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Revisiting ozone measurements as an indicator of tropical width

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Abstract

The total column ozone (TCO) amount varies with latitude, in part due to the difference in tropopause height between the tropics and midlatitudes. This dependency of TCO on latitude has been used to identify the latitudes of the tropical edges and to compute their variations in time. The previously reported poleward movement of the tropical edge latitudes computed from satellite TCO measurements over the past several decades is greater than 3° latitude per decade. This tropical widening rate is significantly larger than a number of independent estimates and if correct suggests a major deficiency in the representation of tropical widening in models. We revisit the previously used TCO tropical edge latitude diagnostic to extend it forward in time with a new data set and to assess its robustness through comparisons with independent tropical edge diagnostics. We find that the previous TCO-based tropical width timeseries contain a spurious jump, likely due to data inhomogeneities. After removal of this jump using an objective statistical breakpoint identification technique, TCO-based tropical widening is reduced to the point that it is not significantly different than other tropical widening estimates. The strong sensitivity of the TCO method to algorithmic choices, its out-of-phase seasonality in the Northern Hemisphere, and its lack of correlation with well-established tropical width metrics on interannual timescales support our conclusion that the TCO-based tropical width diagnostic as previously implemented is not a robust measure of tropical width.

Keywords: Ozone, Tropical width, Tropical widening, Hadley cell, Stratosphere

Introduction

A number of different methodologies and characteristics of Earth's atmosphere have been used to identify the latitudinal boundary between the tropics and extratropics and compute changes in its position with time (e.g., Davis and Rosenlof 2012; Lucas et al. 2014; Seidel et al. 2008). This so-called "tropical edge" roughly corresponds to the location of the subsiding branch of the Hadley cell in each hemisphere at around 30°. Although the Hadley cell and associated subtropical jet provide the physical underpinning for defining a tropical edge, in practice there have been numerous definitions using features that are assumed to be tied to the Hadley cell or subtropical jet, such as the subtropical break in the height of the tropopause.

These various definitions have been at least part of the reason that estimates of changes in the width of the tropics span such a large range of values, from statistically insignificant and near zero to several degrees latitude per decade of poleward movement and highly significant. Widening based on satellite-observed total column ozone (TCO) by Hudson (2012), hereafter H12) and a series of earlier papers (Hudson et al. 2003; Hudson et al. 2006, hereafter H03 and H06, respectively) are the largest estimates of so-called "tropical widening." For example, H12 provides a value of global tropical expansion (Northern Hemisphere (NH) + Southern Hemisphere (SH)) over the period of 1979–2010 of 3.2° latitude per decade, whereas most other metrics show values < 1° per decade. The few other annual-mean global estimates of tropical widening that are larger than 1° per decade are based on tropopause height (Seidel and Randel 2007) and outgoing longwave radiation (OLR; Hu and Fu 2007). However, subsequent studies have shown that the values from these studies were biased high and that more objective metrics based on tropopause height and OLR give significantly smaller estimates that are below 1° per decade (Birner 2010; Davis

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and Rosenlof 2012). More recent studies have also questioned the robustness of tropopause and OLR metrics and demonstrated that they are not always well correlated with more direct measures of the Hadley cell (Davis and Birner 2017; Solomon et al. 2016; Waugh et al. 2018).

In this paper, we revisit the usage of total column ozone measurements for defining the width of the tropics and quantifying tropical widening rates, with the goal of better understanding the apparent discrepancy between the large TCO-based widening found by H06/H12 and other studies. Towards this end, this paper is organized as follows. In the next section, we give an overview of the previously used TCO datasets and tropical width definitions, and new TCO data considered in this study. In the following section, we attempt to reproduce the H12 results using the same TCO data sets used in the original study, and we test the sensitivity of the H12 tropical widening estimates to the TCO dataset by analyzing a newer merged TCO data set. After this, we compare the seasonality and interannual variability of the H12 tropical width to other tropical width metrics.

Methods/Experimental

This section gives a brief overview of the data sets and previously used methodologies for quantifying a tropical edge latitude using TCO. H03 and subsequent papers divided the NH total column ozone field into four meteorological "regimes:" tropical, midlatitude, polar, and Arctic. In later papers (H06, H12), poleward movement of the tropical-midlatitude boundary, the so-called subtropical front, was quantified. It is this subtropical front boundary that is relevant in this study and to the broader tropical widening literature that has addressed changes in the width of the Hadley cell, tropopause, etc.

In essence, the "ozone meteorological regime" methodologies exploit the fact that TCO has a minimum in the tropics and is higher at midlatitudes in order to identify the subtropical boundary. The physical reasoning for this is that the lower stratosphere makes a large contribution to TCO, so the TCO is in some sense a proxy for the tropopause height. Along with the sharp drop in tropopause height in the subtropics, there is a corresponding increase in TCO.

