Narrowing of the Upwelling Branch of the Brewer-Dobson Circulation and Hadley Cell in Chemistry-Climate Model Simulations of the 21st Century

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Popular Summary

Strong evidence of a tropical belt expansion during the last three decades has been reported recently. Observational studies have shown that the Tropics have widened by more than two degrees latitude since 1979. Expansion of the Tropics in the 20th and 21st Century is also simulated by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models. The widening of the Tropics is closely linked to the expansion of the Hadley cell's sinking branches. Because the Hadley cell's sinking branches cause the subtropical deserts, a widening of the Hadley cell means that the subtropical dry zones are moving toward more populated areas, including the American southwest, southern Australia and the Mediterranean basin. In addition, the tropical belt expansion is associated with changes in jet streams and storm tracks, and therefore has important implications in climate change. Understanding the mechanisms responsible for the tropical belt widening, particularly for the expansion of the Hadley cell, is an active research area.

This work investigates two important aspects of tropical expansion that have not been examined in previous studies. The first is the width of the stratospheric circulation (the Brewer-Dobson circulation) under global warming: it is important to understand whether tropical expansion extends into the stratosphere. The second topic is the width of the ascending branch of the Hadley cell: studying changes in the Hadley cell's upwelling will help to understand what causes the expansion of the Hadley cell's sink branch. These two topics were investigated using simulations of the 21st century from the Goddard Earth Observing System Coupled Chemistry Climate Model (GEOS CCM). The model results project a narrowing of the tropical upwelling region in the troposphere and lower stratosphere. However, the mechanisms for the narrowing of the upwelling branch of the Brewer-Dobson and the Hadley circulation are different. The narrowing of the upwelling of the Brewer-Dobson circulation in the lower stratosphere is due to the strengthening and equatorward shift of the subtropical jets, which enhances equatorward propagation of midlatitude eddies. On the other hand, the narrowing of the Hadley cell's ascending branch is caused by suppressed equatorward propagation of eddies, possibly a result of enhanced static stability in the troposphere. The reduced eddy wave activity causes anomalous eastward wave forcing in the subtropical upper troposphere, which drives an indirect circulation whose sinking branch narrows the tropical upwelling region.

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Abstract

Changes in the width of the upwelling branch of the Brewer-Dobson circulation and Hadley cell in the 21st Century are investigated using simulations from a coupled chemistry-climate model. In these model simulations the tropical upwelling region narrows in the troposphere and lower stratosphere. The narrowing of the Brewer-Dobson circulation is caused by an equatorward shift of Rossby wave critical latitudes and Eliassen-Palm flux convergence in the subtropical lower stratosphere. In the troposphere, the model projects an expansion of the Hadley cell's poleward boundary, but a narrowing of the Hadley rising branch. Model results suggest that the narrowing of the Hadley cell ascent is also eddy-driven.

1. Introduction

Strong evidence of a tropical belt expansion during the last three decades has been reported. Observational studies have shown that the Tropics have widened since 1979 by more than two degrees latitude – these studies use different empirical measures of the tropical width, such as the distance between the subtropical jets in the two hemispheres [*Hu and Fu*, 2007], the latitudinal range of tropical outgoing longwave radiation [*Hu and Fu*, 2007], and the subtropical tropopause height [*Seidel and Randel*, 2007]. Expansion of the Hadley circulation in the 20^{th} and 21^{st} Century is also simulated by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models [*Lu et al.*, 2007]. The widening of the Tropics is associated with changes in the precipitation pattern, the hydrological cycle, jet streams, and storm tracks, and therefore has important implications in climate change [*Seidel et al.*, 2008]. Understanding the mechanisms responsible for the tropical belt widening, particularly for the expansion of the Hadley cell, is an active research area.

There are two important aspects of tropical expansion that have not been examined in detail in previous studies. The first is the width of the stratospheric tropical circulation under global warming. The stratospheric circulation in the Tropics is characterized by a slow, rising motion that forms the upwelling branch of the Brewer-Dobson circulation (BDC). The BDC plays a crucial role in the distribution of trace gases, such as ozone and water vapor, in the stratosphere. Because of its important implications for stratospheric ozone recovery, changes in the strength of the BDC in the 21^{st} Century have been extensively studied and nearly all middle-atmosphere models predict an acceleration of the BDC [*Butchart et al.*, 2006]. However so far there has been no dedicated study on the width of the BDC. It is important to understand whether tropical expansion extends into the stratosphere and how the width change of the BDC is related to the strengthening of the BDC.

