# The Role of Stratospheric Vortex Breakdown in Southern Hemisphere Climate Trends

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## Introduction

The Southern Hemisphere (SH) polar stratosphere cooled in the spring and summer in the late 20th century, mainly due to anthropogenic ozone depletion. This cooling trend results in a stronger polar vortex, and it delays the final breakdown of the polar vortex, the stratospheric final warming (SFW), in late spring by about 10 days per decade. Current chemistry-climate models consistently simulate the cooling and the positive trend in zonal winds in the high latitudes of the SH stratosphere. These stratospheric trends can induce significant changes in the SH tropospheric circulation.

The final breakdown of the SH stratospheric polar vortex can play a critical role in the high-latitude ozone concentration and its downward influence on the tropospheric climate. In this study, we investigate the connection between the delay in SFW onset dates and climate trends in the stratosphere and troposphere of the SH.

## Reanalysis data and climate models

- ERA-40 and NCEP/NCAR reanalysis datasets for the period of 1980-2001.

Three climate model outputs (1960-1999) include:

- AM2(SST only): forced by observed changes in sea-surface temperatures (SSTs) and sea ice with fixed preindustrial radiative forcings;
- AM2(SST+RAD(O3)): observed changes in SST, sea ice, and radiative forcings;
- AMTRAC(SST+RAD(ODS)): force by the observed changes in SST, sea ice, with interactive chemistry for ozone depletion.

## Decadal trends

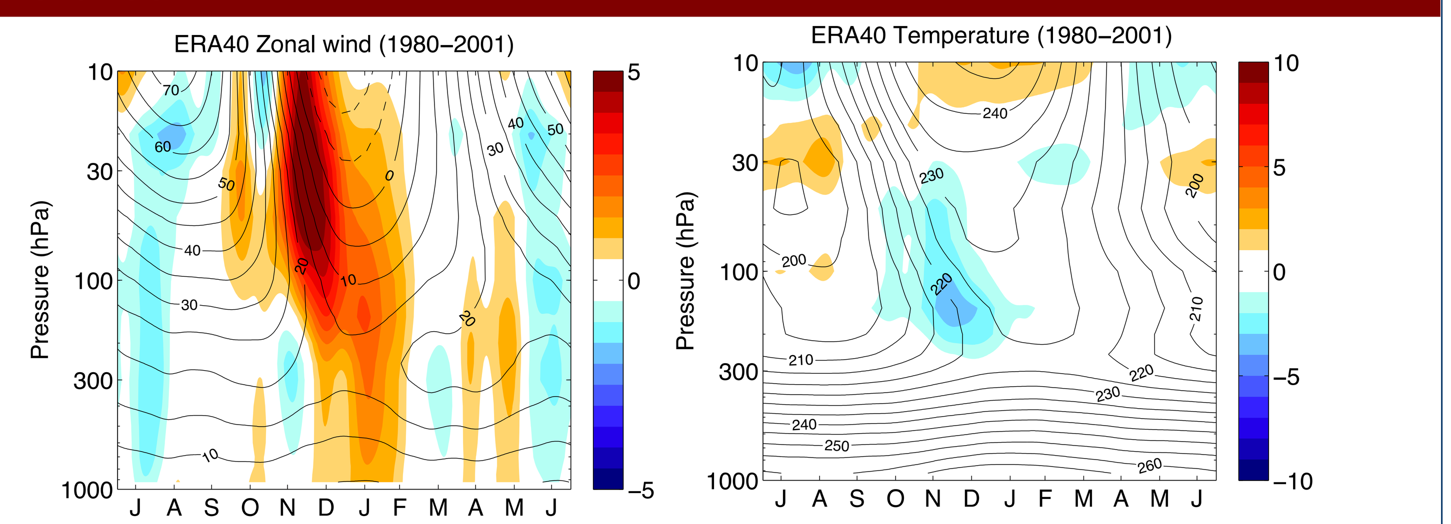



**Figure 1.** (Left): mean zonal wind trend (shade) and annual cycle (contour) averaged at 50°S-70°S in 1980-2001 in ERA-40. (Right): Similar to top, but for 60°S-90°S temperature. . Tick marks on the horizontal axis indicate the middle of the month

- The decadal zonal wind trend shows an increase in zonal winds above 100 hPa throughout spring and summer and extending downwards into the troposphere in December-February. There is a negative temperature trend between 30 hPa and the tropopause, persisting from September to February.
- The delay in the final breakdown of the polar vortex can be seen from the zonal wind and temperature seasonal transitions in the periods of 1980-1990 and 1991-2001.

