Poleward Shift of Subtropical Jets Inferred from Satellite-Observed Lower-Stratospheric Temperatures

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ABSTRACT

One pronounced feature in observed latitudinal dependence of lower-stratospheric temperature trends is the enhanced cooling near 30° latitude in both hemispheres. The observed phenomenon has not, to date, been explained in the literature. This study shows that the enhanced cooling is a direct response of the lower-stratospheric temperature to the poleward shift of subtropical jets. Furthermore, this enhanced lower-stratospheric cooling can be used to quantify the poleward shift of subtropical jets. Using the lower-stratospheric temperatures observed by satellite-borne microwave sounding units, it is shown that the subtropical jets have shifted poleward by 0.6° ± 0.1° and 1.0° ± 0.3° latitude in the Southern and Northern Hemispheres, respectively, in last 30 years since 1979, indicating a widening of tropical belt by 1.6° ± 0.4° latitude.

1. Introduction

By examining atmospheric temperature trends since 1979 based on satellite-borne microwave sounding unit (MSU) data, Fu et al. (2006) identified the enhanced stratospheric cooling and tropospheric warming in the 15°–45° latitude belts in both hemispheres. The changes in meridional tropospheric temperature gradients in the vicinity of the jets provide evidence that the subtropical jets have been shifting poleward (Fu et al. 2006). However, no interpretation has been presented, to date, for the enhanced stratospheric cooling. Recently, Ueyama and Wallace (2010) performed an EOF analysis on the MSU lower-stratospheric temperatures. They showed that the meridional profile of the second EOF has a bulge at ~30°N/S with the corresponding principal component time series closely mirroring the behavior of the global-mean temperature anomaly (see their Fig. 4). Here we show that the enhanced cooling near ~30°N/S is a direct response of the lower-stratospheric temperature to the poleward shift of subtropical jets.

Because the jet streams mark the poleward limit of the tropical belt, a poleward shift of the jet streams implies a widening of the tropical circulation (Fu et al. 2006). Observational evidence from tropospheric temperatures (Fu et al. 2006), column ozone (Hudson et al. 2006), outgoing longwave radiation (Hu and Fu 2007), and subtropical tropopause heights (Seidel and Randel 2007) collectively indicates that the tropical belt has widened by ~2°–5° latitude since 1979 (Seidel et al. 2008). Because of the important implication of tropical expansion to the regional and global climate systems (Fu et al. 2006; Seidel et al. 2008), to the cloud–radiation feedback in terms of related latitudinal shifts in cloudiness, and to the test of global climate modeling (Lu et al. 2007; Johanson and Fu 2009), it is critically important to reliably estimate this expansion observationally. In this article, we show that the enhanced lower-stratospheric cooling near 30° latitude can be employed to quantify the poleward shift of subtropical jets. Using the MSU lower-stratospheric temperature datasets, we find that the subtropical jets have shifted poleward by ~0.6° and ~1.0° latitude in the Southern and Northern Hemispheres, respectively, since 1979, indicating a widening of tropical belt by ~1.6° latitude.

The datasets used are described in section 2. Section 3 interprets the enhanced stratospheric cooling near

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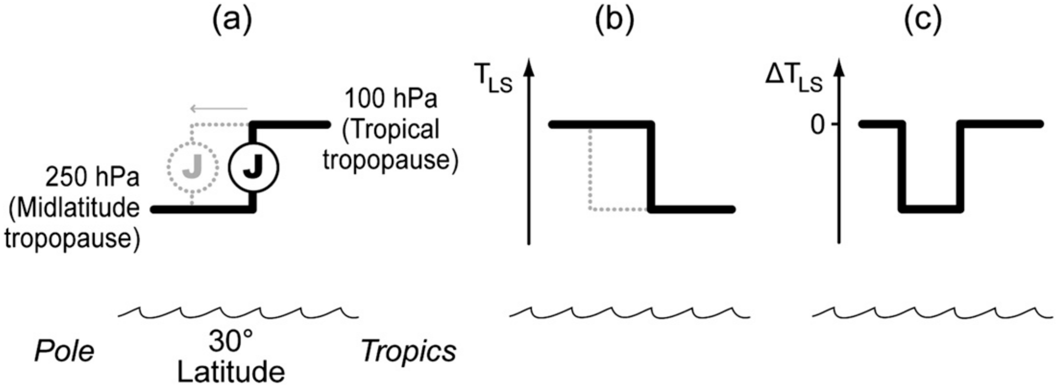

