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On the Identification of the Downward Propagation of Arctic Stratospheric Climate Change over Recent Decades*

DIANE J. IVY AND SUSAN SOLOMON

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts

DAVID W. J. THOMPSON

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Dynamical coupling between the stratospheric and tropospheric circumpolar circulations in the Arctic has been widely documented on month-to-month and interannual time scales, but not on longer time scales. In the Antarctic, both short- and long-term coupling extending from the stratosphere to the surface has been identified. In this study, changes in Arctic temperature, geopotential height, and ozone observed since the satellite era began in 1979 are examined, comparing dynamically quiescent years in which major sudden stratospheric warmings did not occur to all years. It is shown that this approach clarifies the behavior for years without major warmings and that dynamically quiescent years are marked by a strengthening of the Arctic polar vortex over the past 30 years. The associated declines in stratospheric temperatures, geopotential height, and ozone are qualitatively similar to those obtained in the Antarctic (albeit weaker), and propagate downward into the Arctic lowermost stratosphere during late winter and early spring. In sharp contrast to the Antarctic, the strengthening of the Arctic stratospheric vortex appears to originate at a higher altitude, and the propagation to the Arctic troposphere is both very limited and confined to the uppermost troposphere, even when only dynamically quiescent years are considered in the analysis.

1. Introduction

The apparent propagation of some polar circulation anomalies from the stratosphere to the troposphere during winter and spring has been noted for about a half-century (Julian and Labitzke 1965; Quiroz 1977), and has been the subject of intense study since it was shown to be robust in composite analyses by Baldwin and Dunkerton (2001). Stratosphere–troposphere dynamical coupling was first observed in the Arctic on a seasonal basis in winter, where circulation anomalies in the middle stratosphere appear to propagate from the lower stratosphere to the troposphere where they persist for

several weeks (Baldwin and Dunkerton 1999, 2001). This dynamical coupling is most clear in the context of the annular modes and has some skill for tropospheric predictability in certain seasons and locations (e.g., Thompson et al. 2002; Scaife et al. 2005; Sigmond et al. 2013). Evidence for coupling from the stratosphere to the ocean has also been presented (Reichler et al. 2012).

Dynamical coupling between the stratosphere and troposphere has also been observed in the Antarctic, not only on seasonal and interannual time scales (Christiansen 2003; Thompson et al. 2005), but also on multidecadal time scales since about the 1980s (Thompson and Solomon 2002). The mechanisms driving the propagation have been probed in both hemispheres using both observational and modeling approaches [e.g., reviews by Thompson et al. (2011); Gerber et al. (2012), and references therein]. The primary driver of trends in Antarctic stratospheric temperatures, geopotential height, and resulting circulation patterns over the past three decades is the pronounced and extensive ozone loss known as the Antarctic ozone hole. The ozone hole has cooled the Antarctic lower stratosphere in October and

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Corresponding author address: Diane J. Ivy, Massachusetts Institute of Technology, 77 Massachusetts Ave., 54-1710, Cambridge, MA 02139.
E-mail: divy@mit.edu

November by as much as 10°C (Randel and Wu 1999), and thus strengthened the polar vortex (Vaugh et al. 1999). The cooling and circulation changes associated with the springtime Antarctic stratospheric ozone depletion extend into the troposphere with a lag of about a month, where they influence summer surface climate (Thompson and Solomon 2002).

It is clear that variations in the Arctic stratosphere are strongly coupled to the troposphere on intraseasonal time scales. But attempts to link decadal changes in the Arctic tropospheric circulation to changes in the Arctic stratosphere have not previously been successful. In part, this is because the Arctic stratosphere is much more variable from year to year than the Antarctic because of much more frequent occurrences of sudden stratospheric warmings, which are associated with a disrupted polar vortex, weakened zonal-mean winds, and a rise in stratospheric temperatures (e.g., Andrews et al. 1987; Charlton and Polvani 2007). The large interannual variability in the Arctic has made detection and attribution of statistically significant long-term trends there challenging (Manney et al. 2005).

Changes in stratospheric circulation and temperatures would be expected to affect ozone loss through heterogeneous chlorine chemistry involving polar stratospheric clouds, and this provides additional motivation for understanding Arctic coupling processes and trends. Rex et al. (2006) found an increasing trend in the 5-yr maximum volume of air cold enough for polar stratospheric cloud formation (V_{PSC}) averaged over December–April in the Arctic; thus suggesting that the “coldest Arctic winters are getting colder,” while a recent study by Rieder and Polvani (2013) using three different reanalyses found no statistically significant changes in Arctic winter-averaged V_{PSC} . Temperature trend analyses suggest that the proposed increase in the severity of cold Arctic stratospheric winters is equivocal (Manney et al. 2005).

A common technique used to distinguish between the effects of long-term climate change and transient variability is to remove from trends analyses those years that are marked by pronounced episodic behavior. For example, analyses of long-term trends in global stratospheric temperatures often omit periods of volcanic activity (e.g., Randel et al. 2009). In 2002, a major sudden stratospheric winter warming occurred in Antarctica, rendering this year distinctly different to those observed since at least the late 1970s. As a result, studies aimed at identifying Antarctic dynamical coupling often distinguish between this year and others (e.g., Thompson et al. 2005, 2011). In this study, we employ a similar approach for the Arctic by analyzing changes in the stratosphere during years characterized by strong stable

polar vortices, identified as years without major sudden stratospheric warmings, and contrast these with the behavior obtained when all years are considered. We show that statistically significant changes in the Arctic stratosphere in late winter and early spring can be more readily identified over the past 30 years when years without major warmings are explicitly considered. The long-term changes in the stratospheric circulation during dynamically quiescent years propagate downward from the middle stratosphere to the lowermost stratosphere, and exhibit a qualitatively similar albeit muted behavior to that observed in association with the Antarctic ozone hole. We examine ozone losses occurring in these years and probe their relationship to the propagation of the circulation anomalies. Last, we explore the implications of the observed changes in the stratospheric circulation for trends in the tropospheric circulation during years without major warmings.