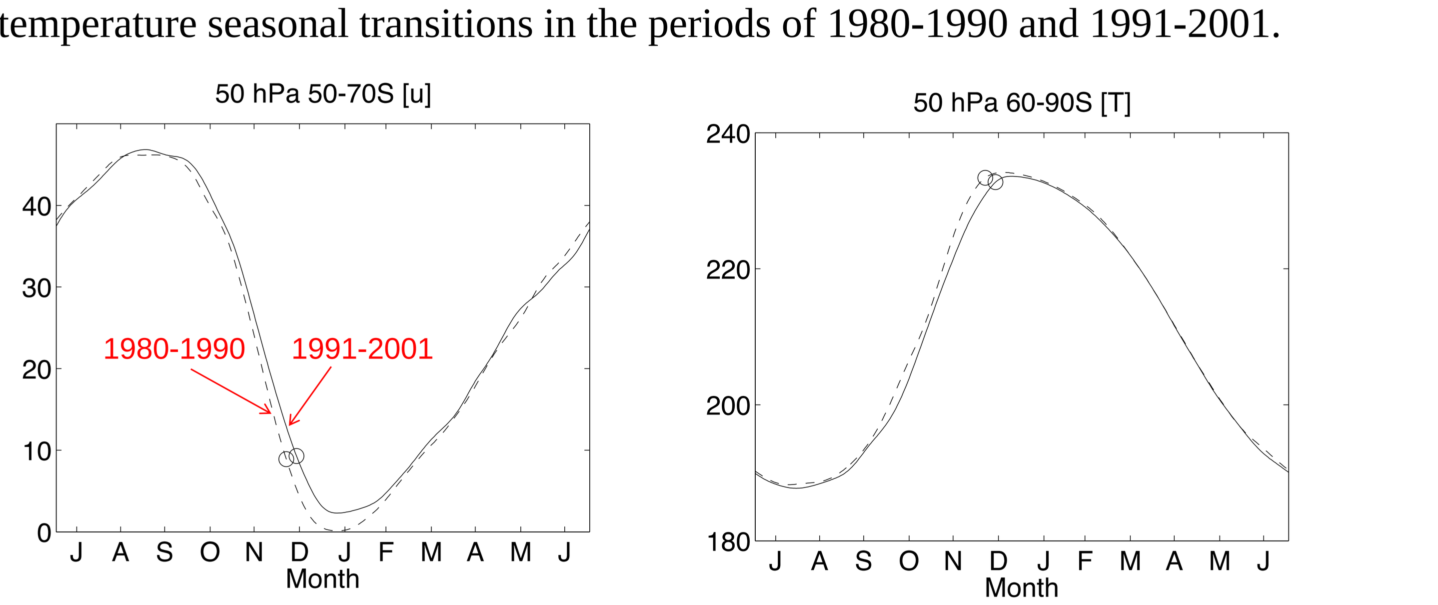
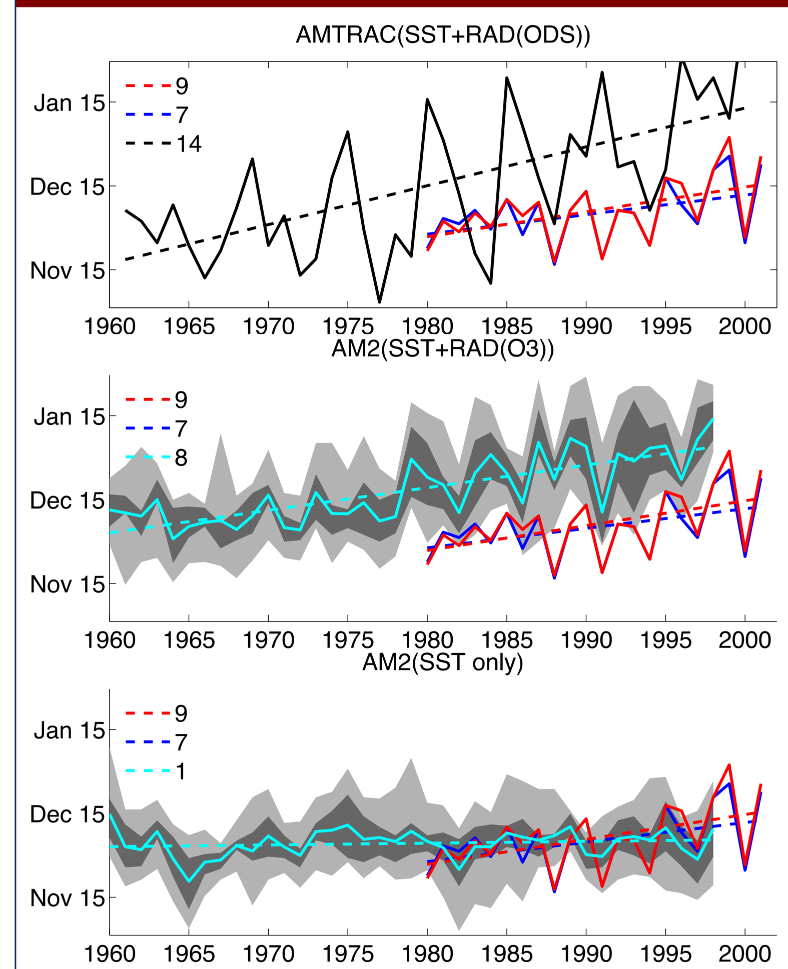