The second topic is the width of the ascending branch of the Hadley cell. Note that Hadley-cell widening refers to the expansion of its descending branch, which does not necessarily indicate a similar expansion of its ascending branch. Studying the width of the ascending branch of the Hadley cell may help to understand tropical expansion.

The purpose of this study is to investigate the response of the width of the upwelling branch of the BDC and Hadley cell to climate change in the 21st Century. Here, we use simulations from the Goddard Earth Observing System Coupled Chemistry-Climate Model (GEOSCCM) to show a narrowing of tropical upwelling in the lower stratosphere and troposphere.

2. Simulations and Methods

Details of the model used in this study, the GEOSCCM Version 1, are given in *Pawson et al.* [2008]. For this work, we analyzed two simulations of the 21st Century (2001-2099), referred to as FA1b and FA2, which used IPCC GHG scenarios A1b and A2. Data from FA1b and FA2 were used in several previous studies, including *Li et al.* [2009] and Oman et al. [2010]. For consistency with the GHG scenarios, the two model runs use single realizations of sea surface temperature (SST) and sea ice from appropriate AR4 scenarios run with the National Center for Atmospheric Research (NCAR) Community Climate System Model 3.0 (CCSM3). Both simulations use an identical halogen scenario (WMO scenario AB) and all other external forcing is identical. Annual-mean results are presented in this study.

The BDC is the mean mass transport circulation in the stratosphere and it should be regarded as a Lagrangian mean circulation, but *Dunkerton* [1978] showed that the BDC could be approximated by the residual circulation under the Transformed Eulearian-Mean (TEM) frame. Here we use the latitudinal range of upward residual vertical velocity ($\overline{w}^* > 0$) in the Tropics as a measure of the width of the BDC's upwelling branch.

We follow previous studies to investigate the Hadley cell under the conventional Eulerian-Mean (CEM) frame. The width of the Hadley cell is defined as the distance between its poleward boundaries, which are in turn defined as the latitudes where the zonal-mean mass streamfunction first becomes zero on the poleward side of its subtropical maxima [*Lu et al.*, 2007]. The width of the ascending branch of the Hadley cell is measured as the latitudinal range of tropical upwelling (vertical velocity $w > 0$). Note that our model results regarding the narrowing of the Hadley cell's rising branch (section 4) do not change when analyzed under the TEM frame. We choose to use CEM to investigate Hadley cell change because the descending branch of the Hadley cell is not well defined in TEM.

3. Narrowing of the Upwelling Branch of the BDC

We focus on 70 hPa when investigating changes in the BDC in order to compare with previous studies [e.g., *Butchart et al.*, 2006]. Figure 1a shows the evolution through the 21st Century of the width and strength of the BDC's upwelling branch at 70 hPa in

FA1b and FA2. Despite different scenarios of GHG employed, the two simulations show the same long-time changes: narrowing and strengthening of the upwelling branch of the BDC.

The strengthening of the BDC has been extensively studied and our model results are consistent with other model results [e.g., *Butchart et al., 2009*]. The trend of the BDC strength at 70 hPa in the 21st Century for FA1b is 1.33 %/decade, which is in the middle of the range predicted by eleven CCMs under the IPCC GHG A1b scenario [*Butchart et al.,* 2009]. But more interestingly for the purpose of this study, the FA1b and FA2 runs project a narrowing of the upwelling region at a rate of 0.41 and 0.61 degrees/decade (significant at the 95% confidence level). Although this change has been noted in recent studies [*McLandress and Shepherd*, 2009; *Li et al.*, 2009], it is not clear what causes this narrowing. Here we investigate the narrowing of the BDC in the lower stratosphere, using an analysis based on the downward control principle [*Haynes et al.*, 1991]. Since this behavior is very similar in both the FA1b and FA2 runs, the remainder of the analysis focuses on FA2.

