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On the influence of anthropogenic forcings on changes in the stratospheric mean age

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[1] A common feature of stratospheric simulations of the past or future is an increase in tropical upwelling and a decrease in mean age. Possible causes of these changes include (1) increases in tropical sea surface temperatures (SSTs) driven by increases in well-mixed greenhouse gases (WMGHGs), (2) the direct radiative effect of increases in WMGHGs, and (3) changes in ozone. Here we examine a suite of simulations from the Goddard Earth Observing System chemistry-climate model (GEOS CCM) to isolate the relative role of these three factors. Our analysis indicates that all three factors cause changes in the mean age, but the relative impact of each factor depends on the time period analyzed. Over the past 30–40 years ozone depletion is the major factor causing the decrease in mean age, with negligible changes due to direct radiative impact of WMGHGs. However, ozone is predicted to recover back to 1970 levels during the next 50–60 years, and this causes an increase in the mean age, whereas the continued increase in SSTs from increased levels of WMGHGs and the direct radiative impact of WMGHGs will still cause a decrease in the mean age. The net impact of these factors will still result in a decreasing mean age although the rate will be smaller than that of the past. The decreases in mean age are primarily caused by increases in upwelling in the tropical lower stratosphere. The increased upwelling from both increased tropical SSTs and polar ozone loss appears to be related to changes in zonal winds and increases in wave activity propagating into the stratosphere. The different contributions of changes in SSTs, WMGHGs, and ozone to the circulation of the stratosphere may help explain the large spread in the rate of change of tropical upwelling seen in previous studies.

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1. Introduction

[2] The circulation of the stratosphere is an important part of the Earth's climate system. Understanding what controls it and how it is likely to change in the future are important for many issues, including the recovery of the ozone hole from decreases in ozone depleting substances [*Butchart and Scaife*, 2001]. Several recent studies have shown consistent long-term changes in the tropical upwelling and mean age in stratospheric simulations. *Butchart et al.* [2006] compared the change in tropical upwelling over a large number of climate models and found the upwelling increased in all models, whether the models included well-mixed greenhouse gas (WMGHG) forcing alone or also included changes in ozone depleting halogens. However, the magnitude of the trend varied among the models. Several studies [*Austin et al.*, 2007; *Garcia et al.*, 2007; *Garcia and Randel*, 2008] examined changes in the mean age in coupled chemistry-climate models and noted significant decreases in mean age. Such a decrease is consistent with increased tropical upwelling [*Austin and Li*, 2006].

[3] The consistent changes in mean age in different chemistry climate models perturbed by similar external forcings (N. Butchart, personal communication, 2007), and the consistent changes in individual ensemble members of the same model [*Austin and Li*, 2006], suggests an external forcing is the cause of these changes. The most likely forcings are those due to changes in WMGHG and halogen concentrations. *Li et al.* [2008] showed that halogen driven ozone depletion had an impact on the stratospheric circulation. They concluded that while ozone depletion had a clear impact on this circulation, SSTs could have also had an impact, but this was not the focus of their study. *Li et al.* [2008] attributed about 60% of the change in lower stratospheric mass flux in their past model simulations to ozone depletion. They did however note that their model produced much more ozone depletion than observed. *Olsen et al.* [2007] showed that stratosphere-troposphere

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Table 1. List of External Forcings Applied to Each Run and the Time Period Simulated

Runs	Time	SST	GHG	Halogen
Reference Past (P1)	1951–2004	Observations	Observations	Observations
Reference Past 2 (P2)	1951–2004	Observations	Observations	Observations
Reference Future (C21-CSST)	2000–2099	CCSM3	A1b	Ab
Low-Cl Past (P-CL60)	1960–2004	Observations	Observations[a]	Fixed 1960
Low-Cl Future (C21-CL60)	2000–2099	CCSM3	A1b[a]	Fixed 1960
Cold Biased SST (C21-HSST)	1971–2099	HADGEM1	Observations and A1b	Observations and Ab
1980 Time slice (TS1980)	1980[b]	Observations, 1979–2004	Fixed 1975	Fixed 1975
2000 Time slice (TS2000)	2000[b]	Observations, 1979–2004	Fixed 1995	Fixed 1995
2020 Time slice (TS2020)	2020[b]	Observations, 1979–2004	Fixed 2015	Fixed 2015
2050 Time slice (TS2050)	2050[b]	Observations, 1979–2004	Fixed 2045	Fixed 2045

[a]Except for GHGs that contain chlorine, which were fixed at 1960 values.
[b]Conditions for this year were run 26 times. (Only SSTs changed; everything else was held constant.)

exchange would increase because of an increasing tropical to midlatitude sea surface temperature (SST) gradient. Studies have also been done to separate the effects of tropospheric versus middle atmospheric CO_2 doubling and most of the change in the residual circulation was attributed to the tropospheric CO_2 doubling [*Sigmond et al.*, 2004; *Rind et al.*, 2002]. *Kodama et al.* [2007] showed that both the direct radiative and indirect SST impact of WMGHGs can also change the stratospheric circulation, but did not look at the effects of ozone depletion. *Hurwitz* [2008] examined a series of time slice experiments to separate the impact of SST, CO_2, and ozone changes to the stratosphere.

[4] The goal of this study is to quantify the influences of different anthropogenic forcings on the stratospheric transport circulation, and how the relative impact of different factors varies over time. We focus on the mean age [*Hall and Plumb*, 1994; *Waugh and Hall*, 2002] as our diagnostic of the time scale of stratospheric circulation. Section 2 describes the model and the various simulations used in this study. Section 3 describes the effect of the forcings on the mean age in the stratosphere and possible mechanisms for this change. Conclusions are presented in section 4.

2. Model and Simulations

[5] The model simulations use the free-running Goddard Earth Observing System (GEOS) chemistry-climate model (CCM) [*Pawson et al.*, 2008], which is based on the GEOS-4 GCM. Simulations were run at a resolution of 2° latitude by 2.5° longitude with 55 vertical layers up to 80 km. The model uses a flux-form semi-Lagrangian dynamical core [*Lin*, 2004]. Also included, is a mountain-forced gravity wave drag scheme from *Kiehl et al.* [1998], as well as waves with nonzero phase speeds [*Garcia and Boville*, 1994] to account for other sources that are important in the stratosphere and mesosphere. GEOS CCM includes a comprehensive suite of stratospheric chemicals and chemical reactions, and also includes a mean age tracer. The surface concentration of this age tracer increases linearly with time, by 1 year every year, and the mean age Γ [*Hall and Plumb*, 1994; *Waugh and Hall*, 2002] in the model determined as the difference between the value and that at a point in the tropical upper troposphere (equator at 200 hPa). The GEOS CCM has been evaluated [*Eyring et al.*, 2006, 2007] against observations and does well in reproducing past climate and key transport processes. In particular, the mean age and tropical tape recorder in GEOS CCM agrees well with observations [see *Eyring et al.*, 2006, Figures 8–10]. Also, *Pawson et al.* [2008] compared the GEOS CCM ozone fields to observations and found reasonable agreement but noted slightly high total ozone bias and a too cold and long-lived Antarctic vortex.

[6] A number of simulations have been performed using the GEOS CCM, to address several different scientific issues. These simulations are used in this study to separate the impacts to changes in mean age. The key features of the simulations used in this study are listed in Table 1. The time periods covered varies between simulations, with transient simulations of the past and of the future, as well as time slice simulations for fixed time periods. In all simulations the SSTs and boundary layer concentrations of WMGHGs and halogens are prescribed, but the values vary between simulations.

[7] The tropical SSTs from the simulations are shown in Figure 1a. The "reference past" and "low-Cl past" transient simulations and all time slice (TS) runs used the observed Hadley SST and Sea Ice data set from *Rayner et al.* [2003] for the past (referred to as "observations" in this paper). There are also two simulations of reference past (P1 and P2) which differ only in initial conditions with 1 January 1951 conditions of P1 used to initialize P2 in 1 January 1950. The "reference future" and "low-Cl future" runs used SST and Sea Ice data from an AR4 integration of the NCAR Community Climate System Model, version 3 (CCSM3). The zonal mean tropical values of these past SSTs are in reasonable agreement with the observed SSTs although differences do exist in other regions. An additional simulation has been performed using SSTs from HADGEM1 [*Johns et al.*, 2006]. As shown in Figure 1a these SSTs are colder than observed, and we refer to this run as the "cold biased SST." The corresponding change in polar ozone (annual average change over 90°–60°S and 60°–90°N) at 100 hPa is shown in Figure 1b for the reference past and future simulations. Figure 1c shows the annual average surface CO_2 concentrations (ppmv) for the same simulations.