2. Data and methods

We analyze temperature and geopotential height trends since the satellite era began in 1979 using monthly-mean reanalysis data from the Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011). The data are available at a horizontal resolution of 0.67° of longitude by 0.5° of latitude and at 42 vertical levels, which extend from the surface to 0.1 hPa. Winters when a major sudden stratospheric warming occurred were identified using the climatologies of major sudden stratospheric warmings (SSW) from Charlton and Polvani (2007) and Kuttippurath and Nikulin (2012) (Table 1). Both studies use daily data to identify the occurrence of a major warming as the time when the zonal-mean zonal wind reverses from westerly to easterly at 60°N and 10 hPa (Charlton and Polvani 2007; Kuttippurath and Nikulin 2012). We also compute results using the alternative definition of major sudden stratospheric warmings based on the distribution of potential vorticity presented in Mitchell et al. (2013). As discussed in the results section (and shown in the supplemental material, Figs. S1–S4), the use of different sudden warming climatologies does not qualitatively affect the results at stratospheric levels. Interestingly, the amplitudes of the tropospheric trends are larger when the Mitchell et al. (2013) definition is used to identify sudden warmings, primarily due to the exclusion of the winter in 2005, which had an early final warming. Key results shown here are reproducible using radiosonde station data obtained from the Met Office Hadley Centre Atmospheric Temperature, version 2 (HadAT2), radiosonde database (Thorne et al. 2005); although the radiosondes display a slightly smaller

TABLE 1. Classification of winters as those with or without major sudden stratospheric warmings. The year in boldface indicates a year with a late major warming.

Major SSW	No major SSW
1979	1981
1980	1983
1982	1986
1984	1990
1985	1991
1987	1992
1988	1993
1989	1994
1999	1995
2000	1996
2001	1997
2002	1998
2003	2005
2004	2011
2006	
2007	
2008	
2009	
2010	

maximum cooling than MERRA (see supplemental material, Fig. S5).

Monthly-mean total column ozone data from the Total Ozone Mapping Spectrometer, version 8 (TOMSv8) dataset were also analyzed (ozoneaq.gsfc.nasa.gov). The total column ozone observations from TOMSv8 are available since 1979, with the exception of 1993–95, on a 1.25° of longitude by 1° of latitude horizontal grid scale. To supplement the gap in the TOMSv8 dataset, we also include data from the merged TOMS/Solar Backscatter Ultraviolet dataset (TOMS/SBUV) for the polar cap-averaged total column observations (acd-ext.gsfc.nasa.gov). However, as the TOMS/SBUV data are at a coarser resolution than the TOMSv8 data, only the latter were used to estimate the spatial patterns of trends in total column ozone. Observations of vertically resolved ozone concentrations at the ozonesonde stations of Alert, Canada (82.5°N , 62.4°W), and Syowa, Antarctica (69.0°S , 39.6°E), provided by the World Ozone and Ultraviolet Radiation Data Centre (WUODC; www.woudc.org), are also employed.

Long-term changes in stratospheric climate were calculated as the differences in the available data for a mean preozone depletion era (1979–84) versus the period after full development of ozone losses (1995–2011; Figs. 1 and 2). For the difference calculations, the preozone depletion era data were not sorted for major warmings as those data do not exhibit large interannual variability (see Fig. 3). Moreover, this allows changes in the Arctic stratosphere presented in Figs. 1 and 2 to be

referenced to a common climatology. We use a linear least squares best fit to either (i) a linear trend (Figs. 3–6) or (ii) an estimate of equivalent effective stratospheric chlorine (EESC; see Fig. 3), in order to examine the potential dependence of changes in the Arctic stratospheric climate on increases in long-lived greenhouse gases as well as ozone loss. The EESC data assume a 3-yr mean age of stratospheric air (Newman et al. 2007). The statistical significance was evaluated using Student's t statistic both for the long-term changes and least squares regressions to the observations (as in Santer et al. 2000). As discussed further below, it is not clear whether a fit to a linear trend or the EESC curve offers a better representation of long-term changes in Arctic climate. For simplicity, we focus on the linear trends for most of our analyses.

We also evaluated the northern annular mode (NAM) indices and the temperature and geopotential trends that are linearly congruent with the NAM (Baldwin and Dunkerton 1999, 2001). The NAM indices are estimated as the principal component time series of the zonal-mean, monthly-mean geopotential anomalies at each pressure level from 20° to 90°N , where the monthly geopotential anomalies were obtained by subtracting the monthly-mean climatology from the data; see Baldwin and Thompson (2009) for details of the computation of the NAM indices. Temperature trends that are linearly congruent with the NAM index were calculated by (i) linearly regressing the monthly-mean temperatures at each pressure level and grid cell against the NAM index at that pressure level, where the resulting regression coefficients are in units of kelvins per standard deviation (K std^{-1}) or meters per standard deviation (m std^{-1}) of the NAM index; (ii) multiplying the regression coefficients by the trend in the NAM index at that pressure level for only those years without major warmings. The trends in the NAM index are in units of standard deviation per decade (std decade^{-1}); hence, the resulting NAM congruent trends are in units of kelvins per decade (K decade^{-1}) or meters per decade (m decade^{-1}).

