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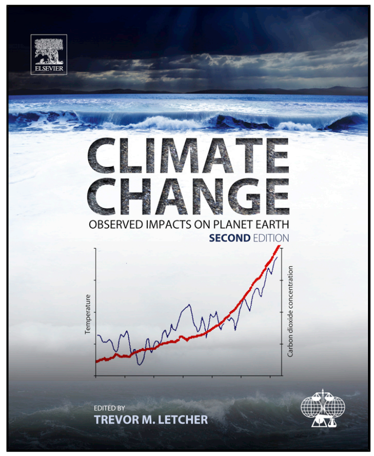

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CHAPTER

POLEWARD EXPANSION OF THE ATMOSPHERIC CIRCULATION

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CHAPTER OUTLINE

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 that have taken place over the past and that are expected to take place in the future with ongoing climate change. These changes are best described as poleward displacements of major wind belts 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 our ecosystems and societies because they control the regional expression of global climate change.

Changes in regional precipitation are amongst the most important and least well-understood consequences of climate change. Such changes are largely determined by shifts in the large-scale circulation, which controls vertical motions, cloud development, and thus precipitation [1,2]. Unfortunately, our ability to understand and predict circulation-related change is low compared to temperature-related change [3,4]. Predictions of circulation-related aspects of climate differ widely amongst models, and even simulations from the same model are strongly affected by internal

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variability [5]. Better understanding circulation change and its relationship to other aspects of climate change is therefore a crucial piece in the puzzle of climate sciences. In fact, the question of how the position, strength, and variability of winds change and how this affects the formation of clouds are at the heart of one of the recently identified Grand Science Challenges of the World Climate Research Programme [6].

This review is focused on important aspects of recent change in the large-scale circulation: First, tropical circulation change related to a poleward expansion and reduced intensity of the Hadley cell (HC), and second, extratropical circulation change, as manifested by a poleward shift of the storm tracks and 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 to what extent the two phenomena are connected.

Much progress has been made over the past decade in the study of the problem, and scientific focus is shifting away from finding evidence for circulation change and determining its magnitude to attributing it to specific causes and understanding the underlying dynamical mechanisms. This review is therefore focused on the causes and mechanisms of circulation change. The reader who is more interested in detection issues is referred to other excellent reviews on the widening phenomenon [7–9]. Further, this review gives about equal room to tropical and extratropical circulation change, as research suggests that both phenomena are important and they are related to each other.

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 problem to reliably monitor 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 [10].

Because of the difficulty of observing the atmospheric circulation and its long-term trends, most studies of circulation change not only rely on observation-based evidence but also include findings from general circulation models (GCMs). GCMs are not perfect, 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. This makes GCMs indispensable research tools, in particular for the search for human influences on climate.

At the beginning of this review, we will develop some basic understanding for the nature of the atmospheric circulation, which is necessary information for the remainder of this chapter. Next, I will give a brief overview of observation and model-based evidence of past and future circulation change. I will also clarify the connection between tropical and extratropical circulation change. Then, I will focus on the two most pressing questions regarding circulation change: what are the causes, and what are the physical mechanisms? As I will explain, there are still many unknowns regarding these questions, but continuous progress is being made and studies begin to converge toward similar answers. I will conclude by summarizing some outstanding research questions and by explaining the significance of circulation change for other aspects of climate change.

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2. THE GENERAL CIRCULATION OF THE ATMOSPHERE

The general circulation of the atmosphere describes the global three-dimensional structure of atmospheric winds. Halley [11] was probably the first to realize that the sphericity of the Earth, and the resulting spatially nonuniform distribution of solar heating, are the basic drivers behind this circulation. The tropics absorb about twice the solar energy than the higher latitudes absorb, creating a meridional gradient in temperature and potential energy. Some of the potential energy is converted into kinetic energy [12], 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' [13].

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 [14]. The resulting tropical circulation is very distinct from the extratropics. The HC [15] 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 air warms, becomes buoyant, and rises toward 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 toward 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.

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The Walker circulation [16,17] 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 [18].

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 [19]. The stirring creates net fluxes of zonal momentum out of the jet and into the midlatitudes, which are so-called eddy stresses or 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 [20]. This jet is often merged with the subtropical jet, giving the appearance of only one tropospheric jet centred at ~30° latitude [21]. Only over the southern hemisphere (SH) and during winter are the two jet systems fairly well separated.

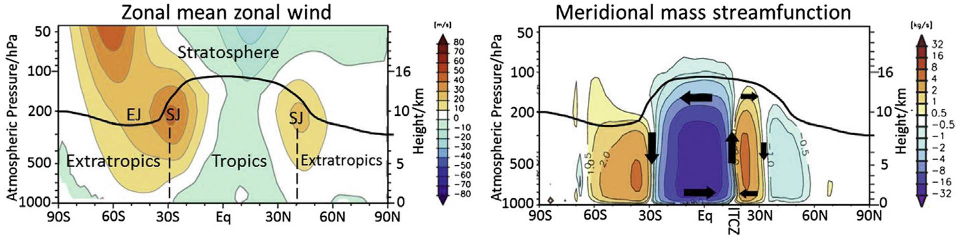

FIGURE 1

Zonal mean view of the general circulation during 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. (Left) Zonal mean zonal winds (in m s^{-1}) derived from NCEP/NCAR reanalysis. SJ indicates the two subtropical jet cores, and EJ denotes approximate position of the eddy-driven jet. (Right) Mean meridional mass stream function (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.

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 happening, discuss the specific causes for it, and explain some of the underlying dynamical mechanisms.

3. EVIDENCE FOR CIRCULATION CHANGE

3.1 THE WIDENING TROPICS

It was about 10 years ago that scientists started to realize that shifts in the atmospheric circulation are amongst the many consequences of climate change. Using a variety of metrics and data, it was found

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that the edges of the HC have been moving poleward at both its northern and southern margins since the 1970s. The finding was significant because the edges of the HC also represent the boundaries of the tropics, regions with sharp meridional gradients in precipitation. There, even small changes in the location of the HC edge can create significant variations in precipitation, leading to either significantly drier or wetter conditions.

Rosenlof [22] was one of the first to mention potential trends in tropical width. She examined the latitudinal extent of the upwelling branch of the Brewer–Dobson circulation in the lower stratosphere, which can be regarded as one indicator for the width of the tropical belt. From reanalysis she found that the width increased by about 3° latitude per decade (1992–2001). From what we know today, this is an unrealistically large trend, which may be related to considerable observational uncertainty.