FIG. 1. Schematic illustration of the poleward shift of subtropical jets and its impact on the lower-stratospheric temperatures (T_{LS}). (a) Jet positions before and after shift, as shown by solid dark circle with dark J and dashed gray circle with gray J, respectively, along with the arrow indicating the shift direction; (b) latitudinal dependences of T_{LS} before and after jet poleward shift; and (c) impact of jet poleward shift on T_{LS}.

~30°N/S and its relation to the poleward shift of the jets. The poleward shift of the jets is quantified by employing the observed meridional profile of lower-stratospheric temperature trends in section 4. Summary and conclusions are given in section 5.

2. Observational datasets

A continuing community effort of the MSU/Advanced Microwave Sounding Unit (AMSU) data analysis has been made since the 1990s to satisfy the climate research requirements of temporal homogeneity and calibration (Karl et al. 2006; Solomon et al. 2007). Several important nonclimatic influences have been identified and removed, including diurnal temperature biases related to local sampling times of the satellite and their changes over its lifetime, warm target-related errors in the MSU calibration, and biases due to decay of the satellite orbits. Although deep-layer atmospheric temperature time series derived from different research groups still give diverse trend results, the MSU/AMSU deep-layer atmospheric temperatures represent one of the most reliable datasets for the trend analyses.

For the analysis of the lower-stratospheric temperature trends, we used the MSU/AMSU lower-stratospheric channel monthly brightness temperature (T_{LS}) gridded (2.5° × 2.5°) data for 1979–2009. The T_{LS} weighting function ranges from ~20 to ~120 hPa and peaks at around 60–70 hPa (Fu and Johanson 2005), and therefore well represents the lower stratosphere. Note that the T_{LS} may also have a contribution from the upper troposphere in the tropics. The MSU measurements extend to 82.5°N/S. We will analyze three T_{LS} datasets that are from the University of Alabama at Huntsville (UAH) team version 5.3 (Christy et al. 2003), the Remote Sensing System (RSS) team version 3.2 (Mears and Wentz 2009), and the National Oceanic and Atmospheric Administration (NOAA) team version 2.0 (Zou et al. 2006). Note that the NOAA team employed an intercalibration algorithm for the MSU/AMSU instruments using simultaneous nadir overpasses, which is very different from that used by the UAH and RSS teams.

3. Enhanced lower-stratospheric cooling associated with poleward shift of subtropical jets

Figure 1 is a schematic illustration of the poleward shift of subtropical jets and its relation to T_{LS}. The tropopause on the equatorial and poleward side of the jet is at ~100- and 250-hPa levels, respectively (Fig. 1a), corresponding to a low and a high tropopause temperature and thus a low and a high temperature in the lower stratosphere (Fig. 1b). Therefore, when the jet moves poleward (Fig. 1a), the latitudinal dependence of the lower-stratospheric temperature would shift poleward (Fig. 1b), which leads to a drop of the lower-stratospheric temperature near the jet latitudes (Fig. 1c).

The subtropical jets are located at ~200 hPa. Below (above) this level, the temperature decreases (increases) with latitude because of the thermal wind balance (Holton 1992). Thus, the smaller T_{LS} within the tropics than that outside is consistent with thermal wind balance associated with the subtropical jets.