The rising branch of the BDC is confined between the turnaround latitudes, defined as the locations where the residual vertical velocity ($\overline{w}^*$) changes sign from tropical upwelling to extratropical downwelling. The turnaround latitudes correspond to the latitudes of the maxima and minima of the residual mass streamfunction (Ψ^*) because by definition $\overline{w}^* = \dfrac{1}{\rho_0 a\cos\phi}\dfrac{\partial\Psi^*}{\partial\phi}$, where ρ_0 is the atmospheric density, a is the Earth's radius, and ϕ is the latitude. The BDC is a wave-driven circulation, and Ψ^* can be approximated as

$$\Psi^* = \int_z^\infty \frac{\rho_0 a^2 \cos^2 \phi}{\partial \overline{m} / \partial \phi} F dz' \tag{1}$$

under steady state conditions, where $\overline{m}$ is the absolute angular momentum, and F is wave forcing that consists of model-resolved wave and parameterized gravity-wave driving [*Haynes et al.*, 1991]. Using the downward control analysis, we can diagnose what causes the equatorward shift of the turnaround latitudes.

Figure 2a shows that at 70 hPa the climatological (2001-2020 mean) downward-control and the actual residual streamfunctions have almost the same turnaround latitudes and similar magnitudes. The downward-control residual streamfunction is dominated by model-resolved wave forcing. At the turnaround latitudes (34°N and 36°S), resolved waves and gravity waves account for 80% and 11% of the actual residual streamfunction, respectively. The magnitude and the latitudinal structure of the trend in the downward-control and actual residual streamfunctions also agree well with each other (Fig. 2b). Comparing Figs. 2a and 2b reveals that the latitudinal distribution of the trend is shifted toward the Equator compared to the climatological distribution. The maxima of the trend are located at 22°N and 20°S, about 15° equatorward of the climatological turnaround latitudes. Changes in the resolved-wave-driving streamfunction demonstrate similar latitudinal shift and dominate changes in gravity wave forcing equatorward of 30°N and S. At the latitudes of maximum trend (22°N and 20°S), resolved wave and gravity wave driving explain 81% and 9% of the actual trend, respectively. Based on the above analyses, it is concluded that the narrowing of tropical upwelling in the lower stratosphere is primarily due to increases in model-resolved wave driving in the subtropics that shifts the EP flux convergence equatorward.

The increase in Rossby-wave driving in the subtropical lower stratosphere indicates enhanced wave propagation into this region (above 16 km in Fig. 2c). Rossby wave propagation is sensitive to changes in the basic state in the upper troposphere and lower stratosphere (UTLS) [e.g., *Garcia and Randel*, 2008]. Figure 2d shows the model simulated temperature trend in the 21st Century. GHG increases warm the troposphere and cool the stratosphere. The strongest warming occurs in the tropical upper troposphere; this enhances the meridional temperature gradient in the subtropical UTLS. Through thermal wind balance, the westerlies in the subtropical UTLS region strengthen (Fig. 2c). The largest westerly wind trends are located at about 30^{o}N and S and 100 hPa (16 km), above and on the equatorward side of the subtropical jets, indicating an upward and equatorward shift of the jets. The strengthening and displacement of the subtropical jets has significant impacts on wave propagation. This may be explained qualitatively by the refractive index, which can be approximated as

$$n_r^2 \approx \frac{\overline{q}_y}{\overline{u}-c}, \qquad (2)$$

where n_r^2 is the square of the refractive index, $\overline{u}$ is the zonal-mean zonal wind, c is the eddy phase speed, and $\overline{q}_y$ the meridional potential vorticity gradient. Rossby waves tend to propagate toward regions of large positive n_r^2, and are reflected away from regions of negative n_r^2. Therefore the equatorward propagation of mid-latitude waves is limited by the critical latitude, where the wave phase speed equals the zonal wind. The westerly acceleration in the subtropical lower stratosphere draws the critical latitude equatorward (for example, between 2001 and 2099 the zero wind lines at 70 hPa are displaced toward the Equator by about 3° of latitude in both hemispheres). As a result, the equatorward propagating extratropical eddies can penetrate deeper into the Tropics in the lower stratosphere (above 16 km in Fig. 2c), shifting the EP flux convergence zone and the turnaround latitudes toward the Equator.