**Figure 2.** (Left): 50-70°S averaged 50 hPa zonal mean zonal wind in 1980 - 1990 (dashed line) and 1991 - 2001 (solid line). (Right), similar to top, but for 50-hPa 60°S-90°S temperature. Circles denote the mean 50 hPa SFW onset dates for the two periods.

## SFW onset dates




- SFW onset date is defined as the first day of the final time that the zonal-mean zonal wind at 60°S drops below 10 m s$^{-1}$ until the fall (Black and McDaniel, 2007).
- With ozone depletion, both reanalysis and climate models show an increasing delay in polar vortex breakdown. In contrast, the model forced only by observed changed in SSTs, AM2(SST only), has almost no trend in the SFW date.

**Figure 3. (Left)** The SFW onset dates in (Top) AMTRAC(SST+RAD(ODS)), (Middle) AM2(SST+RAD(O3)), and (Bottom) AM2(SST only). The numbers in the top left corner denote the linear trend of the SFW onset dates in models for the period 1960-1999 (days per decade), and the red (blue) lines denote the onset dates in ERA-40 (NCEP/NCAR reanalysis) for the period of 1980-2001.

### Regression onto the SFW onset dates

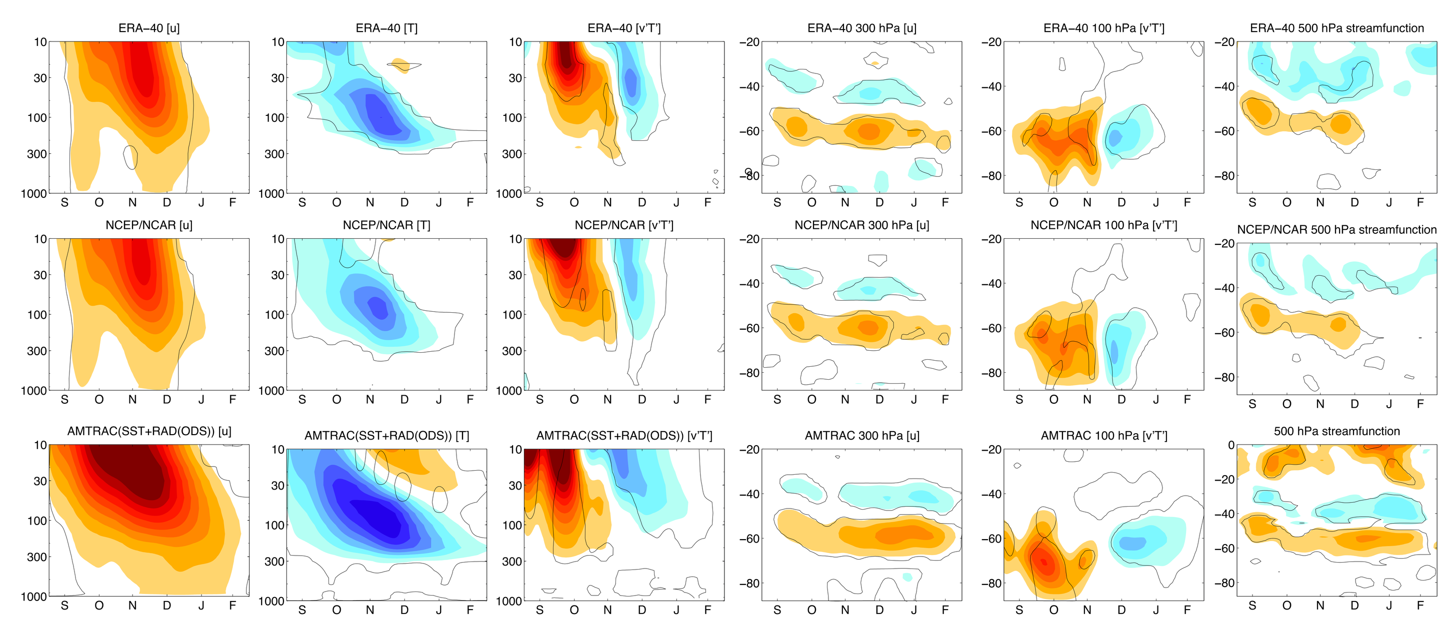