Later, Reichler and Held [23] investigated the structure of the global tropopause surface as another indicator of tropical width. This indictor is based on the well-known distinction between a high (*ca.*16 km) tropical and a low (*ca.*10 km) extratropical tropopause (Fig. 1). Using data from radiosondes (Fig. 2) and reanalyses, it was shown that the tropics have been expanding by about 0.4° latitude per decade since 1979. Similar trends were found from measuring the separation between the cores of the northern and southern subtropical jets.

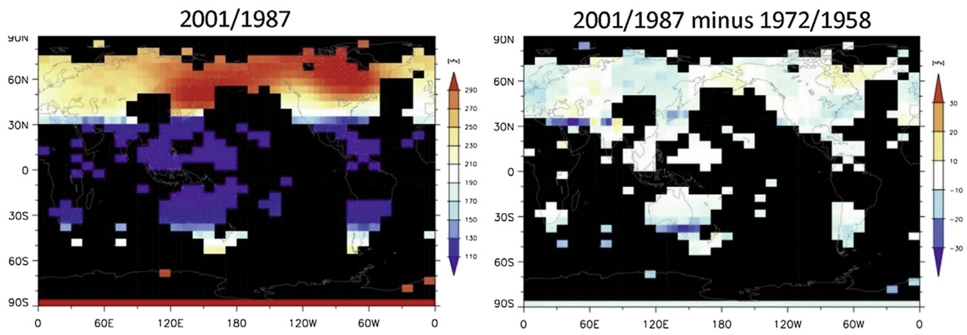

FIGURE 2

Changes in tropopause pressure during boreal winter (DJF) derived from gridded radiosonde data HADRT V2.1 [194]. (Left) Absolute tropopause pressure (in hPa) averaged over 1987–2001. (Right) 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 much lower pressure, indicative for tropical tropopause conditions, and thus a widening of the tropics. *(Adapted from Ref. [23].)*

The initial studies sparked a flurry of new research activity, aimed at detecting and understanding the new phenomenon and its underlying cause. For instance, Fu et al. [24] examined long-term data (1979–2005) from the satellite-borne microwave sounding unit (MSU) and found that the mid-tropospheric 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. [25] 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 for tropical regions, has increased over time. Seidel and

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Randel [26] 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. Additional satellite-derived indicators for tropical expansion are data for precipitation and clouds [27,28], outgoing long-wave radiation [29,30], and lower-stratospheric MSU temperatures [31].

Now, after one decade of research and after multiple independent studies using a variety of metrics were conducted, there is no longer doubt that the tropical belt has been widening and will continue to do so as a consequence of ongoing climate change. Some studies [29] suggest that the trends have a regional and seasonal structure, and that trends are strongest during summer of the respective hemisphere. Other studies [32] find that the hemispheric and seasonal differences in trends are not statistically significant.

3.2 INDICATORS OF TROPICAL WIDTH

A large variety of indicators have been used to determine the tropical edge and other circulation features. Having so many indicators is problematic because outcomes from the individual studies are difficult to compare with each other. The large number of indicators is a consequence of the lack of a unique and commonly accepted definition for the tropics. As shown in Fig. 3, atmospheric properties vary more or

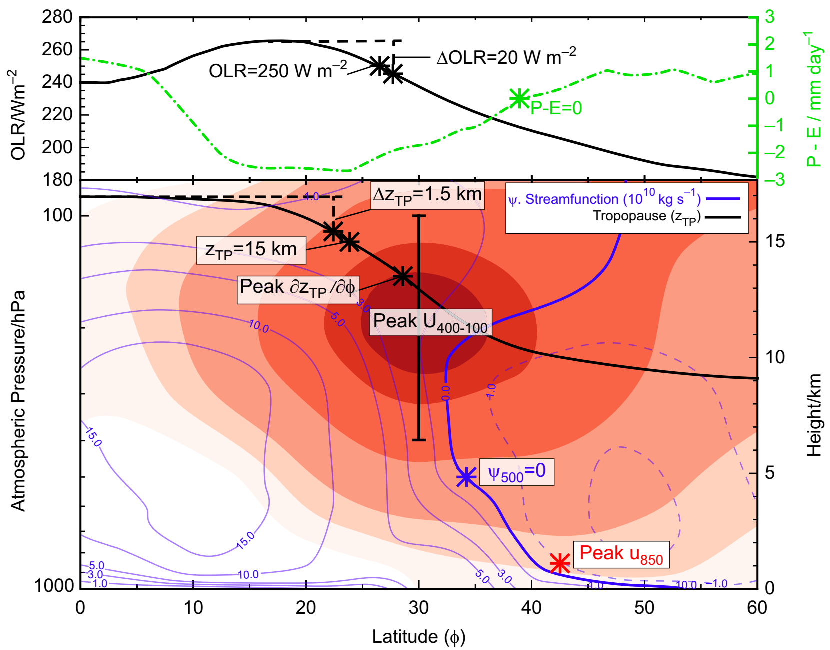

FIGURE 3

Indicators for circulation shifts. Shown are cross-sections of various atmospheric properties used to diagnose the location of the tropical edge and the eddy-driven jet. The quantities are zonal-mean zonal wind (reddish shading, 5 m s^{-1} contours), mean meridional stream function (blue contours), height of the tropopause (bold black line), difference between precipitation and evaporation (P-E, broken green line), and outgoing long-wave radiation (OLR) (top panel black line). The location of the individual diagnostics is denoted by asterisks. *(Adapted from Ref. [32].)*

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less gradually between the tropics and the extratropics, and there is no easily identifiable boundary between the two zones. Some of the indicators involve arbitrary thresholds, which is problematic as changes in tropical width may interfere with other aspects of climate change [32]. For example, Birner [33] found that tropopause-derived widening trends are sensitive to the assumed tropopause height.

The indicators used so far can be roughly divided into two groups. The first group is based on dynamical definitions, focussing on specific aspects of the circulation at the outer edges of the tropics. Examples are the overturning stream function, the subtropical jet cores, or the latitude where low-level winds change from westerly to easterly. The second group is based on more physical properties of the atmosphere, such as the outgoing long-wave radiation, the concentration in stratospheric ozone, the height of the thermal or dynamical tropopause, the relative humidity, or the difference between precipitation and evaporation at the surface. Lucas et al. [9] give a detailed explanation of these and other indicators and provide an in-depth discussion of the differences and uncertainties associated with them.