4. Narrowing of the Upwelling of the Hadley Cell

Readers should be remained that results presented in this section are calculated under the CEM frame. The width of the Hadley cell, diagnosed from the 500 hPa zero mass streamfunction, increases in the 21^{st} Century in our model simulations (Fig. 1b). Our results are consistent with previous modeling studies [*Lu et al.*, 2007; *Johanson and Fu*, 2009]. *Lu et al.* [2007] reported a multi-model mean trend of $0.11\ ^{\circ}$/decade for the A1b scenario and 0.2°/decade for the A2 scenario from 15 IPCC AR4 models (estimated from their Figure 2), which are represented very well by the trends in our FA1b (0.11°/decade) and FA2 (0.14°/decade) simulations.

Figure 1b also shows that the width of the ascending branch of the Hadley cell (region of vertical velocity $w > 0$) narrows, although in FA1b the narrowing is only statistically significant in the upper troposphere (300-200 hPa). This is the opposite behavior to the poleward expansion of the edge of the Hadley cell. The rate of the contraction of tropical ascent is smaller, but comparable to that of the expansion of the Hadley cell's poleward edges. This means that in the GEOSCCM the expansion of the sinking branches of the Hadley Cell occurs on both its poleward and equatorward flanks.

Again we focus on the FA2 run to investigate the mechanism for the narrowing of the Hadley rising branch. Figure 3a shows that trends of the vertical velocity are nearly symmetric between the hemispheres. In the subtropical middle-upper troposphere (4-10 km), trends in the vertical velocity are opposite to its climatology mean, with increased ascent in 20°S-35°S and 15°N-35°N and enhanced descent around 10°S-20°S and 10°N-15°N. The enhanced descent extends into the Tropics (more pronounced in the Southern Hemisphere), pushes the zero-vertical-velocity line equatorward, resulting in a narrowing of tropical upwelling. We suggest that this thermally indirect meridional circulation change is eddy-driven. Figure 3b shows that in the height range 8-12 km, the momentum flux convergence $(-\frac{\partial \overline{u'v'}}{\partial y})$ increases at 10°-25° and decreases at 25°-50° in bother hemispheres. These momentum flux convergence changes are caused by a reduced equatorward propagation of meridional eddy activity flux (the opposite of poleward eddy momentum flux) around 20°-40° latitudes in the height range 6-12 km (Fig. 3c). By applying westerly forcing in the subtropical upper troposphere, the increased momentum flux convergence drives a secondary indirect meridional circulation, which causes the narrowing of tropical upwelling (Fig. 3b). Our interpretation is inspired by *Seager et al.* [2003] who suggested that the mid-latitude cooling during El Niño events could be explained by anomalous ascent due to changes in an eddy-driven meridional circulation.

Now the question is what causes the upper tropospheric eddy flux changes. We note that the suppressed equatorward EP flux propagation between 20° and 40°N and S in the middle and upper troposphere (6-12 km) is accompanied by a reduction in the vertical component of the EP flux (Fig. 3c), that is, the direction of the EP flux trend is opposite to that of the climatological EP flux in this region (upward and equatorward, not shown). This observation suggests that suppression of wave propagation from the lower troposphere, due to changes in the background or source, might be a plausible explanation for the eddy flux changes in the upper troposphere.

We use refractive index to investigate how changes in the background state affect wave propagation in the troposphere. We focus on the meridional potential vorticity (PV) gradient (Equation 2), because the zonal-mean zonal wind trends are small below about 10 km (Fig. 2c) and changes in the refractive index are dominated by those in the PV gradient (assume the eddy phase speed doesn't change). In the spherical coordinate, the meridional PV gradient is

$$\bar{q}_\phi = \frac{2\Omega}{a}\cos\phi - \frac{1}{a^2}[\frac{(\bar{u}\cos\phi)_\phi}{\cos\phi}]_\phi - \frac{f^2}{\rho_0}(\rho_0 \frac{\bar{u}_z}{N^2})_z, \quad (3)$$

where N is the buoyancy frequency, f is the Coriolis parameter, and other symbols have their standard notations. A smaller PV gradient would suppress Rossby wave propagation, and vice versa. Figure 3c shows a large area of decreased PV gradient below about 9 km. The regions of decreased PV gradient coincide with reduced upward and equatorward EP flux propagation. Expanding the right hand side of Equation 3 reveals that the reduction in the PV gradient is mainly due to an increase in the static stability (Fig. 3d). We conclude that changes in the basic state could be at least partly responsible for the reduced wave propagation into the subtropical upper troposphere.