**Figure 4.** The regression onto the SFW onset dates for the 50-70°S zonal mean zonal wind, 60-90°S temperature, 60-90°S eddy heat flux, 300 hPa zonal wind, 100 hPa eddy heat flux and 500 hPa mean meridional circulation in (Top) ERA-40, (Middle) NCEP/NCAR reanalysis and (Bottom) AMTRAC results. Black contours indicate student's t-test 95% confidence level.

The regression pattern corresponds to a delay in SFW by one standard deviation. The similarity with Figure 1 indicates the important role of SFW dates in climate trends.

## Separating the role of SFW in zonal wind trends

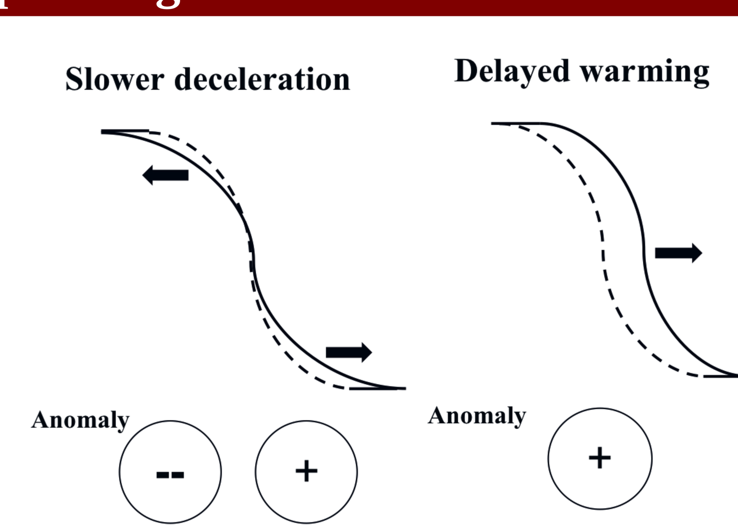



**Figure 5.** Schematic of the zonal-wind transition and anomalies in the two components of the trends.

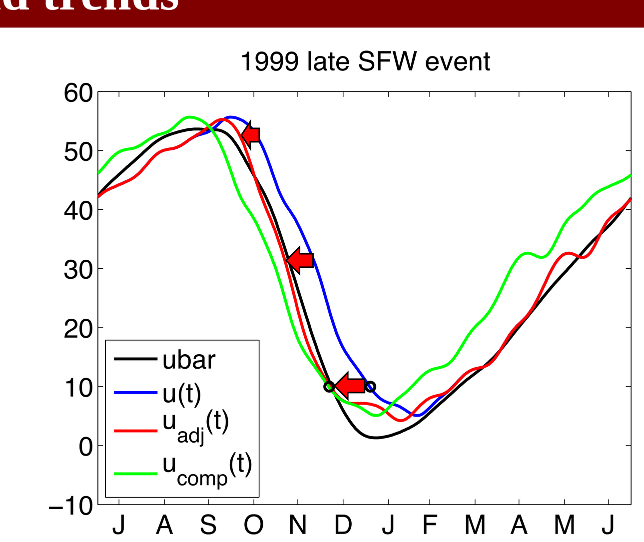



**Figure 6.** One example of the high-latitude zonal wind transition at 50 hPa and our adjustment method.

Climate trends are decomposed into two components: those due to the change in the timing of SFW and those resulting from the change in the vortex breakdown rate.