The latitudinal profile of the annual-mean T_{LS} from observations is shown in Fig. 2a, which has the smallest value of ~204 K within the deep tropics. It increases with latitude up to about 58°N/51°S, and then decreases

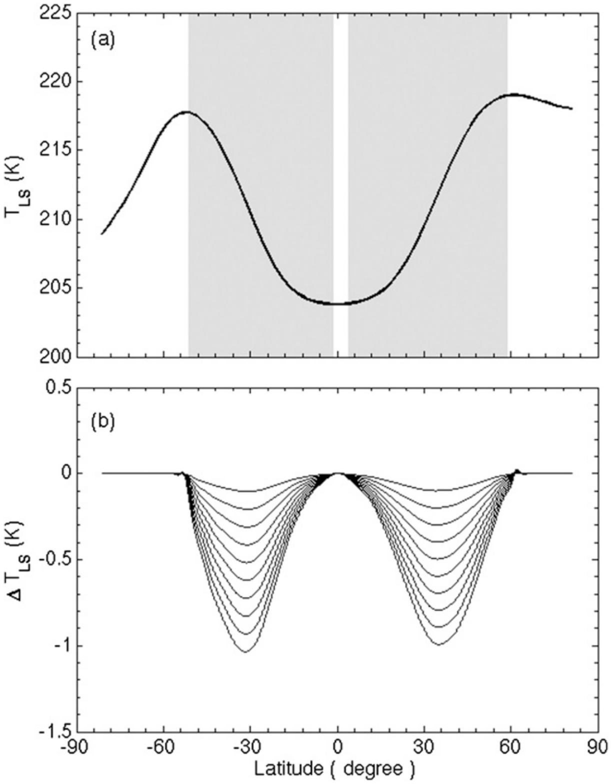

FIG. 2. (a) Latitudinal profile of climatological (1979–2009) annual-mean T_{LS} based on the NOAA MSU dataset; (b) T_{LS} changes corresponding to the poleward shift of the shading area in (a) by 0.2°, 0.4°, 0.6°, . . . , 2.0° latitude.

toward the Poles. The more pronounced polar minimum in the Southern Hemisphere (SH) may be related to the weaker Brewer–Dobson circulation in the SH, resulting in less descent and consequently less adiabatic warming over the southern polar cap region (Ueyama and Wallace 2010). It may also be partly caused by the radiative cooling related to the ozone hole there in recent decades.

Figure 2b shows the T_{LS} changes (ΔT_{LS}) corresponding to a poleward shift of the T_{LS} latitudinal profile between equator and 58°N/51°S (i.e., the shaded region in Fig. 2a) by 0.2°, 0.4°, . . . , 2.0° latitude. Mathematically $\Delta T_{LS} = T_{LS}(L\text{-}\Delta L) - T_{LS}(L)$, where L and ΔL are the latitude and change the latitude, respectively. The ΔT_{LS} presents a bell-shaped cooling in the subtropics. The cooling is stronger for a larger shift. By defining y as the integration of the T_{LS} changes over latitudes for given shift (i.e., $y = \int_{\phi_0}^{\phi_1} \Delta T_{LS}\, d\phi$, where ϕ_0 is zero latitude and ϕ_1 is 58°N/51°S), Fig. 3 shows the y versus the poleward shift x. We thus obtain a linear relation $y = a{*}x$, where a is ~14 and 15 for the SH and NH, respectively. For a given poleward shift x, there is a maximum cooling y' associated with the bell-shaped cooling (Fig. 2b). We also find a linear relation between y' and x (not shown here; i.e., $y' = a'{*}x$, where a' is -0.52 and -0.51 for the SH and NH, respectively.

Herein we interpret the enhanced subtropical cooling in the lower stratosphere as a result of the jet poleward shift (Figs. 1 and 2). We also establish a quantitative relationship between the enhanced cooling and the poleward shift (Fig. 3). Therefore, we can estimate the poleward shift of the subtropical jets based on the enhanced subtropical lower-stratospheric cooling based on observations.