Another possible explanation for the suppressed wave activity in the subtropical upper troposphere is a weakening of baroclinic eddy sources. *Frierson et al.* [2006] and *Lu et al.* [2008] showed that an increase in static stability in the troposphere is a robust response to global warming in AR4 simulations. They argued that the increased static stability in the subtropics stabilizes the baroclinic growth rate and reduces eddy activity there. The GEOSCCM simulates a significant increase of static stability in the subtropics (Fig. 3d), and hence the decrease of equatorward and upward eddy fluxes between 20°

and 40° latitudes may be explained by the stabilization of eddies using the same argument of *Lu et al.* [2008].

The eddy wave activity changes in the troposphere may also be interpreted by changes in the wave phase speed. *Chen and Held* [2007] proposed that westerly accelerations in the UTLS would increase the eastward phase speed of tropospheric waves. Because faster waves have a more poleward-placed critical latitude, an increase in wave phase speed reduces equatorward wave activity fluxes in the subtropics and enhances wave activity in the mid-latitudes, leading to a poleward shift of the momentum flux convergence/divergence patterns: this is exactly what is shown in Figs. 3b and 3c.

5. Discussion and Conclusions

GEOSCCM simulations project a narrowing of the upwelling region in the tropical troposphere and lower stratosphere in the 21st Century. This work has examined mechanisms for the narrowing of the ascending branch of the BDC and Hadley cell. The equatorward and upward displacement of the subtropical jets, due to an enhanced meridional temperature gradient in the subtropical UTLS under global warming, causes an equatorward shift of the EP flux convergence zone and a narrowing of the upwelling in the lower stratosphere. Our results are consistent with *Garcia and Randel* [2008] and *McLandress and Shepherd* [2009] regarding the important role of increased subtropical wave forcing in causing changes in the BDC. *Garcia and Randel* [2008] and *McLandress and Shepherd* [2009] focused on the upward extension of the critical lines that leads to the strengthening of the BDC, but here we address the narrowing of the upwelling of the BDC and concentrate on the equatorward shift of the critical latitudes. These two aspects of BDC changes are connected with each other. The key to understanding this connection is that Rossby waves tend to propagate toward regions of increased westerly winds in the subtropical lower stratosphere.

Our model results indicate that the narrowing of the Hadley rising branch is also eddy-driven. We argue that the subsidence of a subtropical secondary indirect circulation, driven by anomalous momentum flux convergence in the upper troposphere, pushes the boundary of the tropical ascent to move toward the Equator. Three possible mechanisms for the subtropical momentum flux convergence increase have been discussed: decreases in the refractive index that suppress wave propagation, stabilization of eddies due to an increased static stability, and increases in wave phase speed. Note that the last two mechanisms have been used to explain the expansion of the poleward boundaries of the Hadley cell [*Lu et al.*, 2008]. Therefore it is likely that the narrowing of the Hadley cell's ascending branch is closely related to the widening of the Hadley cell's descending branch.

Finally, we want to emphasize that the narrowing of the BDC is driven by enhanced EP flux convergence (easterly acceleration) in the lower stratosphere, whereas the narrowing of the Hadley's rising branch is due to increased momentum flux convergence (westerly acceleration) in the upper troposphere. These results are valid for the GEOSCCM using a single realization of SSTs from CCSM3. The robustness of our results needs to be verified with other CCMs and AR4 models. Of particular important is to identify how different representations of SSTs in CCMs (driven by SSTs from coupled models) and coupled atmosphere-ocean AR4 models influence tropical circulation response to global warming.