3. Observed trends

The Arctic mid- and lower stratosphere has cooled over the past 30 years (1979–2011) in late winter and early spring in years without major warmings (Fig. 1, middle-center panel; see also similar results using radiosonde data in Fig. S5 of the supplementary material). The cooling has occurred together with a 30% decrease in spring Arctic lower stratospheric ozone based on ozonesonde data from Alert at 82°N (Fig. 1, top-middle panel). It is noteworthy that the observed ozone change when all years are analyzed is 3 times weaker and is not

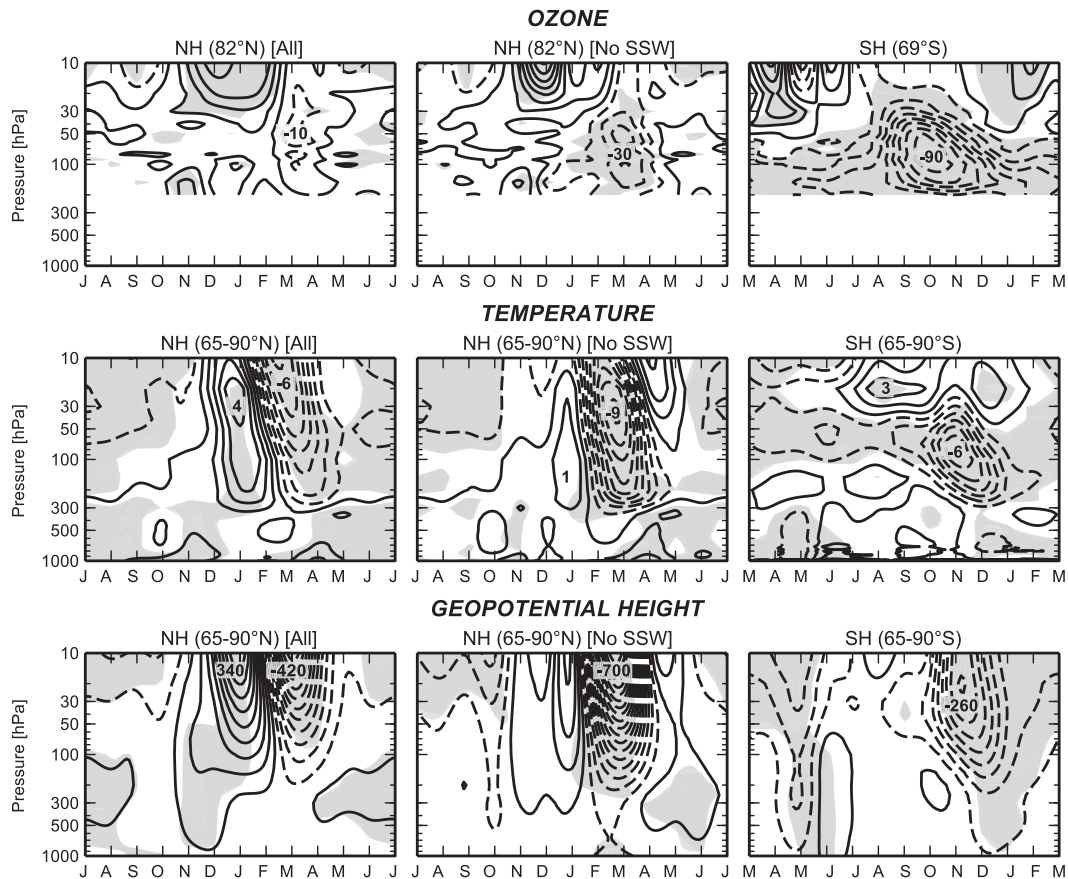


FIG. 1. Observed differences between the preozone depletion (1979–84) and ozone depletion eras (1995–2011) in (top) ozone, (middle) temperature, and (bottom) geopotential height anomalies by month and elevation in the Northern Hemisphere (65°–90°N), (left) for all years and (center) years without major SSW, and (right) in the Southern Hemisphere (65°–90°S), with 2002 removed for the SH. Shading indicates trends that are significant at the 90% level based on a one-sided t test. The ozone data are from the WUOUDC stations: Alert (82.5°N, 62.4°W) and Syowa (69.0°S, 39.6°E), and the temperature and geopotential height data are from MERRA. Contour intervals: ozone is 10%, temperature is 1 K, and geopotential height is 40 m beginning at ± 20 m.

statistically significant (Fig. 1, top-left panel). The results are complementary to those of Kuttippurath and Nikulin (2012), who showed an inverse relationship between chemical ozone loss in the Arctic and the intensity and timing of major warmings.

The corresponding changes in the circulation reveal decreases in polar geopotential height during the Northern Hemisphere (NH) spring that are reminiscent of those found over the Antarctic (Fig. 1, cf. bottom-center and bottom-right panels). In contrast, when all years are considered in the analysis (left panels), the Arctic cooling and geopotential height falls in late winter are relatively weak and are preceded by warming that peaks during early winter. The warming during December–January is consistent with an increase in wave driving, as noted in Thompson and Solomon (2005), but it is weakly statistically significant and depends strongly on the period

considered [e.g., cf. Fig. 1 to Fig. 7 in Thompson and Solomon (2005) covering 1979–2003].