4. Quantification of poleward shift of subtropical jets using MSU T_{LS}

Figure 4 shows the latitudinal distributions of MSU T_{LS} trends for 1979–2009 using the UAH (Fig. 4a), RSS (Fig. 4b), and NOAA (Fig. 4c) datasets. A pronounced feature is the enhanced cooling in the subtropical/midlatitude regions regardless of the datasets used, which is related to the poleward shift of subtropical jets. The T_{LS} trends in last three decades are also caused by the change of the atmospheric compositions such as the increase of the CO_2, O_3 depletion, and possible long-term change of H_2O (e.g., Ramaswamy et al. 2001), and by the change of the Brewer–Dobson circulation (Fu et al. 2010). The T_{LS} trends may also be affected by the El Chichon (1982) and Pinatubo (1991) volcanic eruptions. To isolate the effect of the jet poleward shift on the T_{LS} trend, we need to remove the background trends resulting from other factors. Noting that the poleward shift has little impact on the T_{LS} trend at the equator, 51°S, and 58°N (see Fig. 2b), the trends at these locations are thus the background trends. By assuming that the background trend between equator and 51°S/58°N is linear with latitude, it can be obtained by linear interpolations of trends between equator and 51°S/58°N. We may then estimate the T_{LS} trend due to the jet poleward shift by subtracting the total trends with the background trends.

The thick lines in Figs. 4d–f represent the T_{LS} trend due to the subtropical jet poleward shifts using UAH, RSS, and the NOAA MSU datasets, respectively, after removing the background trends. The thin lines in (Figs. 4d–f) are the same as those in Fig. 2b but from three datasets. We can see that the estimated T_{LS} trend (thick lines) in the SH almost perfectly matches the changes in T_{LS} due to the poleward shift of the latitudinal dependence of the annual mean T_{LS} (thin lines). The comparison of the thick and thin lines indicates a poleward shift of the subtropical jets by about 0.6°–0.7° latitude in the SH, depending on the dataset used. In the NH, the thick lines do not match the thin lines as well as in the SH. The comparison of the thick and thin lines in