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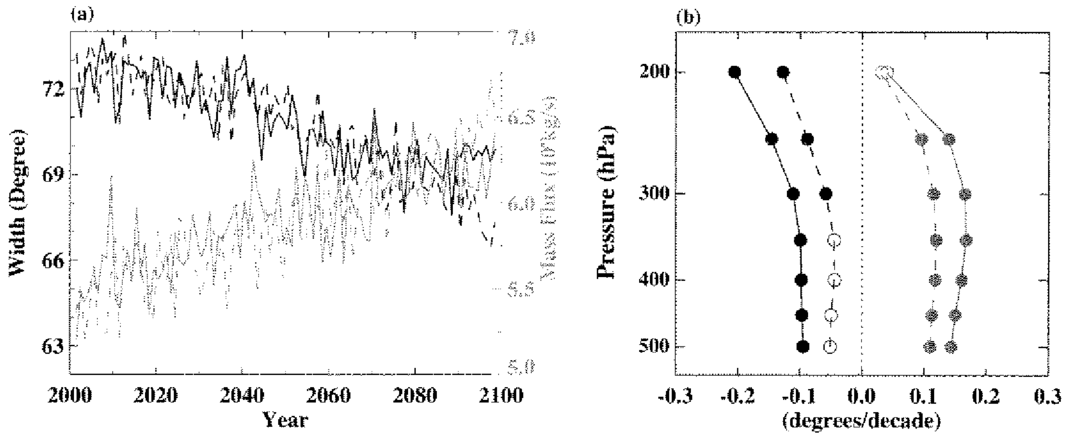

Figure 1: (a) Time series of the width of the BDC upwelling branch at 70 hPa (black, left axis), and the tropical upward mass flux at 70 hPa (blue, right axis). (b) Vertical profiles of the trends of the width of the Hadley cell poleward boundary (red) and the width of the Hadley rising branch (black). Filled circles indicate trends are statistically significant at the 95% confidence level. In both (a) and (b), solid and dashed lines are results from the FA2 and FA1b simulations, respectively.