3.3 THE DECREASING INTENSITY OF THE TROPICAL CIRCULATION

The intensity of tropical circulation systems may also have been changing during recent decades. Although there is no direct observational evidence for it, thermodynamic arguments suggest that global warming should weaken tropical circulation systems like the HC and the Walker cell [34,35]. This can be understood from the increasing moisture-holding capacity of warmer air, which is not followed along by an equivalent intensification of the hydrological cycle. A circulation slowdown is required to compensate for the difference.

Long-term observations of sea level pressure over the tropical Pacific indeed suggest a slowing of the Walker circulation [36,37], as suggested by the theory. Climate model simulations forced with anthropogenic factors are able to reproduce the past trend, indicating that the trend is related to warming SSTs [38]. Model simulations further suggest that mostly the Walker cell and to a much lesser degree the HC are affected by it and that the decrease will continue into the future [35,39–41]. Atmospheric reanalyses give a somewhat mixed picture of past changes, with some indicating intensification and others showing no change in the intensity of the HC [42–44].

3.4 EXTRATROPICAL CIRCULATION CHANGE

After realizing that climate change is connected to an expansion of the tropics, it was found that large-scale extratropical circulation features are also shifting poleward. For example, both the storm tracks and the eddy-driven jets have been moving toward higher latitudes [28] and are expected to continue to do so in the future [45,46]. The poleward movement of the eddy-driven jet is closely related to changes of the annular mode (AM) index [47], which is the dominant pattern of extratropical circulation variability [48]. Changes in the AM index are associated with shifts of atmospheric pressure (or mass) between the high and middle latitudes, and thus with changes in geopotential height, wind, and temperature.

Multiple lines of research indicate that the AMs underwent positive trends during recent decades [49–51]. The trends were unambiguous over the SH [24,50,52] but much less clear over the NH [53–58]. Simulations with climate models indicate that the past AM trends are caused by a warming climate associated with increased amounts of greenhouse gases and by stratospheric ozone depletion

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[59–64]. Further, models indicate that under future increases of greenhouse gases the AMs tend to become even more positive [59,65,66], except over the SH during summer when the expected recovery of stratospheric ozone counteracts the trend from increasing greenhouse gas concentrations. Consistent with positive AM trends, the twenty-first-century simulations of the Coupled Model Intercomparison Project Phase 3 (CMIP3) [60], CMIP5 [66], and other models [67] show that the positions of the extratropical storm tracks and the zone of maximum surface westerlies move poleward and become more intense.

There is evidence that tropical and extratropical circulation trends are connected by similar causes and mechanisms. Kang and Polvani [68] found a significant positive correlation between interannual variations in the latitude of the eddy-driven jet and the edge of the HC—for every degree of poleward HC shift, the eddy-driven jet moves in the same direction by about twice that amount. Staten and Reichler [69] extended this analysis and confirmed that the tropical and the extratropical circulation move in certain proportions. However, the ratio between the two shifts changes by season, hemisphere, model, and even for the same model under different forcings. Kidston et al. [70] suggested that the separation distance between the HC and the eddy-driven jet is a good indicator for the ratio. In other words, the closer the two circulation systems are together, the tighter is the coupling between them.

Tropical and extratropical circulation systems are not only connected on interannual timescales. Analysis of the CMIP3 simulations shows that future upward trends in the AMs explain about half of the future expansion of the tropics [71]. Per standard deviation increase in the AM index, the HC is displaced poleward over the NH by 0.40° and over the SH by 0.26°.

3.5 MAGNITUDE OF PAST AND FUTURE TRENDS

In terms of the magnitude of the past poleward shifts of the HC edge, earlier studies arrived at estimates that ranged between 0.3° and 3° latitude per decade [7]. The large range of outcomes can be explained from observational uncertainties, different data sets, different methodologies, and different start and end dates [32]. Some of the earlier estimates of tropical widening were probably too large because they would have been associated with extreme shifts in climate that were not observed.

Table 1 provides an overview of observational and model based poleward circulation shifts from some of the more recent studies. Compared to the earlier estimates, the trend numbers are now smaller and probably more realistic. Allen et al. [72] used a combination of observations and indicators to arrive at best estimates of past expansion of 0.35° per decade over the NH and 0.17° per decade over the SH, which is at the low end of the earlier studies. Another independent study by Fu and Lin [31], using satellite-derived estimates of lower-stratospheric temperatures, arrives at very similar estimates.

When climate models are driven by the observed history of forcings, the simulations also produce a widening. Most of the twentieth-century scenario integrations from the CMIP3 project reproduce the widening of the tropopause [23]. Using the mean meridional circulation as indicator for the tropical edge, the consensus estimate of all CMIP3 models is a total (NH and SH combined) widening of 0.2° latitude per decade over the period 1979–2005 [73]. The mean of the historical simulations from the latest CMIP5 models arrives at even smaller rates: 0.05° over the NH and 0.13° over the SH [72]. The numbers demonstrate that the model-simulated trends for the past are about 3–6 times smaller than the observed trends, in particular over the NH. This led some to speculate that perhaps model deficiencies are to blame for the discrepancies between models and observations [73]. Seidel et al. [7] raised the possibility that the poor representation stratospheric processes in the CMIP3 models [74,75]

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Table 1 Annual mean expansion rates (in degrees latitude per decade) over NH and SH

Period	Metric	Data	NH	SH	Source
1979–2009	HC edge (combination of 5 methods)	Various reanalyses and observations	0.35°	0.17°	[72]
1979–2009	HC edge (stream function)	Various reanalyses	1° (NH + SH)		[32]
1979–2009	Subtropical jets	MSU lower-stratospheric temperatures	0.5°	0.5°	[31]
1979–2005	HC edge (stream function)	CMIP3 (historical simulations, all forcings)	0.2° (NH + SH)		[73]
1979–2009	HC edge	CMIP5 (historical simulations, all forcings)	0.05°	0.13°	[72]
2000–2100	Subtropical jets	CMIP3 A2	0.2° (NH + SH)		[41,73]
1993–2100	Low-level wind maximum (eddy-driven jet)	CMIP5 RCP8.5	0.09°	0.19°	[66]

may be in part responsible. However, there are also other reasonable explanations, such as the shortness of the observed data record, combined with observational uncertainty and internal climate variability. More recently, Allen et al. [72] found that when the CMIP5 models are forced with the observed history of SSTs, the simulated widening agrees much better with the observations than when the models predict their own SSTs. Allen and colleagues conclude that internal climate variability associated with the recent trend of the PDO is the most likely reason for the discrepancies. If correct, then there is no reason to believe that model-simulated circulation widening is unrealistic.