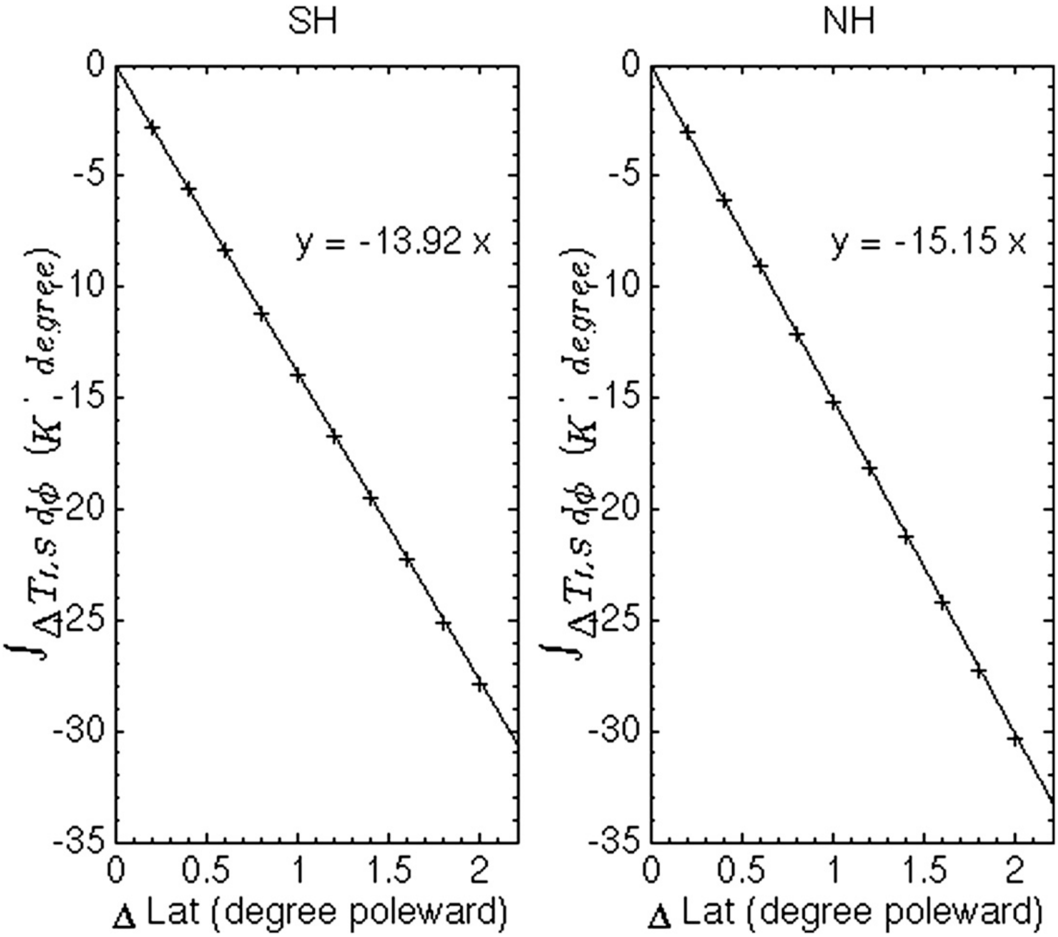

FIG. 3. The integration of T_{LS} changes over latitude (see Fig. 2b) vs the jet poleward shifts for (a) Southern Hemisphere and (b) Northern Hemisphere based on the NOAA MSU dataset.

the NH indicates a poleward shift of about 0.8° to 1.3° latitude.

We quantify $y = \int_{\phi_0}^{\phi_1} \Delta T_{LS}\, d\phi$ based on the thick lines in Figs. 4d–f. By employing the *x*–*y* relationships from each datasets as derived in section 3, we obtain the poleward shifts of the subtropical jets by 0.7° (UAH), 0.6° (RSS), and 0.5° (NOAA) latitude in the SH, and 1.2° (UAH), 0.7° (RSS), and 1.0° (NOAA) latitude in the NH. We also quantify the maximum cooling y' based on the thick lines in Figs. 4d–f. By employing the x–y' relationships, we obtain the poleward shifts of the subtropical jets by 0.7° (UAH), 0.6° (RSS), and 0.6° (NOAA) latitude in the SH, and 1.3° (UAH), 0.8° (RSS), and 1.1° (NOAA) latitude in the NH. The results from the two methods agree well with each other and both are also in general agreement with those from a direct comparison of thick and thin lines in Figs. 4d–f. Therefore, the poleward shift of subtropical jets are 0.6° ± 0.1° latitude for SH, and 1.0° ± 0.3° latitude for NH. The errors here are largely caused by the structural uncertainty in various datasets by applying a different set of reasonable processing choices (Thorne et al. 2005), but also partly caused by the uncertainty related to the methodology used to derive the widening. It is noteworthy that the observed trends over the NH are lager than over the SH. In contrast, Lu et al. (2007) showed similar trends from each hemisphere based on Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models A2 scenario while the modeling analysis by Polvani et al. (2011) showed a dominant trend in the SH.

Since the subtropical jets mark the poleward limit of the tropical belt, we obtain a widening of the tropical belt in last 30 years since 1979 by 1.9° (UAH), 1.3° (RSS), and 1.5° (NOAA) latitude using *x*–*y* relationships, and by 2.0° (UAH), 1.4° (RSS), and 1.7° (NOAA) latitude using x–y' relationships . Thus, our estimate of the tropical widening based on MSU T_{LS} datasets is 1.6° ± 0.4° latitude. This result is consistent with the estimate based