The signal of long-term changes in the Arctic stratosphere has been obscured in previous studies by the warming during dynamically active years. The robustness of the changes during dynamically quiescent years is further displayed in Fig. 2, which shows the observed long-term changes in temperature and geopotential height for years without major warmings using several different endpoints: 1998, 2005, and 2011. The estimated long-term changes in both temperature and geopotential height during years without major warmings all display a coherent evolution from the mid- to lower stratosphere, independent of the chosen end year, with varying magnitudes. In comparison, long-term changes in the Arctic stratosphere are very sensitive to the end years when all years are considered in the analyses (e.g., as noted in Manney et al. 2005).

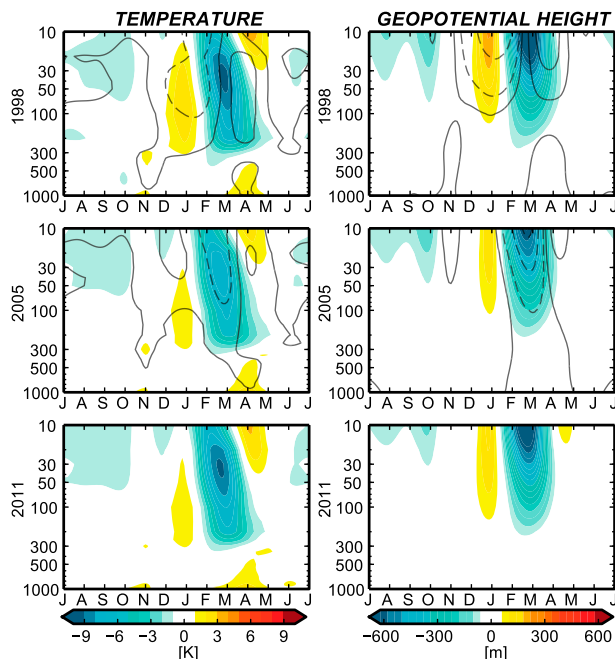


FIG. 2. Observed differences between the preozone depletion (1979–84) and ozone depletion eras (starting in 1995) for (left) temperature and (right) geopotential height anomalies by month and elevation in the Northern Hemisphere (65° – 90° N) for years without major warmings but with different end years (1998, 2005, and 2011). Line contours show the difference in the estimated long-term changes with each end year from those with the end year of 2011. Contour intervals: temperature is 1 K and geopotential height is 40 m beginning at ± 20 m.

The peak magnitudes of the observed changes in temperature in the Arctic during dynamically quiescent years are comparable to those observed in the Antarctic (Fig. 1, cf. middle-center and middle-right panels). However, in contrast to the Antarctic, the cooling in the Arctic is not confined to the lower stratosphere but extends into the middle stratosphere. While the Antarctic cooling appears to be closely associated with the region of local ozone depletion, the Arctic cooling appears to extend and even strengthen above it. The extension of the Arctic trends to the middle stratosphere suggests that factors other than local radiative cooling because of ozone depletion, are contributing to the observed Arctic climate trends.

As is the case for the Antarctic, the Arctic trends in temperature and geopotential height for years without major warmings propagate downward from the middle to lower stratosphere from February through March (Fig. 1, center). The signal in the lower stratosphere is deeper when only years without major warmings are considered (Fig. 1, bottom). In contrast to the Antarctic, the apparent extension of the Arctic stratospheric trends to the troposphere is weak and limited to certain regions

in the uppermost troposphere (see section 4). Below we explore how zonal asymmetries may obscure tropospheric trends in the Arctic, and contrast this further with the much more zonally symmetric trends in the Antarctic.

Temperatures in the middle and lower stratosphere in late winter are strongly correlated with March total column ozone (O_3) during years without major warmings (Fig. 3 and Table 2). Significant correlations between geopotential height, the NAM index, and temperatures are also found between February and March (Table 2), supporting the time-dependent downward propagation illustrated in Fig. 1. The correlations obtained between the February NAM at 10 hPa (NAM_{10}) and March temperatures in the lower stratosphere and total column ozone suggest that changes in the circulation above the region of lower-stratospheric ozone loss (see Fig. 1) play an important role in the long-term trends during dynamically quiescent years. A feedback in which colder temperatures lead to more ozone destruction, further cooling, and strengthening of the vortex can be expected as the anomaly descends, but the data alone are not sufficient to establish this.

Figure 3 shows the time series of the data for Arctic winter, highlighting the years with major warmings (open squares) and without major warmings (filled circles). As shown in the figure, there have been fewer years without major Arctic warmings since the late 1990s than there were prior to that time, a point we return to below. In 2000, the major warming was late (mid-March) and exhibits behavior that is similar to years without major warmings and is therefore identified by an open circle. While there are a limited number of quiescent years after 2000, there is a discernible change in late-winter Arctic stratospheric climate since 1979 in years without (or with very late) major sudden warmings. However, Fig. 3 reveals that we cannot discern whether a linear regression or EESC regression provides an optimal fit to the data. Whether the observed decreases of Arctic stratosphere temperatures in March during years without sudden warmings are linked to increases in carbon dioxide (CO_2) and other greenhouse gases and should be expected to continue to cool further, or are due mainly to ozone depletion and will thus likely reverse in the future cannot be determined here.

In contrast to the cooling trend in March, there is little change or a slight warming trend earlier in the winter (Figs. 1 and 2). As a result of these changes in trends over the season, we do not find a significant change in the corresponding estimate of winter-averaged V_{PSC} , even for years without major Arctic warmings (not shown); thus, our results are broadly consistent with Rieder and Polvani (2013).