Given the relatively small past expansion rates of 0.2°–0.4° latitude per decade, one may ask how models respond to future stronger greenhouse gas increases. Kushner et al. [59] forced a fully coupled GCM with $\sim$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. Under the A2 scenario of the CMIP3 project, models reproduce robust poleward shifts of the jets [76], with an ensemble mean response of about 0.2° latitude per decade (NH and SH combined) over the period 2000–2100 [41,73]. The CMIP5 models under the RCP8.5 scenario predict very similar trends of 0.09° over the NH and 0.19° over the SH [66]. In addition, the speed of the eddy-driven jet is found to increase markedly, but only over the SH [66].

4. CAUSE FOR CIRCULATION CHANGE

Which factors are to blame for atmospheric circulation change? Numerous studies have tried to answer this question, using single-forcing experiments with models to isolate the role of the individual natural and anthropogenic factors. But finding conclusive answers turns out to be difficult, simply because climate change–related shifts of the general circulation are complex. Some of the complicating issues are the superposition of various, partly opposing effects, nonlinearities of the system, previously unknown or unrecognized factors, and unrealistic model responses to such factors.

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Two types of models are commonly used in the study of circulation change. The most common are complex GCMs, which simulate as faithfully as possible most known climate processes. However, the complexity of these models limits the number and length of simulations one can afford. The second type are the relatively simple GCMs. They simulate all details of the atmospheric circulation but represent only crudely the physical processes that force the circulation. The simplicity of these models allows more and longer simulations. Therefore, simple GCMs are mostly used in theoretical studies of circulation change, in particular to study the dynamical mechanisms and the sensitivity to variations in the strength and structure of external forcings.

Studies with relatively simple GCMs use idealized and regionally localized thermal forcings to mimic certain aspects of anthropogenic climate change. For example, heating in the upper tropical troposphere, most commonly associated with the global warming response, produces an expansion of the circulation [77–79], but only if the heating is broad enough [79,80]. Wang et al. [78] find an abrupt and large poleward jump of the circulation when the warming in the tropical upper troposphere exceeds a certain threshold. Cooling in the polar stratosphere, representing the effects of ozone depletion, also drives poleward circulation shifts [77]. Surface warming over the pole, representing the effects of Arctic sea ice decline and the associated polar amplification effect, leads to an equatorward contraction of the circulation [77]. Studies with simple GCMs successfully identified some of the principal drivers for circulation change, but the simplicity of these models produces answers that are of limited practical use. In most cases complex GCMs are required to arrive at more realistic answers.

4.1 DIRECT VERSUS INDIRECT EFFECTS

From a theoretical perspective, circulation change is driven by both direct and indirect effects [38]. Direct effects are due to the radiative forcing from changing amounts of greenhouse gases, ozone, and aerosol. These forcings directly impact the atmosphere's temperature structure and this may in turn alter its circulation. However, the imbalance in the Earth's energy due to the radiative forcings also impacts global SSTs. The SSTs in turn further impact the atmosphere's temperature and circulation, leading to an indirect effect. It is still an open question whether the direct or the indirect effect is more important in creating circulation change. Various studies explicitly investigated the relative roles played by the direct and indirect effect. One study finds that SST forcing and direct atmospheric radiative forcing contribute equally to the circulation trends [38], another study finds that the widening can be attributed entirely to the direct radiative forcing [81], and the remaining studies find that the indirect SST effect is the main driver for circulation change [65,72,82]. Probable reasons for the opposing answers are differences in models and methodologies. For example, it depends on the type, structure, and strength of the forcings, whether ozone depletion is considered as a forcing or not, and on the period and hemisphere under investigation. Waugh and colleagues [83] argue that over the SH during the period 1979–1999 ozone depletion was the single most important driver for the poleward expansion of the HC, but that changes in SST dominated the circulation response after that period.

4.2 NATURAL AND ANTHROPOGENIC SEA SURFACE TEMPERATURE VARIATIONS

SSTs change due to natural and anthropogenic reasons. While warming SSTs due to anthropogenic forcings almost always result in a poleward expansion of the circulation, the oscillatory nature of natural SST modes can cause either contraction or expansion. Natural causes are linked to major

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modes of ocean variability, like ENSO, the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO). Anthropogenic causes are related to radiative forcing from increasing concentrations of greenhouse gases and other constituents and have created a significant long-term warming trend in SSTs [84]. The observed trend over the tropical Pacific somewhat resembles the SST pattern that exists during the warm phase of ENSO, and it is also related to the climate transition from 1976/1977 and the associated upward swing of the PDO [85–87]. Aerosol emissions from human activity and from volcanic eruptions have a regional cooling effect on the oceans, in particular over the North Pacific [87] and North Atlantic [88,89].

4.3 TROPICAL SEA SURFACE TEMPERATURE VARIATIONS

Tropical SST variations, for example, those related to ENSO, impact tropospheric temperatures and circulation in important ways. Lu et al. [81] find that, when a GCM is forced by the observed history of SSTs, and when direct radiative effects from ozone and greenhouse gas changes are excluded, the tropical circulation contracts. This perhaps somewhat surprising result can be understood from the upward trending PDO during the 1980s and 1990s and the fact that a positive PDO is similar to an El Niño-like warming in the equatorial Pacific [57]. In other words, a positive PDO or a warm ENSO anomaly contracts the circulation because equatorial SSTs warm. Impacts of the AMO on the latitudinal extent of the circulation are less certain, but the tropical lobe of the AMO may have similar effects on the atmospheric circulation as the PDO. Indeed, there is modelling evidence [90] that the positive phase of the AMO leads to a negative NAO and thus to an equatorward shift of the eddy-driven jet. If this holds true, the recent trend of the AMO toward its positive phase [57] would counteract the widening of the circulation, at least over the Atlantic sector.

