. The pattern of warming and cooling also affects the zonal wind structure in the region of the subtropical upper troposphere and lower stratosphere (UTLS). This is related to the height structure of the tropopause. In the tropics, the tropopause is high and global warming reaches up to ∼16 km. In the extratropics, the tropopause is low and warming reaches only up to ∼12 km, followed by cooling in the stratosphere above. Thus, at intermediate heights of the UTLS region (∼12–16 km) the tropics warm and the extratropics cool, leading to an increase in meridional temperature gradients, and, by the thermal wind relationship, to an increase of zonal wind speeds above.

Chen and Held [50] proposed a mechanism that establishes a connection between the pattern of warming and cooling in the UTLS region, the associated zonal wind anomalies, and the poleward movements of the jets. Extratropical tropospheric eddies play a central role in this mechanism. The eddies tend to move eastward with the zonal flow and equatorward toward the subtropics until they approach their critical latitudes, where their phase speed equals the speed of the background zonal flow. There, the waves grow in

amplitude, break irreversibly, and decelerate the flow as a result of the absorbed wave activity. A key to understanding the mechanism is that the zonal wind in the UTLS region determines the eastward phase speed of extra-tropical tropospheric waves. Climate change related increases in UTLS winds increase the speed of the waves. According to critical layer theory, the now faster waves cannot penetrate as far equatorward into the regions of decreasing zonal winds. This in turn confines the zone of the eddy-driven jet more poleward and leads to a more positive state of the AMs.

Critical elements of this mechanism were identified in both model simulations and observations [50]. Later, this mechanism was extended by arguing that the poleward shift of the eddy-driven subsidence in the subtropics not only affects the AMs but also the HC related portion of the subsidence, which would move the boundaries of the HC and thus the tropical edges poleward [51].

5.3. Static Stability

Changes in the vertical temperature structure of the atmosphere provide yet another explanation for the tropical widening. Such changes are related to the vertical non-uniformity of the tropospheric global warming signal. Observations as well as model experiments indicate that the global warming signal in the upper troposphere is stronger than in the lower troposphere and that it maximizes in the tropical upper troposphere [52,53]. The upper tropospheric amplification is a well-established consequence of the quasi-moist adiabatic adjustment of the atmosphere, which leads to an increase in static stability in both the tropics [54,55] and extratropics [56–58].

Theory proposed by Held [10] establishes a connection between static stability and tropical width. The theory assumes that the upper, poleward moving branch of the HC is angular momentum conserving. The poleward moving air increases its zonal wind speed until it becomes baroclinically unstable and breaks down under the growing vertical wind shear. This marks the latitude of the outer boundary of the HC. Global warming related increases in static stability postpone the point where the atmosphere becomes baroclinically unstable. As a consequence, the HC expands towards higher latitudes.

The original theory was later refined by arguing that the poleward movement of the HC is intimately tied to the eddy-driven jet [51]. Global warming related reduction of baroclinicity at the equatorward flank of the eddy-driven jet stabilizes eddy growth and moves the jet and the associated subsidence toward the poles. The HC follows along since in the subtropics both HC and eddy-driven jet are associated with subsidence.

Independent of which interpretation is best, studies with both idealized models [41,43] and full global climate models [22,51] confirm that the Held [10] theory holds reasonably well in model simulated climates. For example, in idealized parameter sweep experiments, which were forced with prescribed

SSTs, Frierson et al. [43] find that the global mean warming is the primary reason for the expansion of the HC and that increases in meridional temperature gradients play only a secondary role. It is also noteworthy that the global warming related increase in static stability is expected to be particularly strong during summer and over the SH [57], which is consistent with the regional and seasonal patterns of the observed tropical widening [14,59].

5.4. The Role of SST Forcing

Surface temperatures over the tropical oceans undergo changes over time, which have been shown to have important consequences for the global atmospheric circulation [60,61]. These SST changes are primarily related to the natural ENSO phenomenon and to anthropogenic climate change. ENSO related SST fluctuations are periodic in nature and mainly affect the equatorial Pacific. Besides, global SSTs exhibit significant long-term trends that are associated with anthropogenic climate change [62]. The trends over the tropical Pacific resemble the SST pattern that exists during the warm phase of ENSO, which is related to the climate transition from 1976 to 1977 and the associated upward swing of the Pacific Decadal Oscillation (PDO) [63,64].