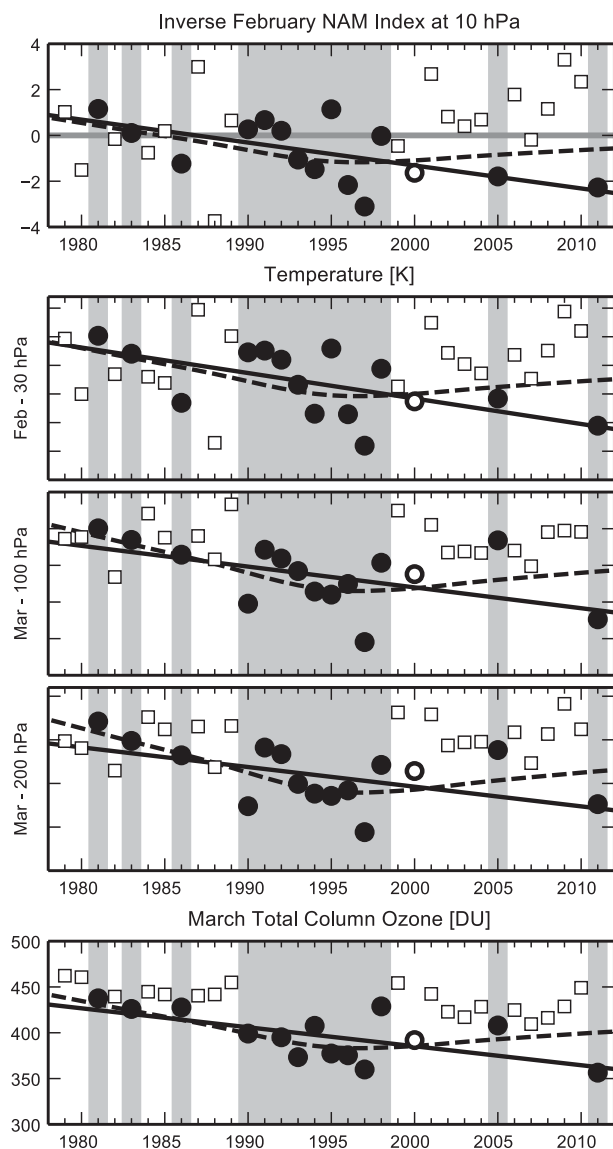


FIG. 3. Time series of polar cap-averaged, monthly-mean (top) February (inverse) NAM index at 10 hPa, (middle) temperatures at indicated pressure levels and months from MERRA, and (bottom) March total column ozone from TOMS/SBUV over the Arctic (65° – 90° N) for years without major sudden warmings (filled circles) and years with major warmings (open squares). The open circle is for the year when the major sudden warming occurred late (i.e., in mid-March). Years without major sudden warmings are also indicated by the gray shading. Linear regressions (solid lines) and regressions to the EESC curve (dashed lines) for years without major warmings are also shown.

4. Spatial patterns of trends

The spatial patterns of trends in temperature and total column ozone for years without major warmings are presented in Fig. 4. A strong cooling trend centered over the pole is observed in February at 10 hPa (not shown)

TABLE 2. Correlation statistics for linearly detrended: February NAM index at 10 hPa, stratospheric temperatures T , and March total column O_3 in the Arctic (65° – 90° N) for years without major warmings at the 30-, 100-, and 200-hPa pressure levels. Boldface values are significant at the 90% level.

	Feb NAM ₁₀	Feb T_{30}	Mar T_{100}	Mar T_{200}
Feb T_{30}	0.97	—	—	—
Mar T_{100}	0.35	0.45	—	—
Mar T_{200}	0.38	0.45	0.97	—
Mar O_3	0.27	0.28	0.71	0.71

and 30 hPa (Fig. 4, top). In the lowermost stratosphere (100–200 hPa), the cooling peaks in March and is centered over Greenland and the North Atlantic. There is also a corresponding strong decline in total column ozone in March. Hu et al. (2005) noted changes in the character of trends in stratospheric dynamics from early winter (November–December) to late winter (February–March) and found January to be a transition month; they emphasized the importance of considering this in seasonal trend analyses. Our analysis likewise finds January as a transition month that exhibits a weak relationship with the trends later in the winter (Fig. 4). In comparison to trends during quiescent years, the trends when all years are considered are much weaker and display smaller areas that are statistically significant (Fig. 5). Likewise, the total column ozone depletion is weaker in all years, as expected from the warmer temperatures associated with the major warmings.

Figure 6 presents the attendant trends in geopotential height (the corresponding results using the potential vorticity definition of sudden warmings are shown in Figs. S3 and S4 of the supplemental material). In February there is a strong downward trend in geopotential height over the Arctic in the middle stratosphere, signifying a strengthening of the polar vortex for years without major warmings. The strengthening of the polar vortex appears to extend into the lower stratosphere in March. The differences between the trends for all years and for dynamically quiescent years (i.e., years without sudden warmings) are striking.