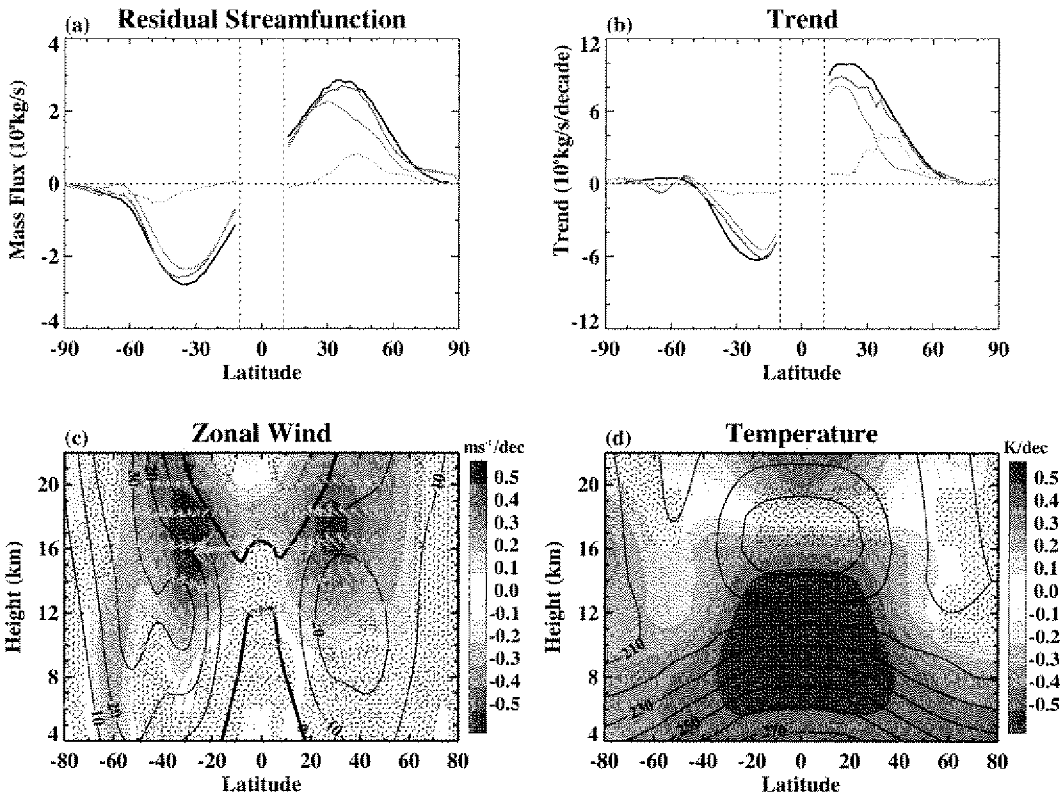

Figure 2: (a) Latitudinal distribution of the climatology (2001-2020 mean) of the actual (black) and downward-control (red for combined resolved and gravity wave driving, blue for resolved wave driving, and green for gravity wave driving) residual streamfunction at 70 hPa. (b) Same as (a), but for the trend in the 21st Century. (c) Trends of the zonal wind in the 21st Century (shading). Stippling indicates that trends are not statistically significant at the 95% confidence level. Contours are 2001-2020 mean. Arrows denote trends in the EP flux. (d) Same as (c), but for the temperature. Results are from FA2.

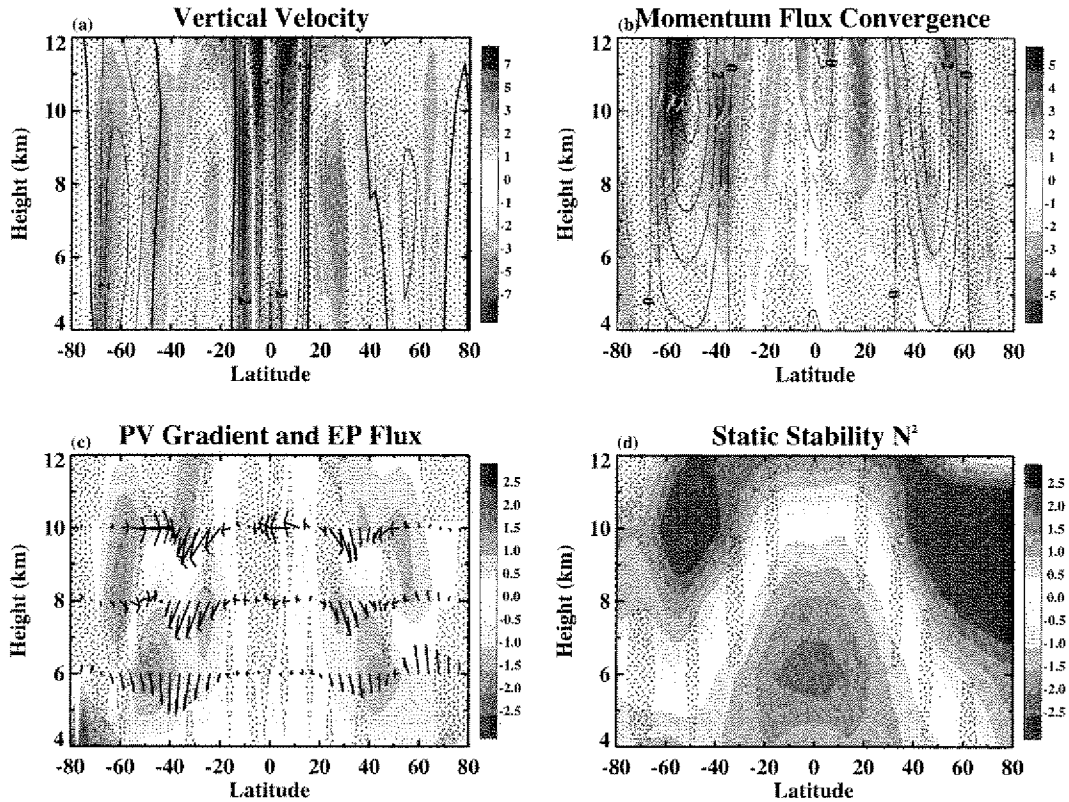

Figure 3: Trends in the 21[st] century of (a) the vertical velocity ($10^{-5}ms^{-1}$/decade), (b) the momentum flux convergence, $-\frac{\partial \overline{u'v'}}{\partial y}$ ($10^{-2}ms^{-2}$/decade), (c) the meridional potential vorticity gradient ($10^{-12}m^{-1}s^{-1}$/decade), and (d) the buoyancy frequency squared ($10^{-4}s^{-2}$/decade). Stippling indicates that trends are not statistically significant at the 95% confidence level. Contours in (a) and (b) are 2001-2020 mean values (black for positive and white for negative values). Arrows in (b) and (c) denote trends in the meridional circulation and EP flux, respectively. Results are from FA2.