Various studies have demonstrated that the tropics are contracting during the warm phase of ENSO (El Niño), as indicated by equatorward displacements of the jet, storm track, eddy momentum divergence, and edge of the HC [33,51,65–68]. This equatorward shift is most pronounced over the SH, but it is also detectable over the NH. One way of understanding the contraction is the intensification of the thermally driven Hadley circulation as the equatorial SSTs become warmer [69]. The stronger HC leads to a westerly acceleration in its upper, poleward moving branch and thus to a strengthening of the subtropical jet. Invoking similar arguments as before, this moves the critical latitude for extratropical wave propagation equatorward, allowing the extratropical eddies to penetrate deeper into the tropics than during normal or cold ENSO conditions. As a result, elements of the circulation, including the tropical edge, shift equatorward.

An alternative explanation for the contraction of the tropics during El Niño is that the increased equatorial heating increases the pole-to-equator temperature gradient and draws the zone of maximum baroclinicity towards the equator. Consequently, the eddy-driven part of the circulation is shifted towards lower latitudes. There is also evidence that the increase in surface baroclinicity in association with El Niño impacts the type and number of non-linear wave breaking, which in turn may change the structure and position of the jet [68,70].

Lu et al. [71] found that the tropics are also contracting when a GCM is only forced by the observed history of SST and sea ice distribution but when atmospheric radiative effects due to natural and anthropogenic sources are

excluded from the forcing. This can be understood from the El Niño-like pattern in the long-term trend of equatorial Pacific SSTs, which causes an equatorward shift of the circulation. This suggests that the tropical widening is largely a result of radiative effects (i.e., increased greenhouse gases and/or stratospheric ozone depletion), and that tropical effects are less important than extratropical effects. The finding by Lu et al. [71] also illustrates that climate change related shifts of the general circulation are complex and that the full response cannot be explained from one single mechanism alone.

6. CONNECTION TO EXTRATROPICAL CIRCULATION CHANGE

The extratropical circulation also undergoes important shifts under climate change, as revealed by observations and model data. The most prominent examples are the AMs, which are the dominant modes of large-scale extratropical variability [72]. The AMs are defined by shifts in sea level pressure between the high and middle latitudes, which are associated with equivalent barotropic changes in zonal winds, temperature, and geopotential height. There exists a tight relationship between AM variability and the position of the eddy-driven jet [65]; in other words, a positive AM is congruent with a poleward shift of the eddy-driven jet and its associated momentum fluxes.

The AMs have exhibited positive trends in both hemispheres in recent decades [73,74]. These were associated with lower than normal pressure over the poles and meridional shifts of the eddy-driven jet and the surface westerlies. The past trends were robust over the SH [15,74,75] but somewhat ambiguous over the NH [76–79]. Climate change simulations suggest that these trends are caused by increases in greenhouse gases and stratospheric ozone depletion [20,80–83].

Changes in the extratropical circulation are largely consistent with trends in the tropical circulation. For example, Previdi and Liepert [84] found in the IPCC-AR4 simulations a significant connection between variability in the AMs and the width of the HC: An increase in the AM index is accompanied by a poleward movement of the HC, and future upward trends in the AMs explain about half of the future expansion of the tropics. Consistent with the tendency toward more positive AMs, the twenty-first century simulations of the IPCC-AR4 [80] and other simulations [85] show that the extratropical storm tracks and the zone of the maximum surface westerlies move poleward and become more intense under global warming.

The observed and projected shifts of the AM under climate change can be explained, at least in part, by the eddy mechanisms [86] mentioned before: increased greenhouse gases and/or stratospheric ozone depletion lead to upper tropospheric warming and lower stratospheric cooling across the tropopause slope, which increases the UTLS winds and the phase speed of midlatitudes eddies. Invoking critical layer arguments, this results in a poleward shift of the eddy momentum flux convergence in the midlatitudes (i.e., a more

positive AM). At the same time, the eddy-driven subsidence in the subtropics is also shifting poleward, which helps to explain the phase variability between the AM and the tropical width.