[8] The WMGHGs used in the simulations are based on observations for the past and *Intergovernmental Panel on Climate Change* [2001] A1b scenarios for the future. Similarly, the halogens are based on observations for the past or a single scenario (WMO Ab) for the future. The exceptions are the "low-Cl" runs which had halogens,

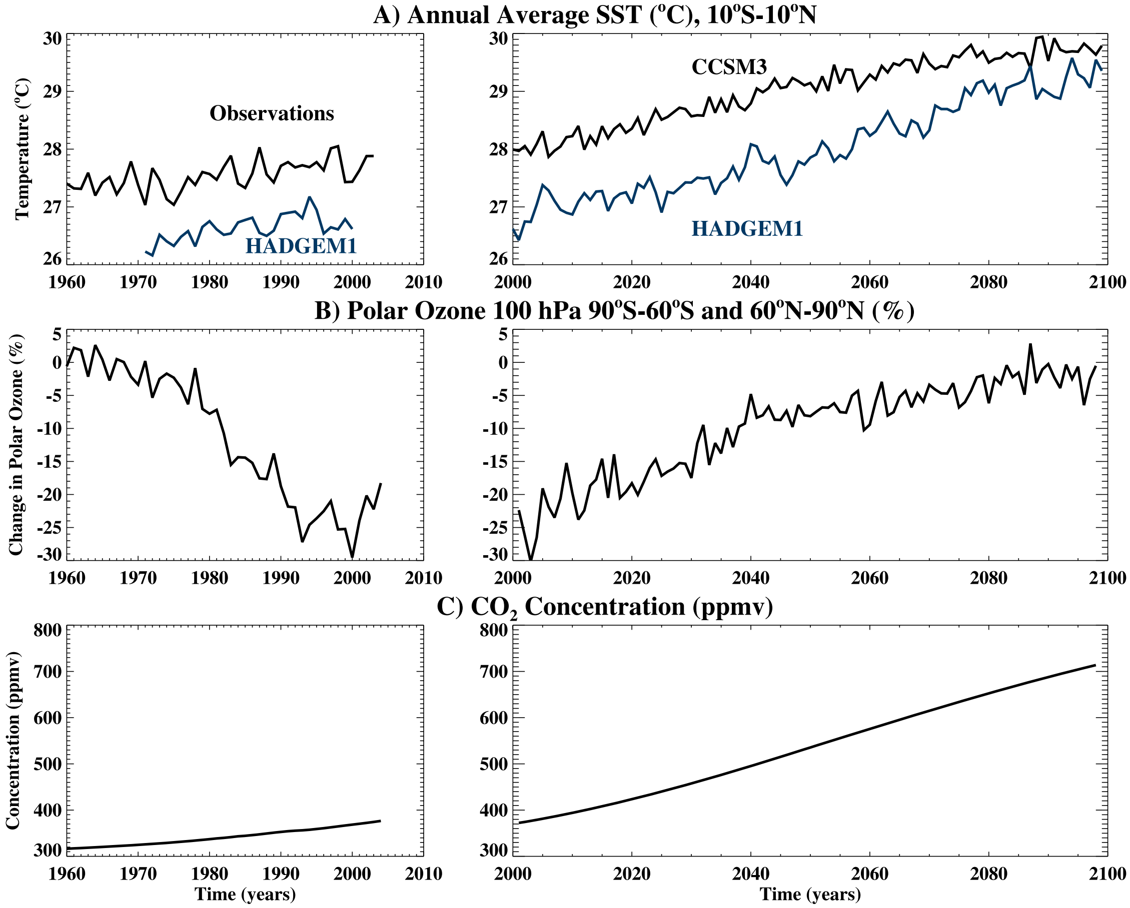

Figure 1. (a) Annual average tropical (10°S–10°N) sea surface temperature (°C) used in the (left) past and (right) future simulations. HADGEM1 has about a 1°C cold bias compared to observations and CCSM3 simulations of future climate. (b) Annual average change (%) in ozone over 90°–60°S and 60°–90°N at 100 hPa with respect to 1960–1969 average values and (c) annual average surface CO_2 concentrations (ppmv) for both (left) past and (right) future simulations.

including chlorine-containing GHGs, fixed at 1960 levels for the entire run.

3. Results

3.1. Simulated Stratospheric Circulation

[9] We first examine the mean age in the reference past and future simulations. The annual mean age, Γ, averaged over 1965–1974 is shown in Figure 2a. The values range from a few months at the tropical tropopause to over 4.5 years in the tropical upper stratosphere as well as extratropical mid and upper stratosphere. This is a reflection of air entering the stratosphere at the tropical tropopause, continuing upward through large-scale upwelling then moving toward the winter pole and downward from large-scale downwelling. Observations of mean age are not available for this early period, but comparisons of GEOS CCM and observed mean ages for the late 1990s show good agreement [*Eyring et al.*, 2006].

[10] As discussed in section 1, the mean age has been found to decrease with time in CCM simulations. This is the case for the GEOS CCM reference simulations, as can be seen in Figure 2b which shows the change in mean age in years from 1965–1974 to 2085–2094. There is a decrease at all locations. The smallest decreases occur over the tropics and the largest decrease, approaching 1 year, occur in the midlatitude Southern Hemisphere at 20 km. Although the mean age change is largest in the mid and upper stratosphere, by looking at the percentage change, it is the lower stratosphere where most of this change is occurring (Figure 2c). There is about 40% decrease in the mean age in the tropical lower stratosphere, whereas over the bulk of the mid and upper stratosphere the percentage change is about half as large (18–22%).

[11] The change in mean age can be examined in more detail by looking at the time series at a few locations in the stratosphere. Figures 3a–3c show the mean age (years) from the past (left) and future (right) simulations for the equator at 3 hPa, 86°S at 3 hPa, and the equator at 30 hPa, for several runs. The black curves show the reference runs and typically they have the youngest mean age over the simulations shown. The blue curves having the oldest mean age show runs conducted using the HADGEM1 SSTs, which as discussed above have a known tropical cold bias [*Johns et al.*, 2006]. This suggests a link between SSTs and the stratospheric mean age, which is explored further below. The runs shown in the red lines have all the same external forcings as the reference runs except that halogens and

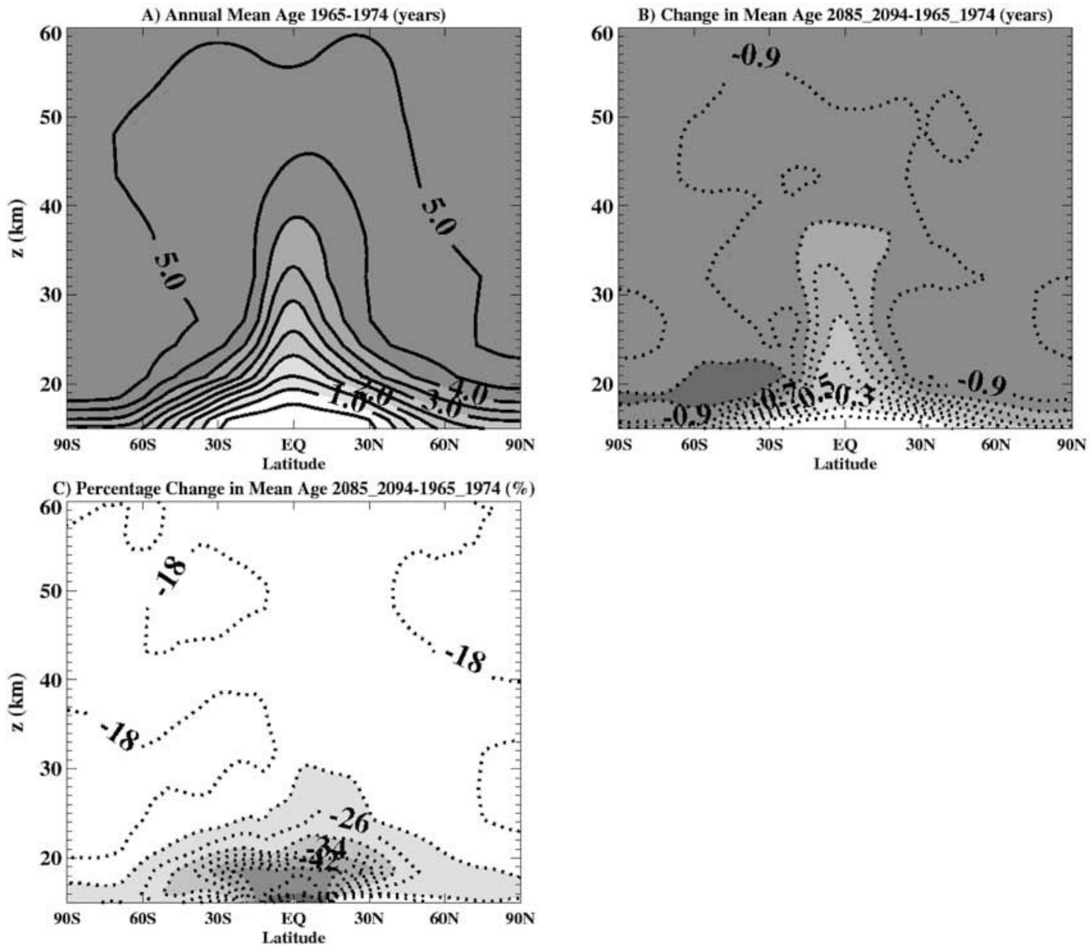

Figure 2. (a) Annual mean age (years) from 1965 to 1974, (b) the change in mean age (years) from 1965–1974 to 2085–2094, and (c) the percentage change in mean age over this same period all from 15 to 60 km.

chlorine-containing WMGHGs are held fixed at 1960 levels. This means no ozone depletion occurs. By comparing this run to the reference runs we can examine the impact caused by ozone depletion. In the low-Cl run the mean age is comparable to the reference run during the 1960s and 1970s, however as ozone depletion increased, during the last 2 decades of the 20th century the change in mean age was not as large as in the reference run. This suggests that ozone depletion also has an impact on the mean age making it younger in these simulations. This is consistent with the findings of *Li et al.* [2008] and *Austin et al.* [2007].