$$\Delta u(t) = \Delta u_{adj}(t) - f(t)\Delta t_O$$

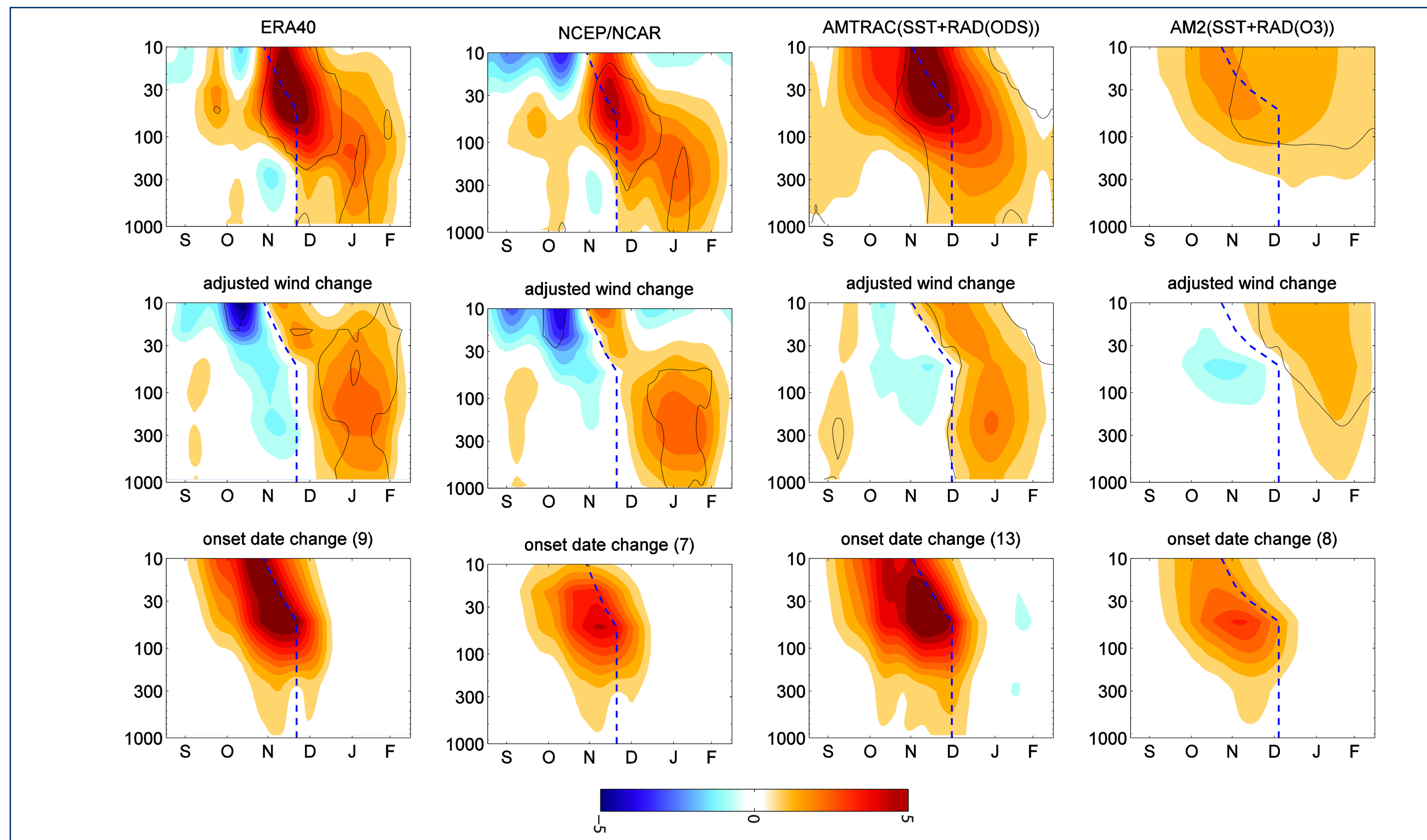
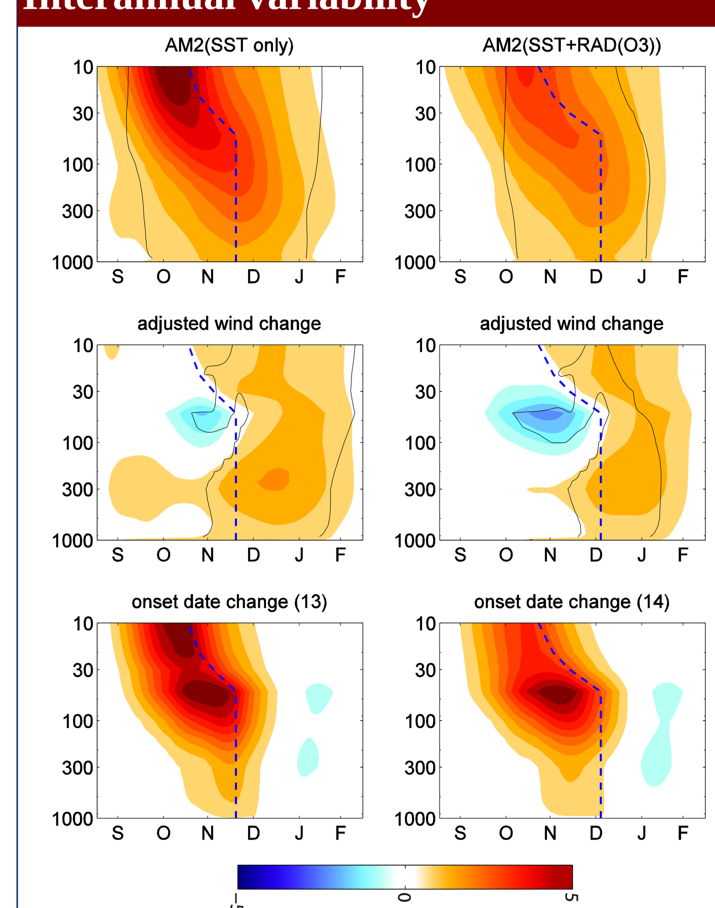