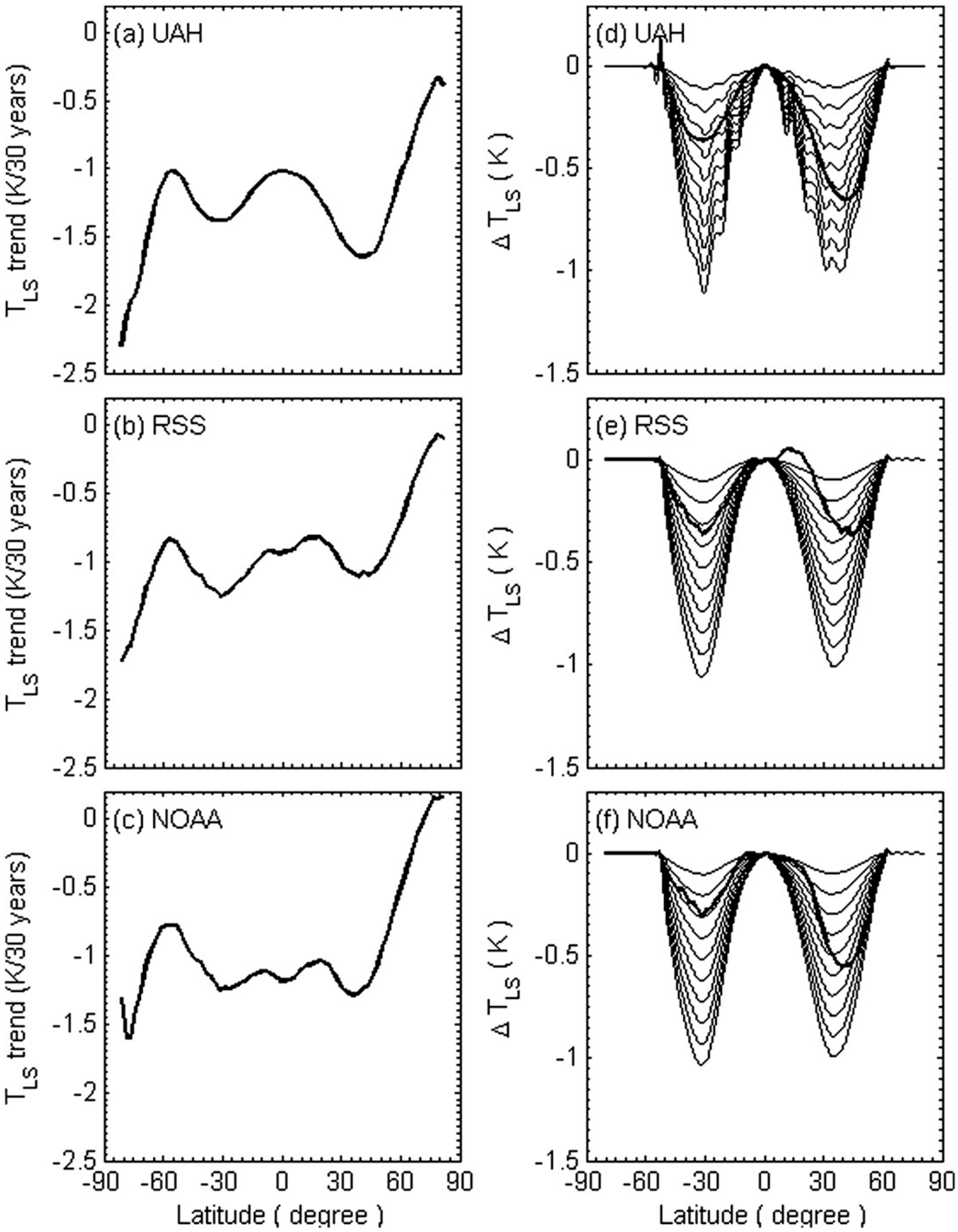

FIG. 4. (a),(b),(c) Latitudinal profiles of T_{LS} trends and (d),(e),(f) the corresponding contributions due to the subtropical jet poleward shifts (thick lines) using UAH, RSS, and NOAA MSU datasets, respectively, for 1979–2009. The thin lines in (d)–(f) are the same as those in Fig. 2b, but from three datasets.

on the changes in meridional gradients of the tropospheric temperatures using the MSU tropospheric temperature datasets (Fu et al. 2006).