[12] Tropical upwelling to a large extent controls the stratospheric mean age with increased upwelling resulting in a younger mean age. Figure 3d shows the tropical (18°S–18°N) upwelling at 70 hPa from the same series of runs. The tropical upwelling increases over time in all runs, and differences between runs are consistent with the differences in the mean age. The reference runs have the largest and the cold biased SST run the smallest tropical upwelling. By removing ozone depletion (red lines) the tropical upwelling is slightly reduced compared to the reference run. This shows a link between both SSTs and ozone to tropical lower stratospheric upwelling (and mean age).

[13] The changes in mean age, and tropical upwelling, in GEOS CCM can be compared with that in other CCMs. Over the past simulation, the change in tropical upper stratospheric mean age of around 5 months in GEOS CCM is similar to the roughly 4 month decrease in WACCM [*Garcia et al.*, 2007; *Garcia and Randel*, 2008], but less than the 8 month decrease in AMTRAC [*Austin and Li*, 2006].

3.2. Contributors to the Mean Age Change

[14] As discussed in section 1, there are several possible factors that could cause thermal and dynamical changes to the atmosphere and ultimately have an impact on the transport circulation of the stratosphere. We focus here on the impact from changes in WMGHGs, both indirectly through SST changes and directly through the radiative effect of WMGHGs, and changes in stratospheric ozone. The impact of each of these factors on the mean age is isolated by comparing different pairs of simulations that differ by only one of these factors. Table 2 shows the cases selected to extract the mean age change due to each factor.

3.2.1. SST

[15] We first consider the influence of differences in tropical SSTs on the mean age. This is determined by

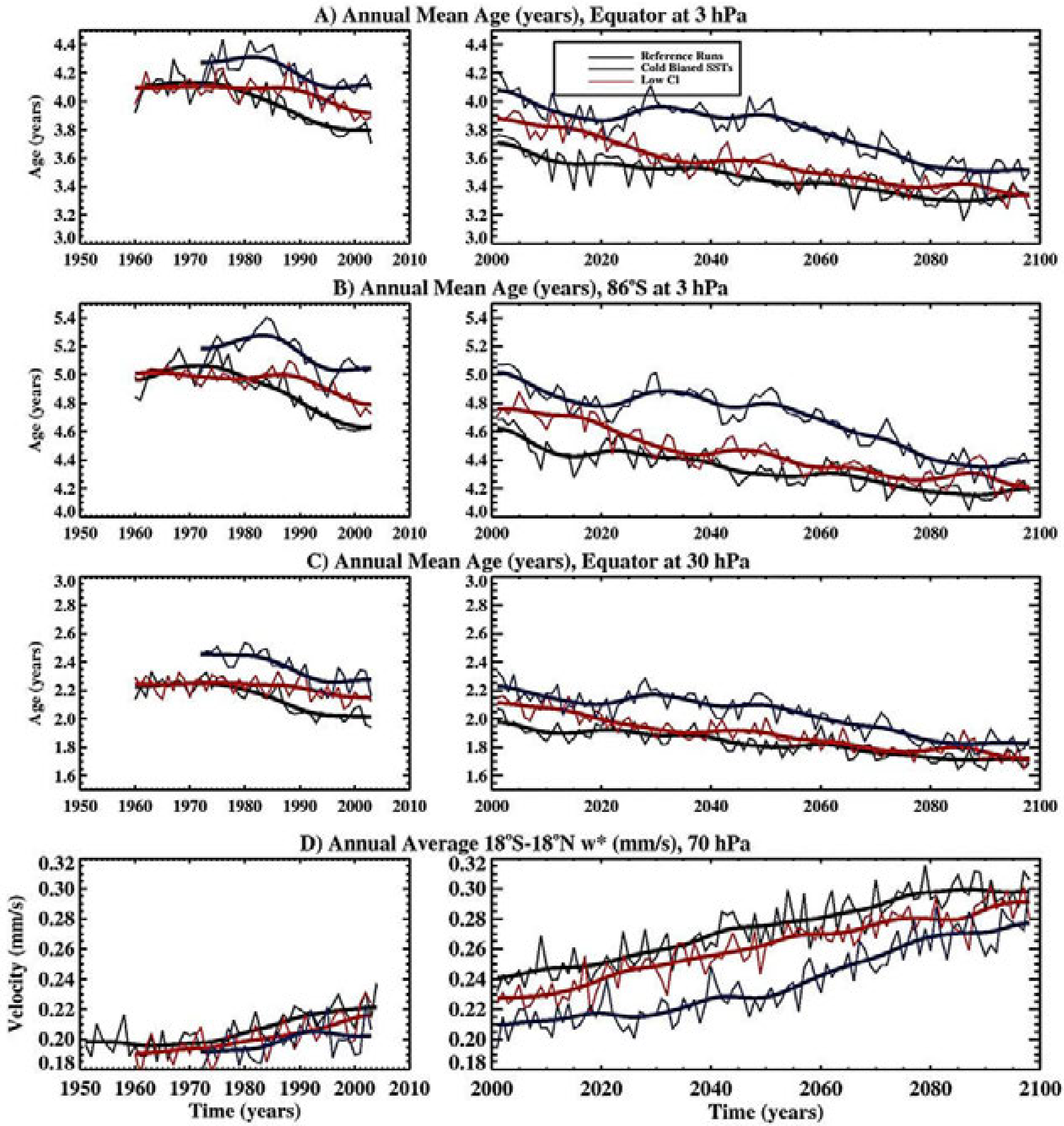

Figure 3. Annual mean (thin line) age (years) from 1960 to 2100 for (a) equator at 3 hPa, (b) 86°S at 3 hPa, and (c) equator at 30 hPa for the (left) past and (right) future simulations. (d) Annual average (thin line) tropical residual vertical velocity (w*) (mm s^{-1}) from 1950 to 2100 for 18°S–18°N at 70 hPa for the (left) past and (right) future simulations. The black line is for the reference runs, the blue line used the cold biased sea surface temperatures, and the red line has low Cl. The thick line is from applying a low-pass filter to remove less than decadal variability.

comparing the reference run to the cold biased SST run, for five different time periods (Table 2). The difference in tropical SSTs between runs averages about 1°C for these five periods (see Figure 1a). For each period we calculate the difference in mean age per 0.5°C difference in tropical (10°S–10°N) SST. Figure 4a shows the $\partial\Gamma/\partial$SST averaged over the five periods (similar results are obtained if SSTs averaged over 20°S–20°N are used). The difference in Γ is fairly constant throughout the stratosphere (around –0.15 years/0.5°C), with smaller differences in the low to mid tropical stratosphere. The difference in Γ is fairly symmetrical about the equator, as might be expected as the tropical SST forcing is also fairly symmetrical.

[16] The difference in Γ per 0.5°C change in SSTs is similar to that shown in Figure 4a for each of the five time periods considered. This can be seen in Figure 4b, which

Table 2. List of Cases Used to Determine the Change in Stratospheric Mean Age Caused by Tropical SSTs, Polar Ozone, and WMGHG Changes

Case	Time Period	Model Runs
$\partial\Gamma/\partial$SST_1	1995–2004	Reference Past – Cold Biased SST
$\partial\Gamma/\partial$SST_2	2015–2024	Reference Future – Cold Biased SST
$\partial\Gamma/\partial$SST_3	2035–2044	Reference Future – Cold Biased SST
$\partial\Gamma/\partial$SST_4	2055–2064	Reference Future – Cold Biased SST
$\partial\Gamma/\partial$SST_5	2085–2094	Reference Future – Cold Biased SST
$\partial\Gamma/\partial O_3$_1	1985–1994	Reference Past – Low-Cl Past
$\partial\Gamma/\partial O_3$_2	1995–2004	Reference Past – Low-Cl Past
$\partial\Gamma/\partial O_3$_3	2005–2014	Reference Future – Low-Cl Future
$\partial\Gamma/\partial O_3$_4	2015–2024	Reference Future – Low-Cl Future
$\partial\Gamma/\partial O_3$_5	2025–2034	Reference Future – Low-Cl Future
$\partial\Gamma/\partial CO_2$	Last 10 years	TS2050 – TS1980

shows the values at three locations over the five cases. There is some variability in the south polar location, but the values at the two tropical locations are similar for all five cases. This similarity suggests the $\partial\Gamma/\partial$SST is fairly robust and not dependent on time periods used to calculate it. The time period in which tropical SSTs increase by 0.5°C varies over the length of the run, however an average time period is around 30 years (with a range of 20–40 years).

3.2.2. WMGHGs

[17] We now consider the direct radiative impact of differences in WMGHGs on the mean age. We do this by comparing two runs with differing amounts of WMGHGs but identical SSTs and very similar polar ozone. Although, the concentrations of CO_2, N_2O, and CH_4 are changing, we use CO_2 concentrations as an index for this forcing and refer only to CO_2 in Figures 4, 6, 7, and 8. (These changes in CO_2 concentration may not be appropriate for other scenarios where the temporal variations in N_2O and CH_4 differ.) This case was formed using the TS1980 and TS2050 where polar ozone was within 2% of each other. Figure 4c shows the resulting difference in Γ for a 300 ppmv change in CO_2. This shows that there are only moderate differences in Γ for large differences in the direct radiative effect of WMGHGs, which only occur over long time periods (e.g., a 300 ppmv change in CO_2 occurs between 1960 and 2060, see Figure 1c). As we had only one case and the response is relatively small, some natural variability is likely still present in Figure 4c. We suspect that this forcing, like the tropical SSTs, would be hemispherically symmetric, although, it should be noted that there is typically more internal variability in the Northern Hemisphere stratosphere.