As is apparent in Figs. 4 and 6, the temperature and geopotential height trends in the stratosphere for years without major warmings qualitatively resemble the NAM. Table 3 shows the polar cap-averaged observed trends, the polar cap-averaged trends linearly congruent with the February NAM at 10 hPa, and the fraction of the observed trends that are congruent with the NAM (taken as one minus the area-weighted root-mean-square error between the observed and NAM congruent trends divided by the area-weighted observed trend). Significant fractions of the observed stratospheric temperature and geopotential trends in February

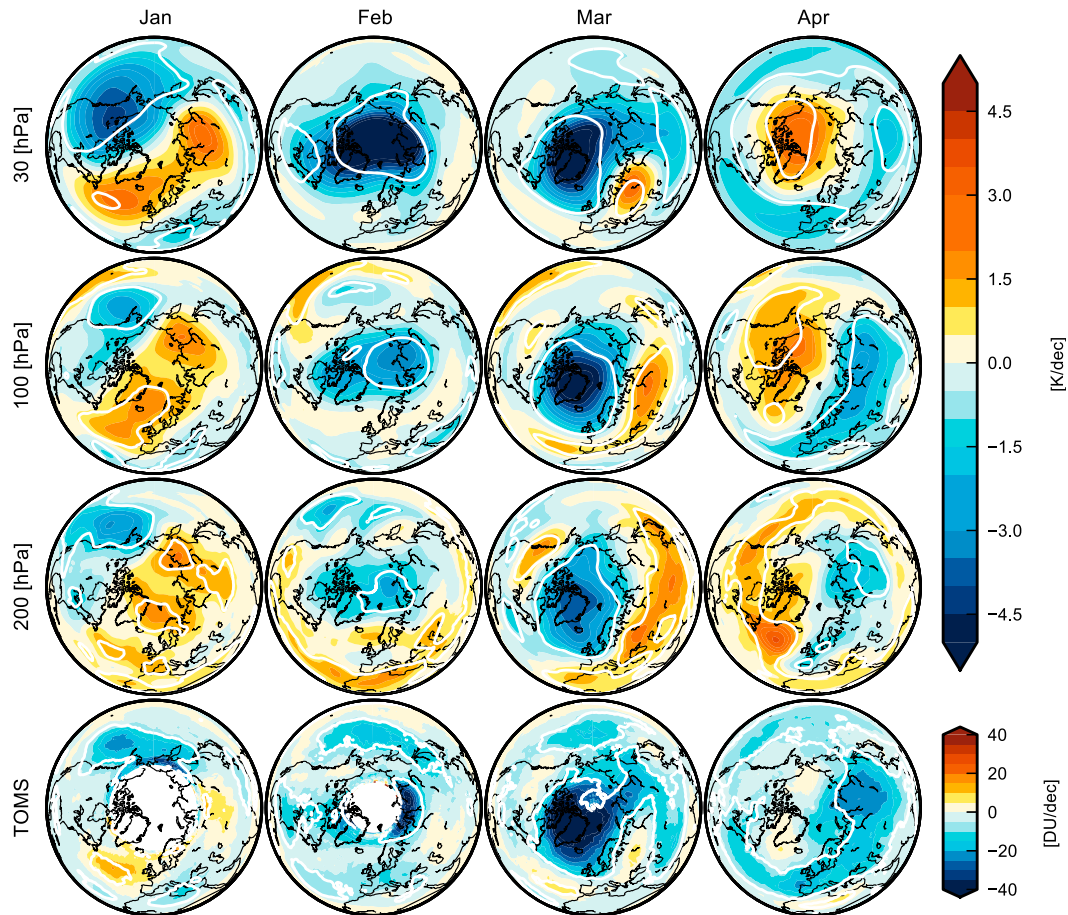


FIG. 4. Monthly linear trend patterns in temperature at 30, 100, and 200 hPa from MERRA and (bottom) total column ozone from TOMSv8 for 1979–2011 in January–April over the Northern Hemisphere for years without major sudden warmings. White contours enclose areas of trends that are significant at the 90% level.

and March are linearly congruent with the February NAM at 10 hPa. Thus, if the middle stratosphere in February were to continue to cool and, therefore, further strengthen the polar vortex in the middle stratosphere, colder temperatures and a stronger polar vortex are expected to follow in the lower stratosphere, with possible implications for heterogeneous ozone depletion in the future.

Figure 1 shows that the Arctic stratospheric trends do not propagate into the polar middle troposphere when averaged over the polar cap, perhaps attributable to the asymmetry of the Arctic polar vortex and the baroclinicity of the Northern Hemisphere troposphere. However, the spatial patterns of the trends in geopotential height shown in Fig. 6 do reveal some regions of local change in the uppermost troposphere. Decreases in geopotential height appear to extend into the uppermost troposphere in February and March. However, the changes are substantially weaker than those found in the lower stratosphere and are obscured by an

area of an increasing geopotential height centered over the pole. The geopotential height trends at the 500-hPa level shown in Fig. 6 do not clearly project onto the NAM. But the March trends in geopotential height in the troposphere over the Atlantic resemble the negative phase of the east Atlantic (EA) pattern. Woollings et al. (2010) found the preferred northern position of the North Atlantic eddy-driven jet to be associated with the negative phase of the EA, and this is consistent with the trend toward a poleward shift of the North Atlantic jet in early spring in years without major warmings shown in Fig. 6.