Allen et al. [72] investigated the role of SST variations in historical simulations of the CMIP5 project. They found that prescribing the observed evolution of SSTs in models yields NH expansion rates that are in very good agreement with the observations. However, when models predict SSTs, they tend to underestimate the recent widening trend, in particular, over the NH. This indicates that the past expansion over the NH is largely driven by natural multidecadal SST variability related to the PDO. The SST influence leads to a contraction when the PDO is in its positive (El Niño-like) phase and to an expansion when the PDO is in its negative (La Niña-like) phase. In other words, it is likely that the recent downward trend of the PDO toward its negative phase reinforces the human driven expansion. Since model-predicted SSTs and also the PDO are not in synch with the observations, this provides a good explanation for why models tend to underpredict the past NH widening. However, a somewhat similar investigation using CMIP3 models does not support this hypothesis since forcing these models with observed SSTs (the so-called AMIP simulations) does not improve model agreement with the observations [73].

4.4 EXTRATROPICAL SEA SURFACE TEMPERATURE VARIATIONS

SST variations over the extratropics also influence the atmosphere and its circulation, in particular, on longer timescales (decades and more). This is suggested not theory [91] and observations [92]. As with tropical SST anomalies, extratropical SST variations are related to both anthropogenic influences and natural modes of ocean variability (AMO and PDO). The SSTs anomalies force the atmosphere, modify its meridional temperature gradients, and influence its circulation. However, relatively little is

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known about the importance and effectiveness of extratropical SST anomalies in driving the circulation. Peings and Magnusdottir [90] found that in terms of the AMO, both tropical and extratropical influences are important, and that the extratropical effect is related to a reinforcement of eddy-mean flow interaction in the atmosphere by the SSTs. Other studies [45,93] also argue that interactive air-sea coupling is crucial in shaping the circulation response to climate change, in particular, over the extratropics. For example, Woolings et al. [45] report that the response of the midlatitude storm track and the eddy-driven jet over the North Atlantic crucially depends on ocean-atmosphere interaction and SST patterns.

4.5 STRUCTURE OF SEA SURFACE TEMPERATURE VARIATIONS

On longer climate change timescales, there is indication that most of the circulation change is the result of global mean warming, and that the exact pattern of warming SSTs has little impact on the response [93]. Frierson et al. [94] studied the response of the HC to global mean and pole-to-equator temperature SST gradients. They also find that the primary sensitivity of the circulation is with increase in mean temperatures. Such findings are also consistent with Deser et al. [5], who argue that the regional details of the circulation response are mostly the result of internal and thus unpredictable variability. However, Gastineau et al. [95] come to different conclusions about the importance of SST patterns in shaping the circulation response. In their model they find that the circulation response is sensitive to the zonal-mean meridional structure of SSTs, and even longitudinal SST variations play some role. Using more idealized models, several studies [79,80,96] also demonstrate that details of the zonal-mean meridional structure of SSTs are crucially important for the latitudinal change of the HC edge and eddy-driven jet. For example, narrow SST warming at the equator produces a contraction of the HC, while a broader, more global warming-like SST increase leads to an expansion.

4.6 ARCTIC TEMPERATURE CHANGE

The global warming single at the surface is particularly strong over the Arctic, a phenomenon commonly referred to as ‘polar amplification’. Polar amplification is thought to be the result from positive feedbacks associated with the melt of snow and ice, as exemplified by the dramatic decline of Arctic sea ice during the past decade. In autumn and early winter the decline produces warmer near-surface temperatures, reduced static stability, and increased lower-tropospheric thicknesses [97]. The study by Butler et al. [77], using a simple GCM, demonstrated that polar warming results in an equatorward contraction of the circulation, presumably because of the decrease of baroclinicity in the atmosphere. Several other modelling studies find a negative NAO during early winter in response to sea ice decline [98–103], consistent with an equatorward movement of the eddy-driven jet. Thus, it is likely that polar amplification and Arctic sea ice decline, particularly that in the Kara Sea to the north of Europe [104], counteract to some extent the effect of most other known forcings in expanding the circulation poleward.

4.7 GREENHOUSE GAS INCREASES

Multiple studies identified the thermal forcing from changing concentrations of greenhouse gases, ozone, and aerosol as an important contributor to circulation change. The 2001 study by Kushner et al.

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[59] was probably the first to recognize this. Many subsequent studies were conducted, using observations [105], specific climate models [61,65,67,81,106–112], or climate models from the CMIP3 [41,60,64,73,76,113–115] and CMIP5 [66,72,82,116,117] archives. Most studies arrive at the same two main conclusions: first, greenhouse gas–related global warming leads to an expansion of the circulation over both hemispheres; and second, historical simulations using predicted SSTs do not simulate the full extent of the widening seen in past observations [7,73]. Allen et al. [72] argue that the discrepancy between models and observations can be explained from the deficient simulation of the effects from natural SST variations and anthropogenic aerosol. There may also be issues with the prescribed ozone depletion that is too weak in some of the studies [83] and with insufficient vertical resolution in the stratosphere [118].

4.8 DEPLETION AND RECOVERY OF STRATOSPHERIC OZONE

Thompson and Solomon [50] were the first to make the connection between upward trend of the southern AM and stratospheric ozone depletion over Antarctica. The initial paper created lots of interest and was succeeded by a large number of modelling studies [62,65,74,109–111,119–123]. The studies confirmed that localized cooling in the lower polar stratosphere due to ozone depletion is an important driver for circulation shifts during late spring over the SH and that models that do not incorporate this effect fail to reproduce the observed trends of the southern AM. Later, it was found that ozone depletion not only affects the AM but also contributes to a poleward shift of the SH tropospheric midlatitude jet and to an expansion of the HC in summer. Further, it was shown that the magnitude of these circulation changes scales quasi-linearly with the stratospheric ozone changes and the associated cooling in the models [121]. Ozone has also been declining over the Arctic, but to a lesser extent than over the Antarctic [124]. The impacts of Arctic ozone depletion to NH tropospheric circulation change are not well understood.

The effects of Antarctic ozone changes for the SH circulation are mostly confined to the period of austral summer (~November–January). Past ozone trends caused a widening and future trends will reverse the previous expansion as ozone is expected to recover. Increasing greenhouse gas concentrations also cause an expansion, but in contrast to ozone, the effects from greenhouse gases are more seasonally uniform and have the same sign in the past and future. A recent observational study [105] finds that past ozone depletion contributed about 50% more than greenhouse gases toward the observed shifts in the SH jet during austral summer. This agrees well with results from several modelling studies [109,119,122], which also find that the ozone effect dominated past trends. In the future, ozone recovery and continued greenhouse gas increases will lead to opposing trends, more or less cancelling their effects on the SH circulation [109,110,119,125]. However, during seasons other than austral summer, the SH circulation is expected to expand because of the continued increase in greenhouse gas concentrations.