3.2.3. O_3

[18] Finally, we consider the impact of differences in stratospheric ozone on the mean age. We calculate the differences in Γ for five pairs of time periods where ozone differs, but SSTs and WMGHGs (except chlorine-containing GHGs) are the same. These cases were formed using differences between the low Cl and reference runs (see Table 2) over different time periods.

[19] There are several different possible indices to use for ozone changes, including polar ozone, global ozone, upper stratospheric ozone, or Equivalent Effective Stratospheric Chlorine (EESC) [*Newman et al.*, 2007]. The results are generally not sensitive to the region used (except for upper stratospheric ozone, see below). Below we use a polar lower stratospheric ozone index based on 100 hPa O_3 averaged over 90°–60°S and 60°–90°N (using areal weighting). Similar results to those shown above are obtained if a different pressure level, between 150 hPa and 50 hPa, or just the Southern Hemisphere was used for the O_3 index (not shown). We focus on polar ozone as recent studies have also shown that polar ozone depletion and recovery has a significant impact on the subtropical jet and tropospheric circulation in the Southern Hemisphere [*Perlwitz et al.*, 2008; *Son et al.*, 2008], and these changes may be expected to modify the wave driving of the stratosphere (see section 3.4).

[20] It is possible that some of the differences isolated from these comparisons could be due to changes in the halogens rather than changes in ozone. However, both runs use the same SSTs so that much of the radiative forcing from halogens are incorporated in both runs. This still does not account for the direct radiative heating of the halogens in the tropical lower stratosphere, however this is likely a small effect and, as shown below, the seasonal cycle in tropical w* changes supports the hypothesis that changes in polar ozone cause the differences in Γ.

[21] The impacts of changes in polar lower stratospheric ozone are shown in Figure 4d which shows the average difference in Γ over the five cases, for an 18% loss in polar ozone (100 hPa O_3 averaged over 90°–60°S and 60°–90°N). The magnitude of the difference in Γ in the middle stratosphere for an 18% loss in polar O_3 is similar to that for a 0.5°C increase in tropical SSTs. However, in contrast to the SST change in mean age, that due to ozone is not hemispherically symmetric. This asymmetry is consistent with the polar lower stratospheric ozone differences, in which much greater ozone loss occurs over the Southern Hemisphere because of the formation of the ozone hole. This causes a much larger difference in the mean age in the Southern Hemisphere. Also, there is somewhat larger variability between the five cases compared to the SST cases, as can be seen in Figure 4e. As with the SSTs, the time for O_3 to change by 18% varies with time period, but as an example O_3 decreases by about 18% from 1980 to 2000 (see Figure 1b).

[22] In the above we focused on impact of differences in polar lower stratospheric ozone. There are however changes in upper stratospheric ozone which might impact the mean age. However, this impact appears to be very small. Figure 5 shows the change in ozone and change in age for two pairs of time slice runs. The change in upper stratospheric ozone is very different between these two pairs. One might expect a decrease in ozone to cause a decrease in mean age (in similar manner to increases in CO_2). However, this is not visible in Figure 5: The decrease in upper stratospheric ozone between the TS2000 and TS2020 (Figure 5a) runs is larger than between the TS2020 and TS1980 runs (Figure 5c), but the decrease in age is actually less (because of smaller changes in polar lower stratospheric ozone).

3.3. Reconstructing Mean Age Changes

[23] If tropical SSTs, polar ozone, and CO_2 are the main causes of changes in the mean age we should be able to reconstruct these changes in the model using the equation

$$\Delta\Gamma = \Delta SST(\partial\Gamma/\partial SST) + \Delta O_3(\partial\Gamma/\partial O_3) + \Delta CO_2(\partial\Gamma/\partial CO_2) \quad (1)$$

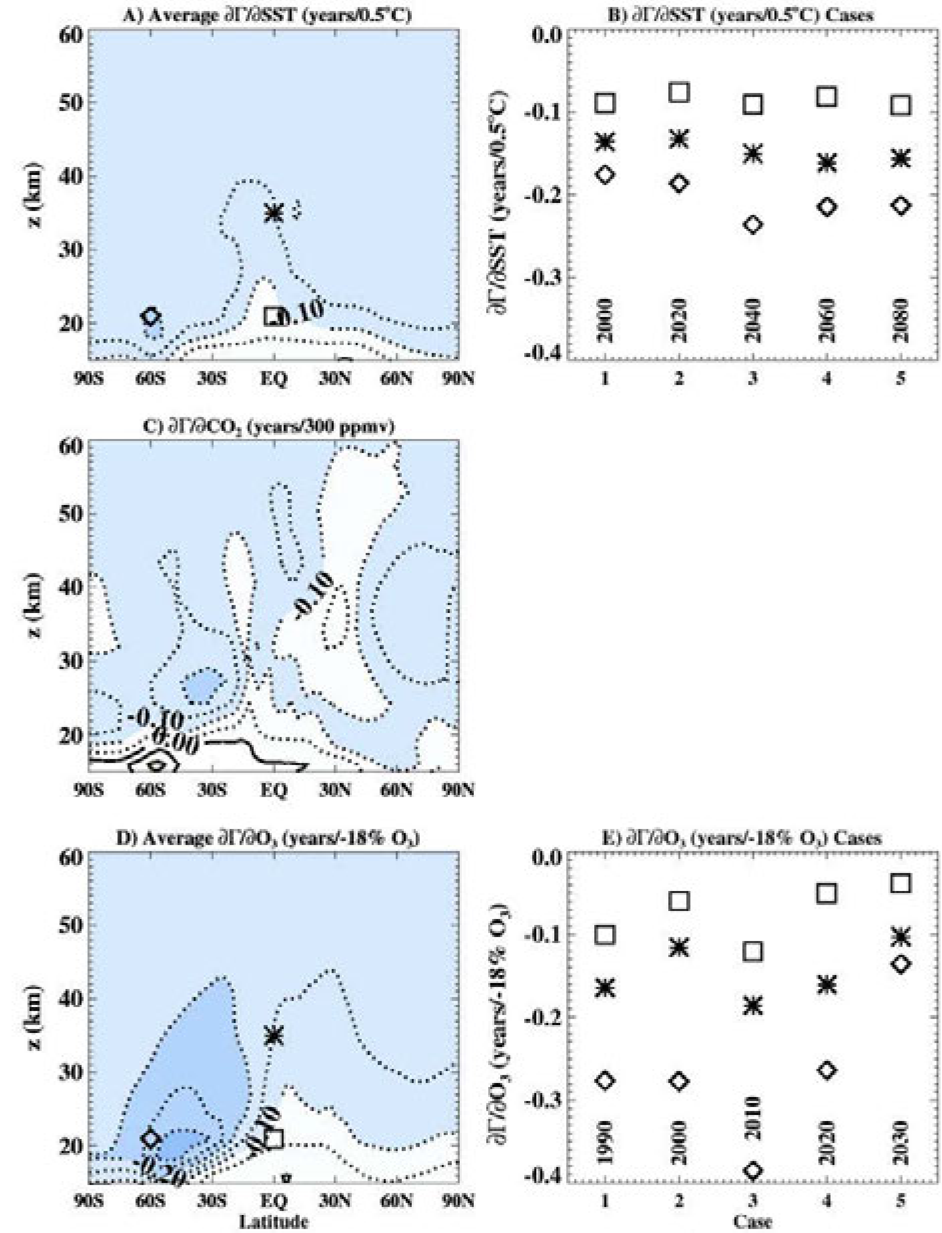

Figure 4. (a) Average $\partial\Gamma/\partial SST$ (years/0.5°C) from 15 to 60 km calculated from five cases and (b) the values at a few selected locations, and year represents the middle of the decadal average. The ∂SST used is the tropical 10°S–10°N average. (c) The $\partial\Gamma/\partial CO_2$ (years/300 ppmv CO_2) from 15 to 60 km for one case. (d) Average $\partial\Gamma/\partial O_3$ (years/−18% O_3) from 15 to 60 km calculated from five cases and (e) the values at a few selected locations, and year represents the middle of the decadal average. The ∂O_3 used is the 100 hPa 90°S–60°S and 60°–90°N weighted average. The locations are shown in Figures 4a and 4d.

where $\Delta\Gamma$ is the simulated change in mean age, ΔSST is the change in tropical SSTs, ΔO_3 is the change in O_3 from 90° to 60°S and 60° to 90°N at 100 hPa, and ΔCO_2 is the change of surface CO_2 concentrations over some period of time, and $\partial\Gamma/\partial SST$, $\partial\Gamma/\partial O_3$, and $\partial\Gamma/\partial CO_2$ are shown in Figures 4a, 4e, and 4c. To test this we consider the change in mean age in a separate ensemble from the past reference run (reference past 2). Figure 6a shows the model's change in Γ between 1960–1969 and 1995–2004, while Figures 6b–6d show the reconstructed changes due to each term on the right hand side of equation (1) (i.e., Figure 6b shows $\partial\Gamma/\partial SST$ multiplied by the change in tropical SST between 1960–1969 and 1995–2004), and Figure 6e shows the sum of Figures 6b–6d. The difference between the constructed mean age change and that produced by the model is shown as Figure 6f and it compares very well above 22 km with differences of less than ± 0.05 years. Over the time period shown, the change in mean age is due mainly to polar ozone loss (Figure 6c) with a secondary impact due to increasing tropical SSTs (Figure 6b). The direct radiative impact of increases in WMGHGs is extremely small (Figure 6d) over this time period.