5. Conclusions

We have shown that statistically significant long-term changes in the Arctic stratosphere have occurred in late winter and early spring over the past 30 years during years without major sudden stratospheric warmings. These changes correspond to a stronger polar vortex and

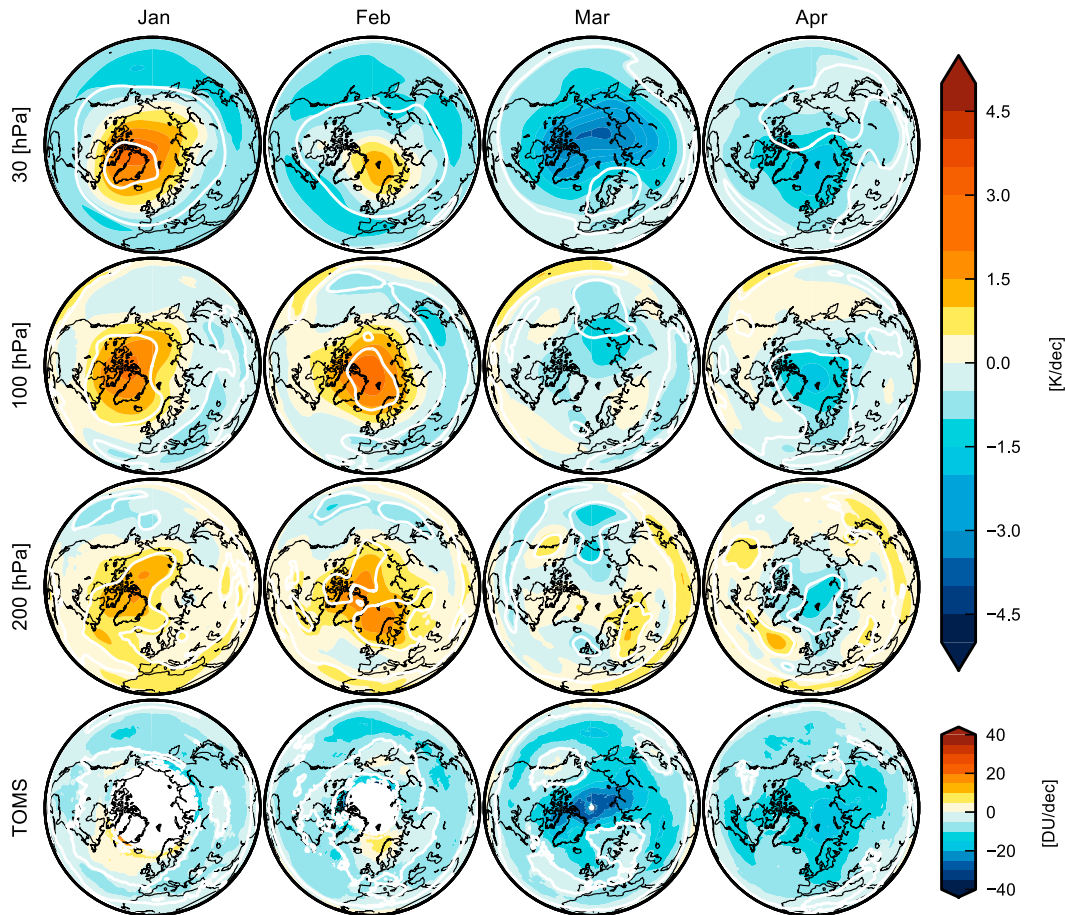


FIG. 5. As in Fig. 4, but over the Northern Hemisphere for all years.

colder temperatures in the middle stratosphere, and the changes appear to propagate down from the middle to the lowermost stratosphere in March, where they are likely linked to an observed decline in stratospheric ozone.

Removing years with major sudden warmings makes much more clear the long-term changes in the Arctic stratosphere. However, it is worth noting that most of the years used in the trend analysis are restricted to the period prior to 2000. Between the late 1970s and mid-1990s, major sudden stratospheric warmings occurred roughly every other year. However, in the past decade there has been an increase in the frequency of major warmings (there are only two quiescent years since 2000). Thus, the sampling may result in a bias in the presented trends associated with decadal variability. As is the case in the Antarctic, the downward propagation of the Arctic trends during dynamically quiescent years is extremely robust at stratospheric levels. However, unlike the Antarctic, the stratospheric trends are not clearly coupled with those in the Arctic troposphere, and this study has extended previous work highlighting this difference. The

relatively weak linkages between the Arctic stratospheric and tropospheric trends during late winter/early spring may reflect fundamental differences in drivers of variability in the stratosphere and troposphere of the two hemispheres that prevail even in dynamically quiescent years, but other explanations are also possible. Although we note that the coupling to the troposphere is stronger in the results using the Mitchell et al. (2013) definition for quiescent years as shown in Figs. S1–S4, sampling issues increase as a result of even fewer available years in this case. Aside from the limited sampling as an impediment to identifying linkages, spatial variations in the strong warming climate of the Arctic (e.g., due to changes in sea ice, sea surface temperature patterns, and/or cloudiness) or in tropospheric variability (e.g., ENSO and east Atlantic pattern) could also influence the results.

Rex et al. (2006) suggested that the coldest stratospheric winters are becoming more extreme over the past few decades, and thus that the volume of winter air cold enough for polar stratospheric cloud formation has increased. Yet, a recent study by Rieder and Polvani (2013)