4.9 SOLAR VARIABILITY

Natural variability of the sun associated with the 11-year sun spot cycle has been repeatedly suggested as a driver for tropospheric circulation shifts. Observational and modelling studies find that solar maximum produces a poleward shifted jet [126] and a positive NAO [127], and that solar minimum leads to a negative AM response [128]. However, CMIP5 models do not produce significant AM

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responses in response to solar irradiance variations [117], which may be either related to the unrealistic stratospheric representation and solar forcings in these models or to solar influences that are too tiny to be detectable. Overall, the issue of solar influences is controversial, simply because the observational record is too short, irradiance changes associated with the solar cycle are small, and unknown amplifying mechanisms are required to produce a consistent tropospheric circulation response.

A so-called 'top-down' mechanism was suggested to explain solar forcing of the troposphere [129]. In this mechanism, enhanced UV radiation associated with the solar cycle heats the tropical stratosphere and causes shifts in the tropospheric circulation by changing eddy momentum fluxes and reinforcing feedbacks between eddies and the circulation [60]. Another suggestion for solar influences is the so-called 'bottom-up' mechanism, in which the solar forcing warms the oceans [130] and perhaps induces an extratropical ocean-atmosphere feedback [127]. Meehl et al. [130] find that both the top-down and the bottom-up mechanisms are important in producing a consistent solar response in a model.

4.10 NATURAL AND ANTHROPOGENIC AEROSOL

Strong equatorial volcanic eruptions are observed to be followed by winters with an anomalously positive NAO [131]. It is suggested that this is related to the localized heating of the tropical stratosphere due to the radiative effects from the volcanic aerosol, strengthening the equator-to-pole temperature gradient. However, the CMIP3 [132] and CMIP5 [117,118,133] models do not simulate significant and consistent AM changes in response to volcanic eruptions. This indicates that either the models' responses or the observational basis for volcanic effects are flawed.

A relatively small number of studies examined the effects of anthropogenic aerosol on the circulation. Arblaster and Meehl [61] found that past aerosol emissions from natural and also from anthropogenic sources led to a small negative trend of the southern AM. However, Cai and Cowan [134] found the opposite, that ocean cooling from past anthropogenic aerosol emissions shifted the AM over the SH toward a more positive state. Over the NH, the CMIP5 models suggest a small widening trend when forced with the observed history of aerosol [72]. This impact is assumed to be the consequence of an indirect cooling effect of the aerosol on the PDO.

Aerosol may also directly impact the circulation by cooling or warming the atmosphere. Chen et al. [135] found this effect to be relatively small. Later, Allen and Sherwood [136] found in a model a considerable poleward jet shift from modest heating due to prescribed black carbon and sulphate aerosol. They explained the shift from the heterogeneous nature of the aerosol, which impacts only certain regions, and which creates meridional gradients in warming. The differential nature of anthropogenic aerosol over the NH can be somewhat compared to Antarctic ozone depletion, which represents the main heterogeneous forcing agent over the SH. In a follow-up study, Allen and colleagues [137] found that forcing from black carbon and tropospheric ozone is particularly important for the simulation of the observed widening trend, providing a nice explanation for why past model simulations were unable to replicate the magnitude of the observed NH widening.

4.11 LINEARITY OF THE RESPONSE

An interesting question is how additive the effects of individual forcings for the overall circulation response are in the presence of many nonlinear processes in the climate system. In other words, how

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meaningful are single forcing experiments with models, and does the sum of individual forcings lead to the same circulation response as that seen when using the combined forcings? There is unanimous agreement amongst studies with complex GCMs [65,38,109] that the response of the circulation to individual forcings is linearly additive, and that to a very good degree the sum of circulation responses to individual forcings equals the response when all forcings are applied simultaneously. Butler and colleagues [77], however, find in their simple GCM considerable nonlinearities in the responses to various thermal forcings. The reason for this discrepancy may be related to the more idealized character of the latter study.

5. EMERGING DYNAMICAL MECHANISMS

Understanding the dynamical mechanisms by which anthropogenic and natural factors modify the circulation is an area of active research. Climate change is related to anomalous heating of atmosphere and the surface. The regionally uneven distribution of the heating creates spatial temperature gradients, alters the baroclinicity, modifies the mean wind, and changes the structure and propagation of atmospheric waves. However, the importance of the individual events, the sequence in which and the region where they take place, how they are initiated, and how exactly they lead to an expansion of the circulation have yet to be fully unravelled. Past research into these issues led to a range of explanations, indicating that the problem is complex and that perhaps no single answer can provide a full explanation. It further indicates the need for additional research, since understanding the mechanisms will perhaps help reduce the prediction uncertainties of models.

5.1 RELATIONSHIP BETWEEN CIRCULATION, CLOUDS, AND RADIATION

Circulation change is closely linked to change in cloudiness and precipitation [41,123]. Lu et al. [41] demonstrated that the expansion of the HC is correlated with the poleward expansion of the subtropical dry zone. Changes in cloudiness lead to localized anomalies of latent and radiative heating, which in turn change baroclinicity and create feedbacks on the circulation. This raises the question whether and how changes in clouds, radiation, heating, and circulation are connected to each other. Several recent studies started to investigate these and similar issues. All studies highlight the problem of model uncertainties related to change in cloud properties in response to climate change. Grise and Polvani [138] show that cloud changes seen in some of the CMIP5 models in response to jet shifts are inconsistent with the observations, and they argue that this is relevant for future SH circulation change. Ceppi et al. [116] found in the CMIP5 models a tight relationship between changes in the meridional gradient of absorbed shortwave radiation and shifts in the SH jet. The authors argue that intermodel differences in jet shifts are related to model-specific change of cloud properties, which impact shortwave radiation and baroclinicity. Voigt and Shaw [139] also find that different regional circulation responses in a model are related to the way cloud radiative properties respond to global warming.

5.2 STRATOSPHERIC LINKAGES

Many studies have suggested links between climate change in the stratosphere and tropospheric circulation change over the SH. Observed increases in greenhouse gases and ozone-depleting substances over the past led to substantial cooling of the stratosphere, especially over the higher latitudes [140].