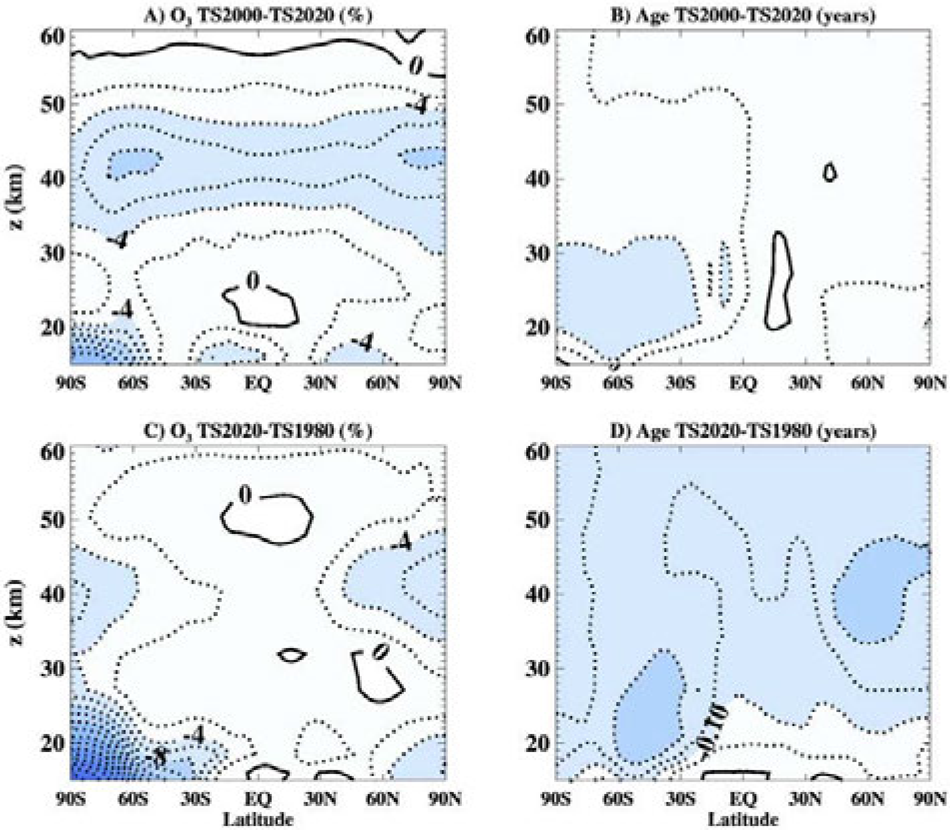

Figure 5. (a) Change in ozone (%) between TS2000 and TS2020 and (b) the change in age between the same two runs. (c) Change in ozone (%) between TS2020 and TS1980 and (d) the change in age between the same two runs.

[24] However, ozone depletion in the model is transient (with maximum polar depletion around 2000) and the influence of ozone on changes in mean age varies with time. To illustrate this consider the changes in mean age between 1970 and 2090. In GEOS CCM polar lower stratospheric ozone recovers to 1970 levels by approximately 2090, so all changes in mean age between 1970 and 2090 should be explained by increases in tropical SST and CO_2. Figure 7 shows the analogous fields to Figure 6 except for the differences between 1965–1974 and 2085–2094. The change in mean age over this time period approaches 1 year over much of the stratosphere outside of the low to mid tropical stratosphere. The reconstructed mean age change again compares well with the simulated change (Figure 7f), with most differences less than ± 0.10 years above 22–24 km. (Most of the structure above 22–24 km in the difference field can probably be attributed to the impact of natural variability in the estimate of the change caused by CO_2.) Comparison of the contribution due to the different factors shows, as expected, insignificant contribution from polar ozone, and the change in mean age is primarily due to increases in SSTs. There is now, because of the larger change in CO_2 over this longer time period, some change because of the direct CO_2 impact (Figure 7d), but it is much smaller than the impact from tropical SSTs.

[25] Figures 6 and 7 show that the method of linearly adding the individual components works well above about 22–24 km in the stratosphere. In the extratropical lowermost stratosphere this method does not compare well to the model age changes, and may give spurious results in this region. There is much larger horizontal transport [*Shepherd*, 2007] and the differences in this region may indicate that this method does a better job in explaining differences in the vertical residual circulation than horizontal mixing in the lowermost extratropical stratosphere.

[26] The above comparisons have shown that equation (1) can be used to quantify the relative contribution of different factors on changes in the mean age, and that these relative contributions vary with time. To examine these variations in more detail we can examine the contributions of each forcing to the mean age change over the entire time series for a single location. Figure 8a shows the annual mean age reconstruction (years) over the equator at 30 hPa with respect to 1960–1969 base period. The blue line is the mean age due to tropical SST changes, the red line is the mean age change due to changes in polar lower stratospheric ozone, and the green line is that due to the direct radiative impact of WMGHGs (labeled CO_2) changes. The orange line is the total of the individual components and the black line is the models mean age change. The total of the three components matches reasonably well during the entire time series.

[27] Over the past 30–40 years all three factors cause a decrease in mean age, with polar ozone depletion being the major factor (and negligible changes due to direct radiative WMGHG impact). However, polar ozone recovers backs to

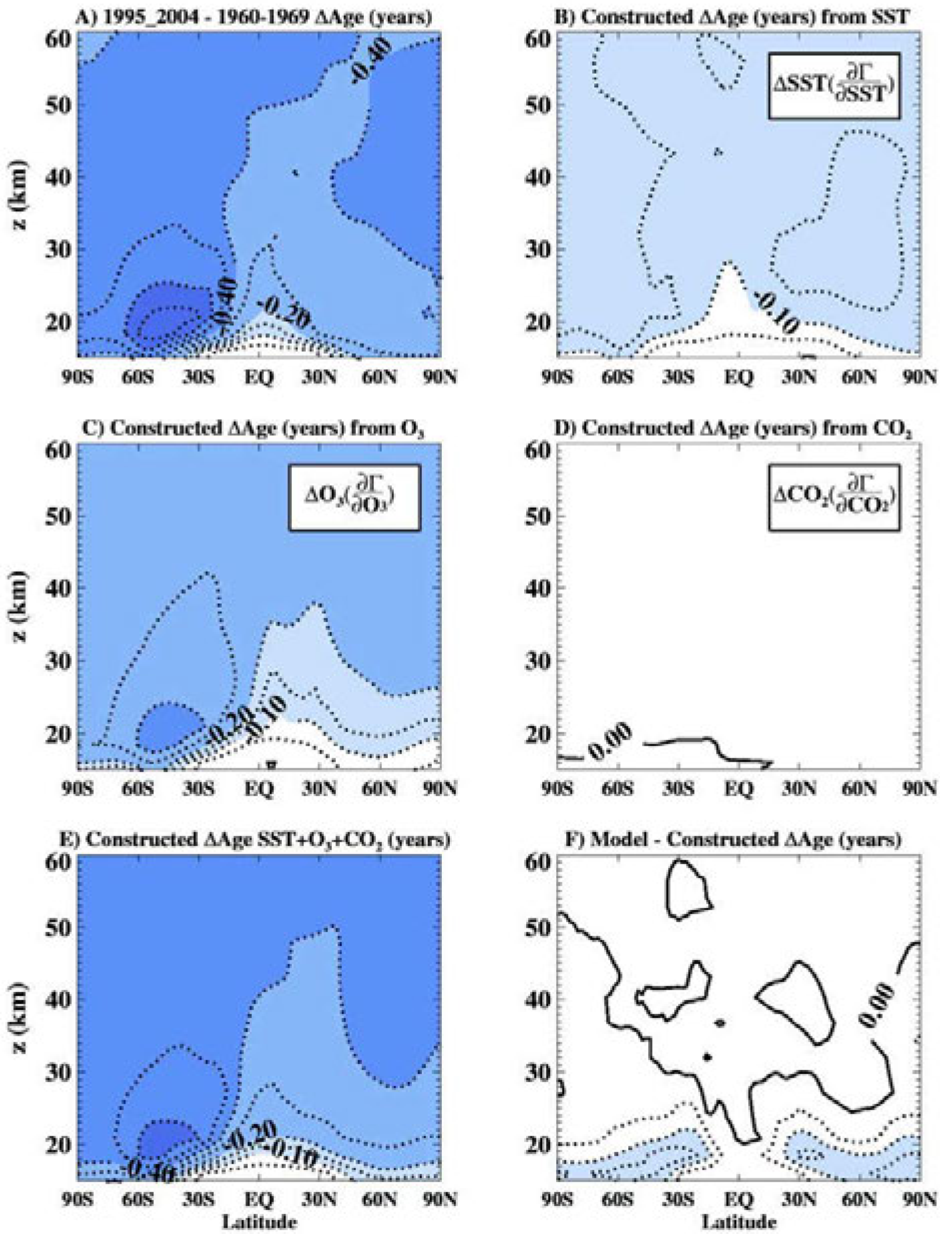

Figure 6. (a) Model average change in mean age from 1960–1969 to 1995–2004. Constructed mean age changes due to (b) sea surface temperature, (c) polar ozone, and (d) CO_2. (e) The composite of all three components and (f) the difference between the constructed and model changes in mean age, all for 15–60 km and units in years.

1970 levels during the next 50–60 years, and this causes an increase in the mean age, whereas the continued increase in SSTs and WMGHGs still causes a decrease in the mean age. The simulated changes in polar ozone after 2040 are relative small and the mean age decreases because of increases in tropical SSTs, with some additional impact from the direct radiative effect of the large change in WMGHGs. Figure 8b is similar to Figure 8a except that it is for changes in tropical w* (mm s^{-1}) at 70 hPa and shows that over the past simulation there are about equal contributions to the upwelling change from changes in polar ozone depletion and tropical SSTs.