It is noted that we may not be able to fully justify the linearity assumption to remove the T_{LS} background trends. Quantification of the latitudinal dependence of T_{LS} trends due to the changes of the atmospheric composition and large-scale circulations is beyond the scope of the present paper. But it is argued that the linearity assumption may be a good one for the following reasons.

First, the remaining trends in the SH after removing the linear background trends almost perfectly matches the shape of the T_{LS} change by shifting climatic T_{LS} poleward (Figs. 4d–f); although in the NH, the thick lines may not match the thin lines as well as in the SH, which may be partly caused by the nonlinear latitudinal dependence of the background trends. Second, the latitudinal dependences of T_{LS} trends using three MSU datasets are quite different from each other (Figs. 4a–c), but the remaining trends after removing the background effects agree well (Figs. 4d–f). Third, what we derived is the annual mean trend where the background trend is expected to have less latitudinal structures. We did find that our technique does not work well when applying to various seasons when the background trends may have large latitudinal dependences. It is our future research effort to quantify the uncertainty associated with the nonlinear latitudinal dependences of T_{LS} background trends.

The estimate of tropical expansion from this study is at the low end of the range based on various observational analyses (Seidel et al. 2008), but we may have more confidence on the present result for the following reasons. First, many of the other analyses might overestimate the expansion. This is because the threshold values of the total column ozone concentration, outgoing longwave radiation, and tropopause heights that are used to define the tropical belt, are not only affected by the tropical widening, but also by other factors (Davis and Rosenlof 2011). For example, both an increase of the tropospheric temperature and a decrease of the stratospheric temperature lead to an increase of the tropopause height (Santer et al. 2003), which is not related to tropical widening. In addition Birner (2010) shows that the widening trend is sensitive to changes in the assumed tropopause height threshold. Note that in the present study, we do not assume a threshold value. More importantly the background trends resulting from factors other than the jet poleward shift are removed before estimating tropical widening. Second, the MSU data used in this study has been scrutinized in much more detail than other observational datasets to satisfy the temporal homogeneity for the trend analysis. More importantly is the use of the shape of remaining temperature trends as a function of latitude, which separates the results from the absolute values of the trends. The latter is more subject to calibration uncertainties in the datasets that occurs because of the merging together of many different satellites.

5. Summary and conclusions

One pronounced feature in observed lower-stratospheric temperature trends is the enhanced cooling in the subtropical/midlatitude regions in both hemispheres. We demonstrate that this enhanced cooling is a direct response of the lower-stratospheric temperature to the poleward shift of subtropical jets. We show that this enhanced lower-stratospheric cooling can be used to quantify the poleward shift of subtropical jets. Using MSU-observed lower-stratospheric temperatures we find that the subtropical jets have shifted poleward by 0.6° ± 0.1° and 1.0° ± 0.3° latitude in the Southern and Northern Hemispheres, respectively, since 1979, indicating a widening of tropical belt by 1.6° ± 0.4° latitude. The errors here are largely caused by the structural uncertainty in MSU datasets and also partly caused by the uncertainty related to the methodology used to derive the widening. Note that the error due to the possible nonlinear latitudinal dependence of T_{LS} background trends is not included here. In contrast to many other observational analyses of tropical widening, we do not assume a threshold value, but we remove the background trends resulting from factors other than the poleward shift before estimating the tropical widening. The estimated widening from the present study agrees well with that by Fu et al. (2006) based on the changes in meridional gradients of the MSU tropospheric temperatures and both estimates are at the low end of the range from various observational analyses.

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