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The resulting changes in the zonal winds and the subsequent dynamical effects on the troposphere [141,142] influence the tropospheric circulation [75]. Despite intensive research over the past decade, the exact mechanisms behind this influence are not well understood [143,144]. Possibilities include the balanced tropospheric response to stratospheric climate change [145], change on tropospheric eddies exerted by the stratosphere [146], or influences of lower stratospheric temperature perturbations on tropospheric baroclinic instability [147]. The lower stratospheric cooling from changing levels of ozone and greenhouse gases also increases the height of the extratropical tropopause, which may be linked to tropospheric circulation change.

Polar amplification and Arctic sea ice decline have been repeatedly associated with a tendency toward a negative NAO and equatorward circulation shifts [148]. The stratosphere may be involved in the response of the circulation to polar warming. This may be related to changes in the amplitude and position of planetary waves by the surface heating, enhancing the upward planetary wave flux and weakening the stratospheric polar vortex [149–153]. The dynamical coupling between the stratosphere and troposphere could explain the subsequent tendency toward a negative NAO.

5.3 TROPOPAUSE HEIGHTS

Analysis of radiosonde [154] and reanalysis data [155,156] 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 [106,157]. The increase is related to systematic temperature changes below and above the tropopause [158]. Temperatures have been warming in the troposphere and cooling in the stratosphere, both of which have been shown to be related to anthropogenic activity [159–161]. 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 $\sim$16 km. In the extratropics, the tropopause is low and warming reaches only up to $\sim$12 km, followed by cooling in the stratosphere above. Thus, at intermediate heights of the UTLS region ($\sim$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.

Various studies related the lifting of the tropopause to the poleward expansion of the circulation [41,76,162]. According to a theory from Held and Hou [163], the meridional extent of the HC varies proportionally with the square root of its vertical depth. However, applying this scaling to the past observed tropical tropopause height increase of about 200 m [154,157] leads to a tropical expansion of only 0.1° latitude per decade, which is much less than what is suggested by the observations and by most models. Analysis of idealized [164,165] and complex models [41,94] also demonstrates that the Held and Hou theory does not provide a full explanation for the parameter dependence of the meridional extent of the HC, indicating that additional mechanisms are at work.

Some model studies suggest that lifting of extratropical tropopause heights is connected to poleward shifts of the jet and the tropical edges [76,126,166]. However, some caution is required. Studies lift the tropopause by imposing external thermal forcings to their models. This not only affects the height of the tropopause but other aspects of the atmosphere as well, like the meridional temperature gradient, the zonal wind, and the vertical wind shear. The additional changes make it difficult to unequivocally assign the cause for the tropical widening to the lifting of the tropopause. In addition, lifting of the extratropical tropopause in itself still does not provide a satisfying dynamical

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interpretation for the poleward expansion. A study by Wu et al. [167] finds little evidence for the rise in tropopause leading to poleward jet shifts, arguing that an increase in the spatial scale of Rossby waves is responsible for the tropopause rise and poleward shifting jets.

5.4 STATIC STABILITY

Changes in the vertical temperature structure of the atmosphere provide another plausible explanation for the tropical widening. Vertical temperature changes are primarily related to the vertical nonuniformity of the tropospheric global warming signal. Observations as well as model experiments indicate that global warming in the upper troposphere is more pronounced than in the lower troposphere and that the signal maximizes in the tropical upper troposphere [168,169]. This so-called upper tropospheric amplification is a well-established consequence of the quasi-moist adiabatic adjustment of the atmosphere, which increases the static stability in both tropics [170,171] and extratropics [172–174].

The theory by Held [19] 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 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 toward higher latitudes.

The original theory [19] was later refined, arguing that the poleward movement of the HC is intimately tied to the eddy-driven jet [175]. Global warming–related reductions of baroclinicity at the equatorward flank of the eddy-driven jet stabilize eddy growth and move 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 [94,164] and full models [41,162,175] confirm that the Held [19] theory holds reasonably well. For example, in idealized parameter sweep experiments, which were forced with prescribed SSTs, Frierson et al. [94] 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 [173], which is consistent with the regional and seasonal patterns of the observed tropical widening [23,29].

5.5 TROPICAL PUSH

As the HC edge represents the tropical-extratropical boundary, one may ask whether there are factors that push the HC edge outward from the tropics and factors that pull it in from the extratropics. Indeed, past research finds that both factors play a role in shaping circulation change.

A good indication for tropical push factors is the observation that heating of the deep tropics is an effective driver for the extent of the global atmospheric circulation [176,177]. Concentrated heating around the equator leads to meridional contraction, including equatorward displacements of the jet, storm track, eddy momentum divergence, and edge of the HC [47,38,175,178–180]. Heating in the tropics can have several causes. Global warming projects on tropical SSTs [84] and leads to pronounced warming in the upper tropical troposphere. There are also natural reasons for warming of tropical SSTs,

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such as the warm phases of ENSO (El Niño), PDO, and AMO. Modelling studies [69,162] suggest that the warming tropics explain roughly one-third of the total climate change–related HC expansion.

Tropical SST anomalies can influence the extratropical circulation through the generation of Rossby waves [18]. However, this does not explain meridional circulation shifts. The contraction of the HC under warm equatorial SSTs can be better understood from the fact that the circulation of the HC tends to intensify in response to the warming SSTs [181]. The stronger HC leads to a westerly acceleration in its upper, poleward moving branch and thus to a strengthening of the subtropical jet. As discussed by various authors [164,175,178,179,182], the strengthening zonal winds allow extratropical Rossby waves, which tend to propagate toward the equator, to penetrate deeper into the tropics before they dissipate. In more technical terms, increasing zonal winds move the critical latitude for equatorward extratropical wave propagation in the subtropics toward the equator. Since the zone of dissipation marks the edge of the HC, the HC shifts equatorward as equatorial SSTs and zonal winds intensify. During neutral and cold ENSO conditions the opposite relationship holds.

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 toward the equator. Consequently, the eddy-driven part of the circulation is shifted toward lower latitudes. There is also evidence that the increase in surface baroclinicity in association with El Niño impacts the type and number of wave breaking, which in turn may change the structure and position of the jet [180,183]. Rivière [147] used similar arguments to explain the global warming related expansion as a response to enhanced upper-tropospheric baroclinicity.

5.6 EXTRATROPICAL PULL

Past research demonstrated that extratropical processes are crucial for the circulation widening [123,175,184]. This can be demonstrated by the aforementioned close connection between shifts of the AMs, the eddy-driven jet, and the HC edge [71]. This influence is related to the action of dissipating extratropical Rossby waves and how extratropical climate change alters the propagation of the waves. There is also evidence that not only the width but also the strength of the HC is controlled by extratropical waves [182,185,186].