3.4. Zonal Winds, Eddy Heat Fluxes, and Residual Circulation

[28] The above analysis indicates that increases in tropical SSTs and WMGHGs and decreases in polar ozone cause decreases in the mean age, but does not provide information on the mechanisms/processes involved. For example, are the same dynamical processes involved or does each factor cause a different process to change? It is difficult to isolate individual processes within fully coupled chemistry-climate models. However, using an analysis similar to that used for mean age changes in sections 3.2.1 and 3.2.3 for other fields provides some insights. We again will look at the impact of SSTs and O_3 that have occurred in the model simulations

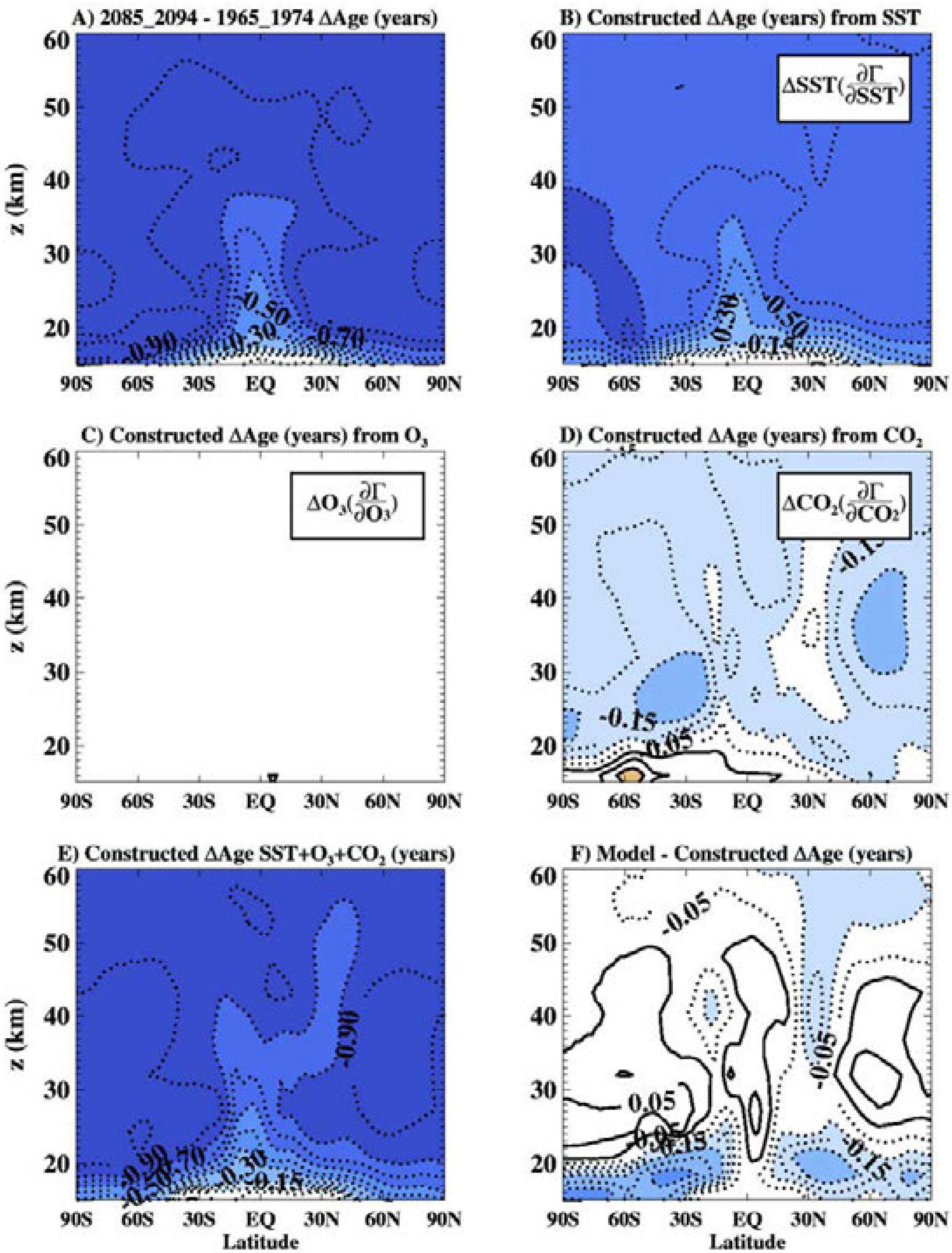

Figure 7. (a) Model average change in mean age from 1965–1974 to 2085–2094. Constructed mean age changes due to (b) sea surface temperature, (c) polar ozone, and (d) CO_2. (e) The composite of all three components and (f) the difference between the constructed and model changes in mean age, all for 15–60 km and units in years.

over the past (1965–2000). This is calculated by multiplying the monthly sensitivities of w* by the change in tropical SSTs and polar ozone depletion.

[29] There are changes in tropical upwelling from increasing tropical SSTs throughout the year, see solid curve in Figure 9. However, there is a clear seasonal cycle in changes in the upwelling, which match the seasonal cycle of Southern Hemisphere polar ozone depletion with a 1–2 month lag, with the largest increase in upwelling occurring during austral spring and summer, see dashed curve in Figure 9. We therefore examine the annual mean changes due to SSTs but austral spring and summer changes due to

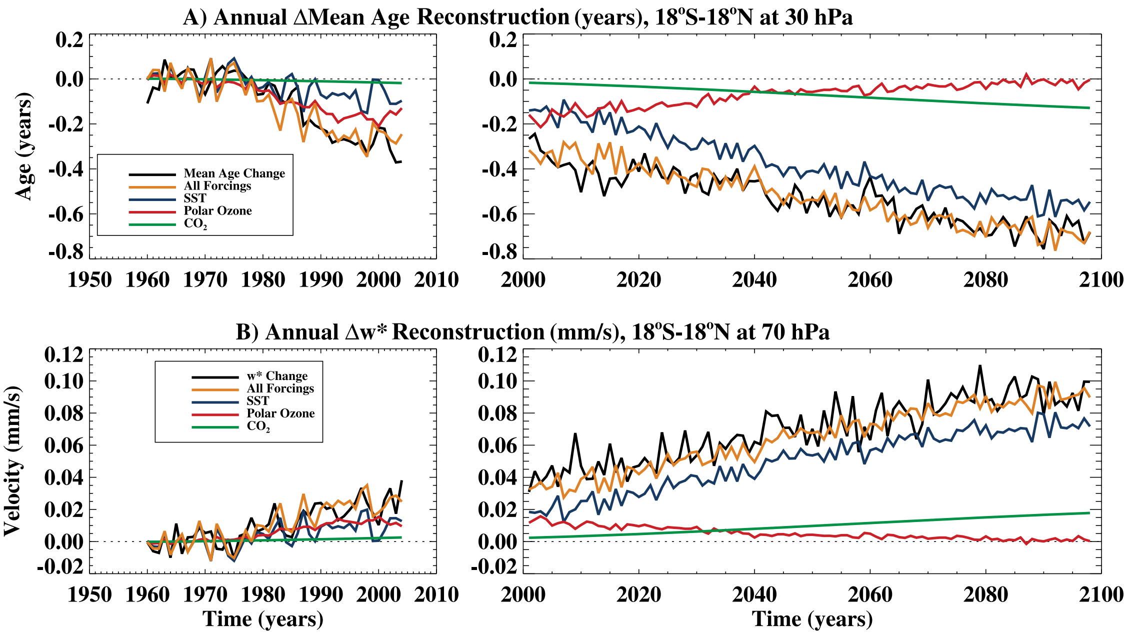

Figure 8. (a) Annual mean age change reconstruction (years) over 18°S–18°N at 30 hPa and (b) annual mean w* change reconstruction (mm s^{-1}) over 18°S–18°N at 70 hPa, both with respect to 1960–1970 base period. The blue line is the change due to tropical SST changes, the red line is the change due to changes in polar ozone, and the green line is that due to the direct radiative impact of WMGHG changes (labeled CO_2). The orange line is the total of the individual components, and the black line is the model's actual change.

polar ozone depletion. It is possible that some of the change in upwelling could be due to the direct radiative heating of the halogens in the tropical lower stratosphere, however we believe that the seasonal cycle in tropical w* changes supports the conclusion that it is polar ozone depletion causing the change.

[30] Increasing tropical SSTs resulting from increasing WMGHG concentrations warms the tropical troposphere. Figure 10a shows the annual atmospheric temperature change from a 0.5°C change in tropical SSTs. The peak warming of 0.8°C occurs in the tropical upper troposphere (200–300 hPa) with smaller changes occurring in the extratropics at these levels. The warming in the tropics continues up to the tropopause and it is this region in the upper troposphere where the meridional temperature gradient is increasing. Polar ozone loss in the lower stratosphere also changes the temperature gradient; see Figure 10a, which shows the change for October to February (ONDJF). There is a cooling in high latitudes through the radiative effect of reduced ozone levels, but little or no temperature change in the tropical upper troposphere. As a result the ozone loss also increases the meridional temperature gradient.