Stratospheric climate change also seems to be connected to the widening of the circulation. Increases in greenhouse gases and ozone depleting substances over the past have led to a substantial cooling of the stratosphere, especially over higher latitudes [48]. The resulting changes in zonal wind structure and subsequent dynamical interaction between the stratosphere and troposphere [87,88] may influence tropospheric climate [25]. The recent increase in the AM index over the SH has been linked to stratospheric ozone depletion over the Antarctic [74,81,82]. In the future, the additional build-up of greenhouse gases is expected to lead to a year-round positive shift of the AMs in both hemispheres. Over the SH, this positive trend is opposed by the expected recovery of stratospheric ozone over the SH [26]. Model simulations indeed demonstrate that ozone recovery has a seasonal effect that dominates and reverses the positive AM trend during summer [24,89].

7. OUTSTANDING PROBLEMS AND CONCLUSIONS

In summary, there exists considerable scientific evidence that key-elements of the atmospheric circulation have been moving poleward during the last few decades. Current theories as well as model experiments indicate that human activity in association with greenhouse gas increases and stratospheric ozone depletion is the most likely cause for the trends. However, it cannot be ruled out that natural climate variability also plays an important role, and there are many other aspects of these shifts that are not well understood.

The most notable reason for this deficit is the lack of climate-quality observations. Such observations are required to accurately characterize the nature of change, to validate climate models, and to falsify theories. However, as demonstrated by the wide range of outcomes from the tropical widening studies, the uncertainties in observing this phenomenon are large. Better observations are also needed to explore the regional and seasonal characteristics of the trends, and to decide how much of the observed change is due to natural low-frequency variability. It is hoped that some of these issues can be resolved in the near future, when satellite-based observation records will be long enough to be useful for climate studies. One of these records could come from the global positioning system radio occultation (GPS-RO) technique, which has great potential for monitoring the poleward edges of the tropics [90].

To some extent, model simulations can make up for what observations are lacking. But, as with the observations, the spread of outcomes in the current generation of models is still unsatisfactorily large. Although most models indicate a tropical expansion over the past, some actually simulate a contraction. These discrepancies may be related to differences in forcings, but

important systemic inter-model differences are likely to be responsible as well. Understanding why the various models arrive at different answers and reconciling the differences would greatly aid in understanding the underlying causes and mechanisms for the widening and lead to more reliable simulations of the future widening.

There has been a marked improvement in our theoretical understanding of the circulation change. Three important mechanisms have been presented in this review, but it is still unclear which, if any, is correct. If several mechanisms are involved, then their relative contributions need to be understood. There is a strong indication that structural changes in extratropical eddies in relationship with lower stratospheric temperature change are behind some of the trends. However, increasing amounts of water vapor in a warmer climate may also modify eddy structure and thus lead to circulation change. This issue has not been adequately addressed, so far. A related question is whether the extratropical and tropical circulation trends have a common cause and whether they are connected to a similar mechanism.

What are the consequences of changes in the general circulation for other components of the Earth climate system? So far, the basic structure of the atmospheric circulation has remained unaltered and the position changes are only of modest amplitude. But even small shifts in the location of the HC, jets, and stormtracks can have important implications for regional climates by modifying patterns of storminess, temperature, and precipitation [85,91]. Particularly sensitive are regions with large spatial gradients in their normal distribution of precipitation, like the subtropical dry-zones (Fig. 4). There, even small trends decide whether there is a surplus or a deficit in overall rain. For example, the expansion of the HC may cause drier conditions over the subtropical semi-arid regions, including the Mediterranean, the southwestern United States, southern Australia, and southern Africa [23], and it was speculated that this process is already under way [91]. Atmospheric circulation change may also alter ocean currents. Because oceans are important regulators of climate, this may induce complicated and unexpected feedbacks, which either amplify or diminish the original cause for change.

Given the important role of the atmospheric general circulation for climate, any change in its structure is of concern. It may lead to profound changes in other parts of the global climate system with potentially important implications for natural ecosystems and human societies.

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APPENDIX: LIST OF ABBREVIATIONS

AM	annular mode
ENSO	El Niño Southern Oscillation
GCM	general circulation model
HC	Hadley cell
IPCC-AR4	fourth assessment report of the intergovernmental panel on climate change
ITCZ	inter tropical convergence zone
NH	northern hemisphere
PDO	Pacific decadal oscillation
SH	southern hemisphere
SST	sea surface temperature
UTLS	upper troposphere/lower stratosphere

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