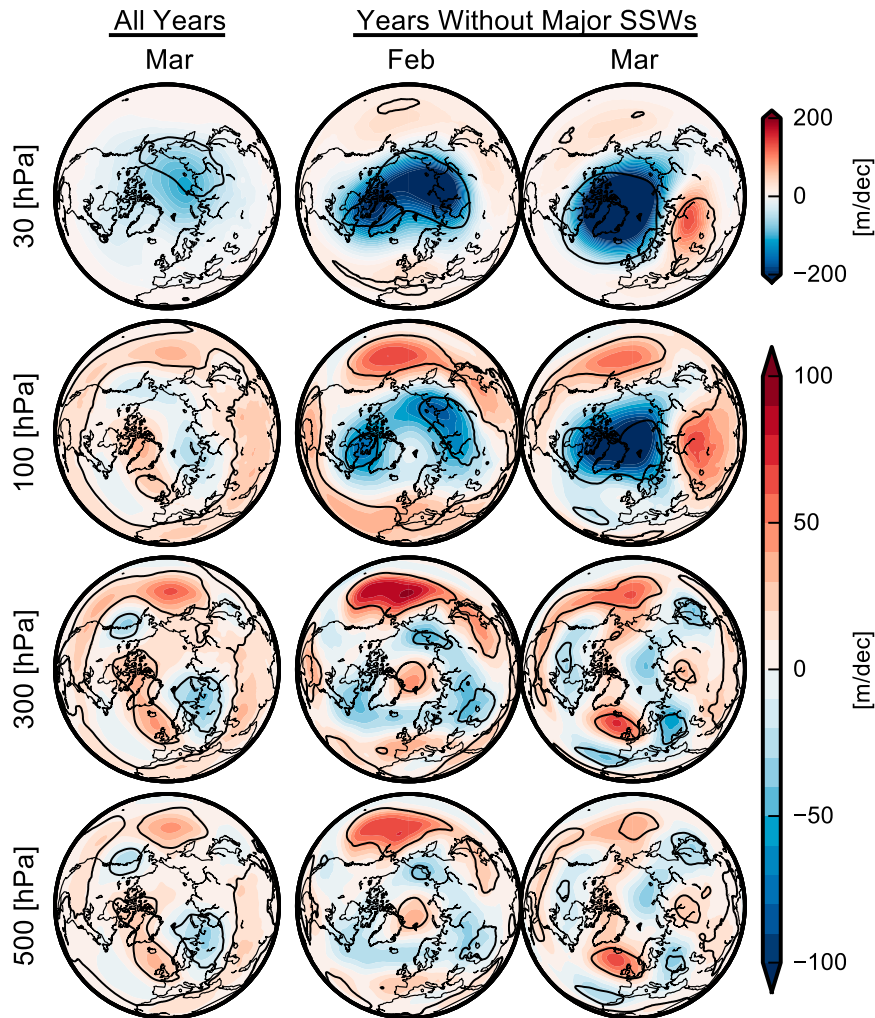


FIG. 6. Monthly linear trends in geopotential height at 30, 100, 300, and 500 hPa from MERRA for (left) all years and years without major warmings for 1979–2011 in (center) February and (right) March. Black contours enclose areas of trends that are significant at the 90% level.

showed that the increasing trend in winter-averaged V_{PSC} was not a robust result in recent reanalysis datasets. We find significant cooling of the lower stratosphere in late winter (especially March) in years without major warming, but no significant changes in winter averages (December–April), consistent with [Rieder and Polvani \(2013\)](#). If the observed late-winter trends in the middle stratosphere were to continue, significant ozone losses similar to the winter of 2011 may recur in future Arctic years without major warmings ([Manney et al. 2011](#)). However, we have shown that the observations to date do not allow discrimination between a continuing linear trend and a smooth function to approximate ozone loss as characterized by EESC (see [Fig. 3](#)). It is important to emphasize that if stratospheric ozone losses are the dominant factor in the observed behavior, then

a recovery rather than a further cooling of the polar stratosphere in late winter should be expected in the next several decades.

In closing, we briefly note some relevant literature regarding radiative and dynamical contributions to Arctic stratospheric trends and connections to further research suggested by our study. A study by [Fu et al. \(2010\)](#) suggested that changes in stratospheric dynamics had a considerable contribution to the observed cooling of the lower stratosphere in March. However, the main driver of these trends in stratospheric dynamics has not been established. [Hu et al. \(2005\)](#) found negative trends in the refractive indices in February and March, corresponding to more planetary waves propagating equatorward, possibly resulting from changes in the horizontal temperature gradient

TABLE 3. Polar cap-averaged observed linear temperature (T) and geopotential height (Z) trends; temperature and geopotential height trends linearly congruent with the February NAM at 10 hPa; and the fraction of the observed trend linearly congruent with the NAM for the Arctic (65° – 90° N) for years without major warmings. The temperature and geopotential height trends are at the 30-, 100-, and 200-hPa pressure levels.

	Observed trend	NAM congruent trend	Fraction congruent
Feb T_{30} (K decade $^{-1}$)	−4.45	−4.31	0.74
Mar T_{100} (K decade $^{-1}$)	−2.84	−1.79	0.59
Mar T_{200} (K decade $^{-1}$)	−2.25	−1.46	0.61
Feb Z_{30} (m decade $^{-1}$)	−169.2	−169.8	0.69
Mar Z_{100} (m decade $^{-1}$)	−67.9	−46.1	0.59
Mar Z_{200} (m decade $^{-1}$)	−16.2	−12.6	0.31

associated with increased greenhouse gases and ozone depletion. Further, an increase in tropospheric planetary wave activity is also expected to accompany increases in long-lived greenhouse gases, and, hence, an increase in the frequency of major warmings (e.g., see Eyring et al. 2013). In years with weak wave driving, the role of radiative processes in driving stratospheric temperature and geopotential height trends is not juxtaposed on large dynamic variability in the circulation. Therefore, the approach used in this study may be useful for distinguishing between contributions of changes in radiative forcing and in wave driving to Arctic stratospheric trends.

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