[31] The temperature changes due to changes in both tropical SSTs and polar ozone effect the zonal mean zonal

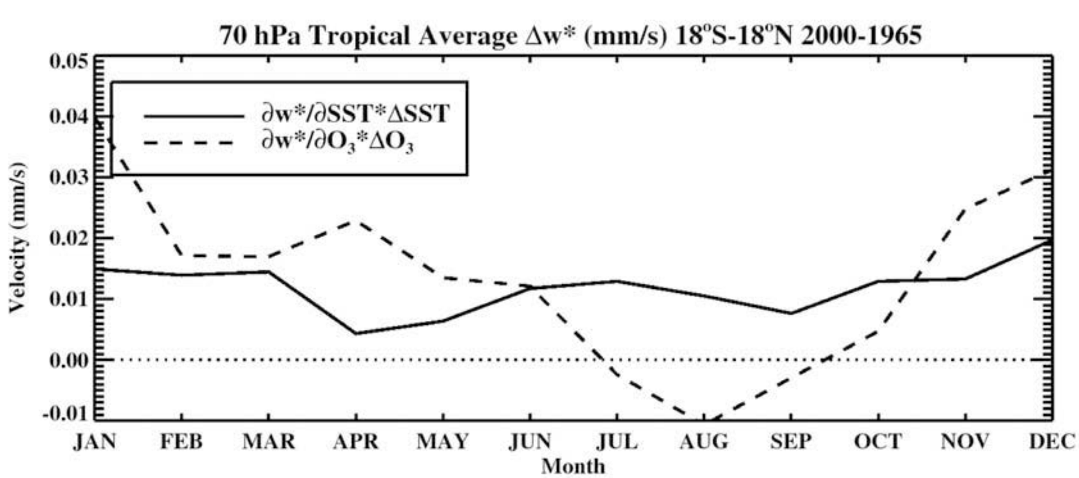

Figure 9. Change in monthly average tropical (18°S–18°N) w* (mm s^{-1}) at 70 hPa due to changes in tropical SSTs (solid line) and polar ozone (dashed line) for the time period 1965–2000.

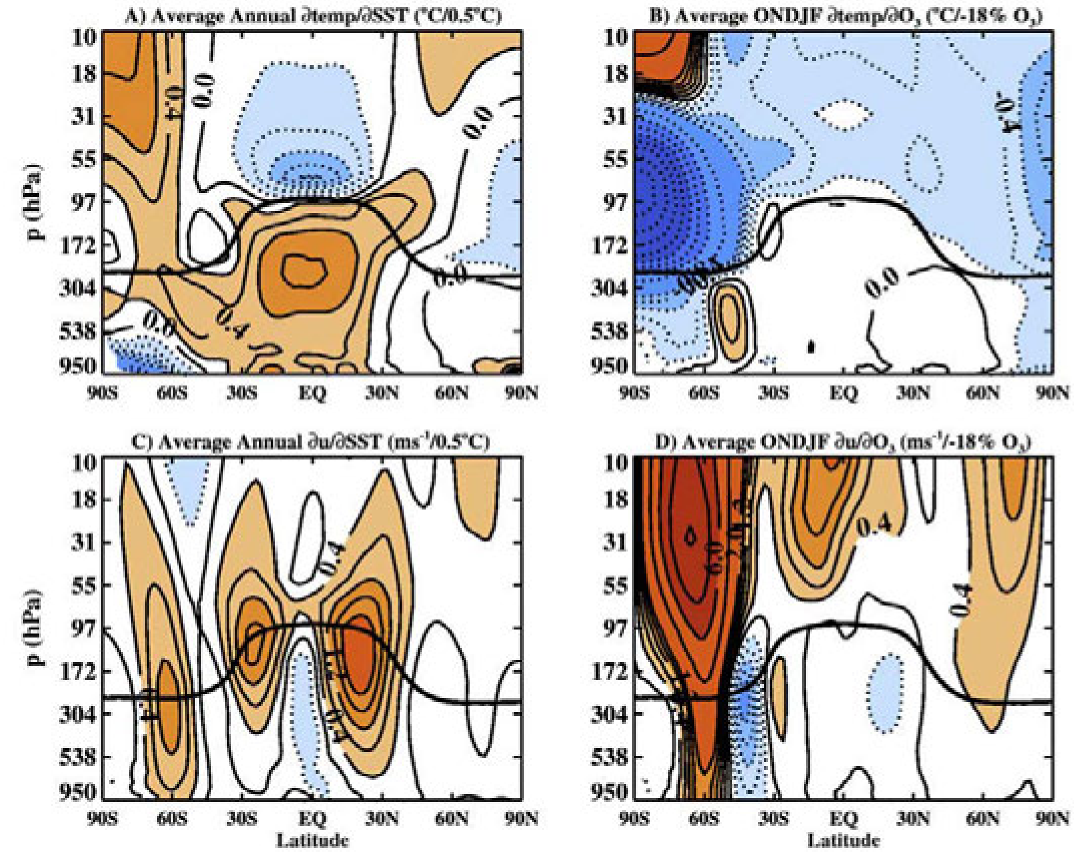

Figure 10. (a) Average annual ∂temp/∂SST (°C/0.5°C) from 950 to 10 hPa and (b) average ONDJF ∂temp/∂O_3 (°C/−18% O_3) from 950 to 10 hPa. (c) Average annual ∂u/∂SST (m s ^{1}/0.5°C) from 950 to 10 hPa and (d) Average ONDJF ∂u/∂O_3 (m s ^{1}/−18% O_3) from 950 to 10 hPa. All were calculated from the five cases for SST and polar ozone described in sections 3.2.1 and 3.2.3 with the same time periods and simulations as Table 2. For reference, the typical height of the tropopause is shown. For Figures 10a and 10b the contour interval is 0.2 from [−1, 1] and 1 for values >1 and < 1. For Figures 10c and 10d the contour interval is 0.4 from [−2, 2] and 2 for values >2 and < 2. (e) Average annual ∂EPFz/∂SST (kg s ^{2}/0.5°C) from 950 to 10 hPa and (f) average ONDJF ∂EPFz/∂O_3 (kg s ^{2}/−18% O_3) from 950 to 10 hPa. (g) Average annual ∂w*/∂SST (mm s ^{1}/0.5°C) from 950 to 10 hPa and (h) average ONDJF ∂w*/∂O_3 (mm s ^{1}/−18% O_3) from 950 to 10 hPa. All were calculated from the five cases for SST and polar ozone described in sections 3.2.1 and 3.2.3 with the same time periods and simulations as Table 2. Only values above the typical height of the tropopause are shown. For Figures 10e and 10f the contour interval is 200 from [−1000, 1000] and 1000 for values >1000 and < 1000. For Figures 10g and 10h the contour interval is 0.01 from [−0.05, 0.05] and 0.05 for values >0.05 and < 0.05.

wind, as shown in Figures 10c and 10d. However, there are differences in how each impacts the zonal wind. For tropical SST changes, the maximum increase in zonal winds are near the tropical tropopause around 20°−30°N and S with less change above this level. For polar ozone losses the largest changes are for the polar stratospheric jet stream in the Southern Hemisphere as we would expect from the large ozone losses poleward of that region.

[32] The above changes in zonal winds may affect the propagation of planetary waves from the troposphere into the stratosphere. *Chen and Robinson* [1992] showed the propagation of planetary waves is sensitive to changes in vertical wind shear near the tropopause, with increased wave propagation for increased vertical shear. Zonal wind changes caused by increasing tropical SSTs increase the vertical shear (Figure 10c) and Figure 10e shows a clear increase in the vertical component of the Eliassen-Palm flux, with increased wave activity into the stratosphere. This enhanced wave activity especially in the subtropics is similar to that seen by *Garcia and Randel* [2008]. This increase in the Eliassen-Palm flux is mainly seen in the SH during ONDJF for increased polar ozone loss, see Figure 10f.

[33] The increased wave driving due to changes in the tropical SST and polar ozone lead to changes in the residual vertical velocity (w*) with increased tropical upwelling being balanced by increased midlatitude downwelling in the lower stratosphere (Figures 10g and 10f). The changes in simulated mean age are consistent with changes in the tropical upwelling (vertical residual velocity). It is however of interest to examine the changes in residual circulation in other regions, in particular in polar regions. Figure 11a shows the change in w* and streamlines between 1970 and