**Figure 7.** Zonal wind trends averaged at 50°S-70°S in (Left) ERA-40, (Middle left) NCEP/NCAR reanalysis, (Middle right) AMTRAC(SST+RAD(ODS)), and (Right) AM2(SST+RAD(O3)). The (Top) total zonal wind trends are separated into (Middle) the adjusted wind trends about the mean SFW onset date and (Bottom) the trends due to the changes in the SFW onset date shown in the brackets (days per decade). The contour interval is 0.5 m s$^{-1}$ decade$^{-1}$. The blue dashed lines denote the mean onset dates. The black lines indicate the trend significant at 95% confidence level by a t-test.

- Much of the stratospheric trends are attributable to the delay in the final warming onset date.
- Most of the downward influence of the stratospheric trends is associated with the slowing of the spring-to-summer transition after the onset date each year is adjusted to the mean onset date.

## Interannual variability




The decomposition into the contributions from the adjusted changes about the mean onset date and the changes in onset date associated with interannual variability are similar to the decomposition of the decadal trends, especially the 100-300 hPa peak in the adjusted wind trends about their mean SFW onset dates. This suggests that the differences in zonal wind between late final warmings and early final warmings are an important contributor to the decadal trend due to stratospheric ozone depletion.

**Figure 8.** As in Figure 7, but for the zonal wind anomaly regressed onto the interannual variability of SFW onset dates in (Left) AM2(SST only) and (Right) AM2(SST+RAD(O3)). For the latter, the SFW dates are are first detrended by removing the 10-member ensemble mean. The SFW dates are normalized in both cases, and the pattern corresponds to a delay in SFW by its one standard deviation shown in the brackets in the bottom panels. The contour interval is 0.5 m s$^{-1}$. The blue dashed lines denote the mean onset dates. The black lines indicate the trend significant at 95% confidence level by a t-test.

## Discussion

Our study suggests two mechanisms by which ozone depletion influences SH climate trends: First, the zonal wind trend due to the delay in the SFW progresses downward from the stratosphere to the lower troposphere, similar to the interannual variability documented by Black and McDaniel (2007). Moreover, late final warmings show a slower deceleration and an earlier recovery in the stratospheric zonal wind in the late spring and summer, accompanied by persistent anomalies in tropospheric winds.