Rossby waves are large-scale atmospheric waves that transport momentum and other properties through the atmosphere. The propagation of Rossby waves follows laws similar to that of sound or electromagnetic waves. For example, Rossby wave propagation depends on the size and phase speed of the waves and on the state of the atmosphere in which the waves travel. This is somewhat analogous to the wavelength-dependent refraction of light passing through a prism. Rossby waves can also be reflected, very much like light hitting a mirror.

Interaction of Rossby waves with the background mean flow extracts momentum at one location and deposits it at another. More specifically, momentum is deposited where the waves are created and from which they propagate, forming the so-called eddy-driven jet, and momentum is extracted from locations where the waves dissipate, which is usually the subtropical jet. Anthropogenic climate change and other natural factors can alter the characteristics of the waves and of the mean flow. This alters how the waves propagate and transport momentum and leads to shifts in the latitudinal position of the jet and HC. This is the basic idea behind most expansion mechanisms proposed that involve extratropical processes. The different mechanisms differ only in the details of how climate change alters the eddies and their propagation.

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Chen and Held [187] were the first to suggest a connection between climate change and the behaviour of extratropical Rossby waves. Rossby waves tend to move equatorward toward the subtropics until they approach 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 expansion mechanism proposed by [187] is that the zonal wind in the UTLS region determines the eastward phase speed of extratropical tropospheric waves. 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 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 AM. At the same time, the eddy-driven subsidence in the subtropics is also shifting poleward, which helps to explain the correlation between AM and tropical width. Critical elements of the mechanism were identified by [187] in model simulations and in observations. Later, this mechanism was extended by arguing that the poleward shift of the eddy-driven subsidence in the subtropics not only affects the AM but also the edge of the HC [175].

Another extratropical mechanism is based on the model and observation-derived evidence [188] that Rossby waves tend to grow in size in a warmer climate. Kidston et al. [189] argue that the increase in length scale causes a decrease of the waves' phase speed relative to the mean flow. This allows the waves to travel further away from the jet before they reach their critical latitude and dissipate. Kidston et al. hypothesize that this leads to acceleration on the poleward flank of the jet and thus to a poleward movement of the jet.

Lorenz [190] focuses on the possibility that climate change alters the conditions for Rossby wave reflection on the poleward side of the jet. Climate change–related increases in wind speed create more favourable conditions for wave reflection, such that more poleward propagating waves are reflected back toward the equator. The result is that more waves dissipate on the equatorward side of the jet. Since wave dissipation is equivalent with momentum removal, this leads to a poleward-moving jet.

Both Wu et al. [167] and Staten et al. [191] used a large number of switch-on forcing experiments with climate models to prove or disprove some of the proposed mechanisms. Staten et al. found some evidence for the Chen and Held eddy phase speed mechanism but concluded that it more likely plays the role of a feedback and not that of an initiator. Using a different model, Wu et al. were unable to find evidence for the Chen and Held mechanism. They argued that changes in eddy phase speed are model dependent, citing results from other studies [147,192]. Staten et al. found some support for Kidston's length scale mechanism but concluded that it is probably the least important one. Likewise, experiments by Wu et al. could not validate the eddy length scale mechanism as initiator for poleward jet shifts. Staten et al. found solid evidence for the Lorenz mechanism and concluded that Rossby wave reflection provides the most plausible explanation for the poleward expansion of the circulation.

6. SUMMARY, OUTSTANDING PROBLEMS, AND CONCLUSIONS

After one decade of intense research there is now overwhelming evidence that key elements of the atmospheric circulation have been moving poleward. Detection studies found that the past trends have been about 0.2° degree latitude per decade and per hemisphere. Climate model simulated future expansion rates are somewhat smaller as such estimates do not include the effects from natural climate

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variability. Based on climate models, by the end of the twenty-first century, the width of the tropical belt is expected to expand by about 200 km–300 km. Experiments with climate models also indicate that long-term circulation trends can be attributed to anthropogenic activity, in particular, to changes in greenhouse gases, stratospheric ozone, and aerosol. On shorter, decade-long timescales, natural climate variability associated with major modes of ocean variability is also important.

There has also been a marked improvement in our theoretical understanding for circulation change. For example, there is strong indication that circulation change is largely driven by extratropical processes in association with changing Rossby wave behaviour. Several plausible dynamical mechanisms have been proposed so far, but still it is not entirely clear which, if any, is correct. Since there are different causes for circulation change, it is conceivable that not one single mechanism can explain the entire changes. The still existing lack of understanding for the dynamical mechanism indicates the need for additional research. This includes the role of change in stratospheric ozone and the dynamical coupling between the stratosphere and the troposphere.

What are the consequences of circulation change for climate? So far, the changes in position and intensity have been modest in magnitude. But even small shifts in the location of the HC, jets, and storm tracks can have important implications for regional climates by modifying patterns of storminess, temperature, and precipitation [67,193]. Particularly sensitive are regions with large spatial gradients in their normal distribution of precipitation, like the subtropical dry zones. 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 semiarid regions, including the Mediterranean, the southwestern United States, southern Australia, and southern Africa [7], and it was speculated that this process is already under way [193]. 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.

Studies agree that circulation change is closely linked to regional aspects of climate change, in particular to those related to precipitation. Improved regional climate information would have tremendous societal value, but such information is still severely lacking from most circulation studies. In part, this is related to the little confidence one has in the regional details of model simulated circulation change. Past studies of circulation change were almost exclusively focused on zonal means, since at this level there is acceptable agreement amongst the different models. However, as our understanding for cause and effect of circulation change grows and as model predictions converge, it is to hope that regional predictions will improve as well. Several forcings known to impact the circulation have a spatially heterogeneous character, which may create local circulation changes that have not been studied yet. It is also conceivable that some forcings, like a cooling PDO and a warming AMO, have opposing but regionally limited circulation impacts, which may lead to complex regional circulation responses. These issues need to be addressed in future research.

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LIST OF ABBREVIATIONS

AM	Annular mode
AMO	Atlantic Multidecadal Oscillation
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
ENSO	El Niño Southern Oscillation
GCM	General circulation model
HC	Hadley cell
ITCZ	Inter tropical convergence zone
NAO	North Atlantic Oscillation
NH	Northern hemisphere
PDO	Pacific decadal oscillation
SH	Southern hemisphere
SSTs	Sea surface temperatures
UTLS	Upper troposphere/lower stratosphere

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