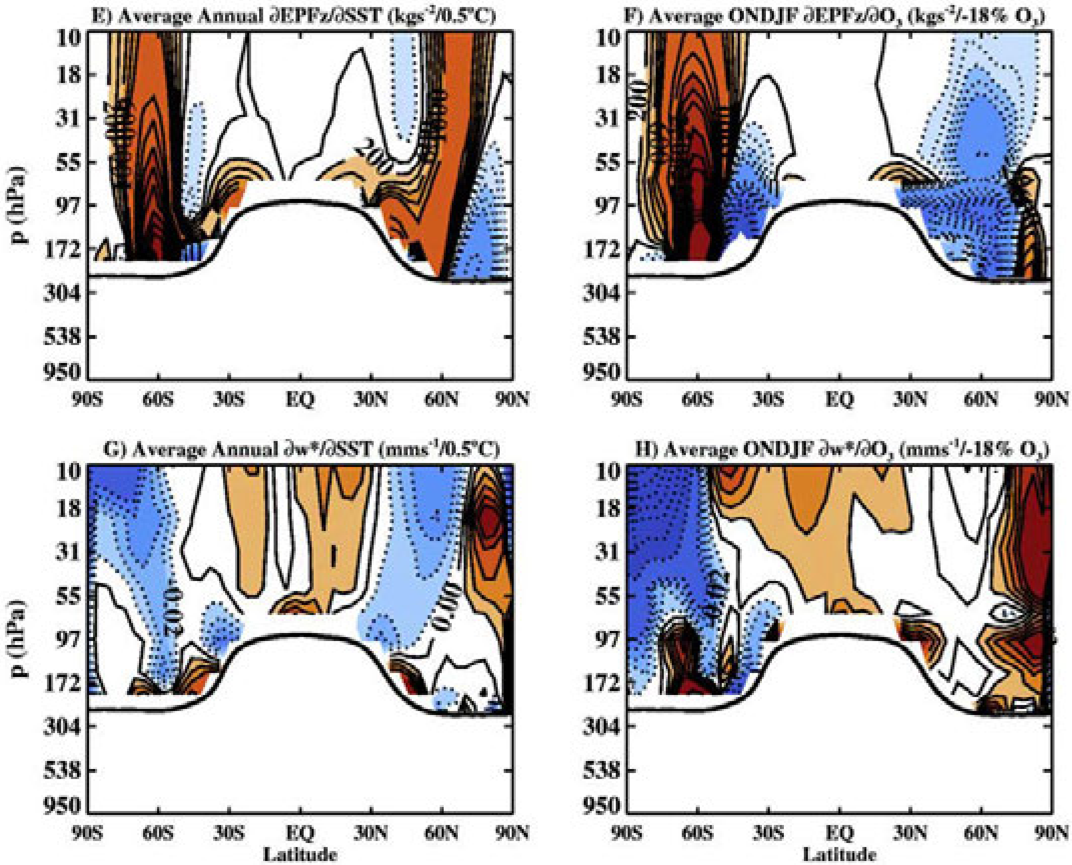

Figure 10. (continued)

2090. This shows a clear increase in the tropical lower stratosphere, but also shows changes in other regions. There appears to be a clear increase in polar mid to upper stratospheric downwelling. However, this is not propagated into the polar lower stratosphere. Instead we see increased lower stratospheric downwelling in the midlatitudes and some decreased upwelling in the subtropics to balance the increased tropical upwelling. This increased circulation does not seem to result in increased polar downwelling in the lower stratosphere in these simulations. A review of the published literature on this response varies widely between model simulations and suggests that the lower stratosphere polar response is not robust [*Austin et al.*, 2003]. As discussed earlier there is very little difference in polar lower stratospheric ozone between 1970 and 2090, so one would expect the majority of the change in vertical residual velocity to be dominated by the change in tropical SSTs. This is indeed the case as can be seen by comparing Figure 11b and Figure 11a. Figure 11b is calculated using Figure 10g and multiplying it by the 2.2°C change in tropical SSTs.

[34] While we have focused mostly on the annual average change in the residual circulation, the seasonal variations are broadly consistent with those shown by *Li et al.* [2008] for AMTRAC simulations. The largest seasonal variations occur in the Southern Hemisphere where Antarctic polar ozone loss causes a peak polar downwelling during the austral spring in the mid to upper stratosphere and during austral summer in the mid to lower stratosphere. This is, however, mostly balanced by decreased downwelling in the austral winter resulting in a near zero net impact on an annual basis over the polar lower stratosphere.

4. Conclusions

[35] GEOS CCM simulations show a significant decrease in the mean age from 1960 to 2100, with a fairly spatially uniform decrease outside the tropical lower middle stratosphere (0.07 years/decade) which is consistent with an increase in upwelling in the tropical lower stratosphere. This increase in tropical upwelling and decrease in mean age is a common feature of chemistry-climate simulations of the past or future [e.g., *Butchart et al.*, 2006; *Austin and Li*, 2006; *Garcia et al.*, 2007; *Garcia and Randel*, 2008].

[36] We have examined the impact of changes in tropical SSTs, direct radiative effect of WMGHGs, and polar ozone on the mean age by comparing different pairs of simulations that differ by only one of these factors. Our analysis indicates that all three factors cause changes in the mean age, but the relative impact of each factor depends on the time period analyzed. Over the past 30–40 years all three factors cause a decrease in mean age, with ozone depletion being the major factor (and negligible changes due to direct WMGHG impact). However, ozone is predicted to recover back to 1970 levels during the next 50–60 years, and this causes an increase in the mean age, whereas the continued increase in WMGHGs manifested through increasing tropical SST and the radiative cooling of the stratosphere will still cause a decrease in the mean age. The net impact of

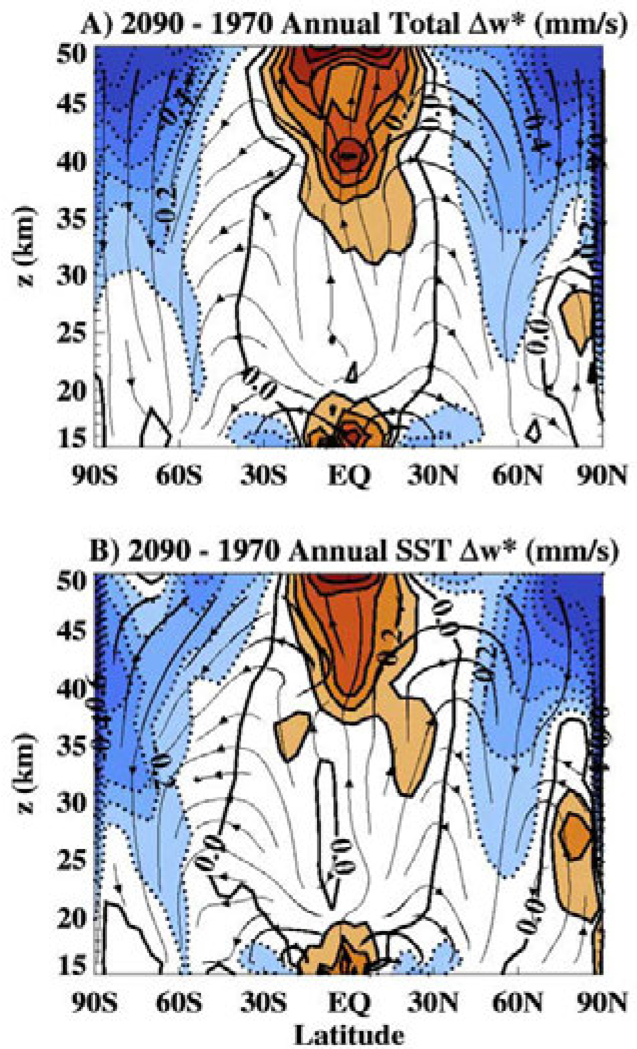

Figure 11. (a) Annual average change in w* (mm s^{-1}) from 1970 to 2090. (b) Change in w* calculated from Figure 10g due to the change in tropical SSTs over this same period. The change in stratospheric circulation is overlaid in each plot.

these factors will still result in a decreasing mean age although the rate will be smaller than that of the 1970–2000 period. The simulated changes in polar ozone after 2040 are relatively small, and the mean age decreases because of increases in tropical SSTs, with some additional impact from the direct radiative effect of the large change in WMGHGs.

[37] The above statements are based on correlated changes between mean age and tropical SSTs, WMGHGs, and ozone, and do not prove causality or provide information on the mechanisms/processes involved. However, analysis of tropospheric meteorology indicates that increasing tropical SSTs and polar ozone losses increase the meridional temperature gradient, which impacts the zonal mean zonal wind. In general the tropical SSTs have their largest impact on the subtropical westerlies near the tropopause. Polar ozone losses have a larger impact in the mid stratosphere especially on the Southern Hemisphere polar jet. Increased tropical SSTs allow a greater wave flux into the stratosphere to drive circulation changes. This increased wave flux is consistent with the findings of *Li et al.* [2008], *Kodama et al.* [2007], and *Garcia and Randel* [2008]. Polar ozone losses also allow a greater wave flux in the stratosphere especially during austral spring and summer when the Southern Hemisphere ozone loss is greatest. The increase in tropical upwelling from increased tropical SSTs does not seem to be accompanied by a clear increase in lower stratospheric polar downwelling, instead significant changes occur in the midlatitudes to balance the increased flux in the tropics.

[38] This study presents results from a single model so it is important to test these findings against other models to see if they produce similar changes in mean age. CCM simulations forced by similar changes in SST, WMGHGs, and halogens have been performed by several different modeling groups [*Eyring et al.*, 2006], and similar changes in mean age might be expected. However, there is a large spread in the simulated polar ozone depletion and recovery [*Eyring et al.*, 2007] as well as the hemispheric partitioning of polar ozone loss, and this could cause differences in the simulated change in the stratospheric circulation and mean age. This could cause models with higher than average ozone loss to see proportionally larger changes in mean age over the past. This seems to be the case as *Garcia et al.* [2007] mentioned their mean age changes were about half as large as those by *Austin and Li* [2006]. *Li et al.* [2008], who used the same or similar runs as *Austin and Li* [2006], mentioned that their model had much larger polar ozone losses than most [*Eyring et al.*, 2007]. In addition the mean age changes in this study seem to be more consistent with those by *Garcia et al.* [2007] with similar polar ozone losses.

[39] Using the relationship between tropical SST changes and the resulting differences in tropical upwelling could be very helpful in understanding the large spread among models in the tropical mass flux seen in Figure 6a of *Butchart et al.* [2006]. While all models show an increase in the tropical mass flux over time, the rate varies from 0.1 to 17.8 kt s^{-1} a^{-1}. Looking more closely, the lowest three rates are from model runs in which the SST were fixed allowing only small changes in WMGHGs. In contrast, the five largest rates are from model simulation in which there was large changes in SSTs either from doubled CO_2 or time periods that have higher than average SST rate increases (mid to late 21st century). Taking into account the rate at which tropical SSTs increase could remove much of the spread seen between models.

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