Total column ozone data

The total column ozone data used in H03, H06, and H12 came from several satellites including the Nimbus-7 total ozone mapping spectrometer (TOMS, 1978–1993, McPeters et al. 1996) and Earthprobe TOMS (1996–2005, McPeters et al. 1998) version 8 data, the Advanced Tiros-N Operational Vertical Sounder (ATOVS) from several of the NOAA polar orbiting satellites, and the ozone monitoring instrument (OMI; Bhartia and Wellemeyer 2002) aboard the NASA Aura-EOS satellite. In all cases, daily gridded data were used. For TOMS and TOVS, the data were gridded at 1.25° lon × 1° lat horizontal resolution, whereas for OMI the data are provided at 1° lon × 1° lat resolution (i.e., the OMTO3d.003 product).

Here, we also use version 3.3 ("patched") of the Bodeker Scientific merged total column ozone data set (hereinafter BODSCI, Bodeker et al. 2005; Muller et al. 2008; Struthers et al. 2009). This data set merges measurements from four TOMS instruments, three different retrievals from the Global Ozone Monitoring Experiment (GOME), four Solar Backscatter Ultra-Violet (SBUV) instruments, and Aura OMI. In this data set, data from the ground-based World Ozone and Ultraviolet Data Center (WOUDC) Dobson and Brewer spectrophotometer network were used to remove offsets and drifts between the different data sets to produce a global homogeneous total ozone column data set. The BODSCI data set is provided at daily temporal resolution and on a 1.25° lon × 1° lat horizontal grid.

Total column ozone "meteorological regime" methods

The basic method for identifying the ozone boundaries in the NH is described in H03, and H06 presents a further modification to the H03 method. The H06 method is also used in H12. Although the methodology described in H03/H06 is for the NH, a similar methodology was also applied to the SH (Ph.D. dissertation, Flores 2004) and included in H12. For simplicity, and since the NH method is documented in the peer-reviewed literature, our primary focus will be on the NH. The reader is referred to H03 and H06 for a more in-depth description of the methods.

The H03 method is an iterative approach that uses daily gridded TCO data and daily isentropic potential vorticity (PV) from the NCEP-NCAR reanalysis (Kalnay et al. 1996) to compute the four ozone regimes (i.e., tropical, midlatitude, polar, and Arctic) and their boundaries. These regimes are intended to characterize regions of quasi-constant TCO that are separated by regions of relatively rapid changes in TCO, and the boundaries between these TCO regimes are supposed to correspond to meteorological phenomena such as the jets. For example, the tropical–midlatitude boundary occurs at the subtropical jet/tropopause break, where the abrupt change in tropopause height causes an abrupt change in TCO values. Similarly, the midlatitude–polar boundary is intended to correspond with the location of the polar front jet, and the polar-Arctic boundary occurs at the edge of the stratospheric polar vortex. By construction, the Arctic regime is the region within the polar vortex, when the vortex is present during winter. The Arctic regime is excluded from subsequent analysis in order to focus on dynamically induced changes to the TCO field and remove air masses that have been potentially affected by heterogeneous ozone chemistry. In H03, the Arctic regime was identified by using the position of the 31.5 PVU (1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}) boundary on the 450 K isentropic surface. TCO data poleward of this boundary are excluded from further analysis because of their potential to be impacted by ozone loss chemistry. In subsequent studies (H06 and H12), the polar vortex boundary was defined based on the PV value associated with the position of the maximum gradient in PV on the 550 K surface, again using NCEP-NCAR reanalysis data. This procedure was applied using daily data, and a 5-day running mean of the PV threshold was used to reduce noise (Follette 2007).

There are several ambiguities in the vortex definition in H12. First, there are multiple ways one could determine a PV value that is associated with the position of the maximum PV gradient. Also, no discussion is provided of how to define when a vortex is not present, as is the case for most of the year outside of winter months. To avoid these ambiguities, we mask out the polar vortex by using the vortex edge definition given by Nash et al. (1996). As with H12, this definition is applied to daily PV fields at 550 K from the NCEP-NCAR reanalysis, and the 5-day smoothing of the daily PV values at the vortex edge is also applied.

Following H12, after masking out the Arctic regime, a first-guess TCO value for the tropical-midlatitude (i.e., the subtropical front) and midlatitude-polar boundary (i.e., the polar front) is applied to make an initial identification of the three remaining regions. The first-guess TCO thresholds are based on previous work (Karol et al. 1987; Shalamyanskiy and Romashkina 1980) and vary as a function of month (see Fig. 3, H03). A contour program is used to identify the regime boundaries from the first guess, and pixels within each regime are grouped together. Pixels within 2° of latitude and longitude of the boundaries are excluded. The daily mean TCO for each regime is then simply an average of the data within the regime, and the next-guess boundaries are defined as being halfway between the averages for each regime. This iterative process is then repeated until convergence is obtained (i.e., regime area changes by less than 5%) and a final set of TCO boundaries is determined. For the final identification of the regimes, a 30-day running mean of the TCO thresholds is used to reduce noise (Hudson et al. 2003).

In H06/H12, a second iterative process was added to this method to allow for a latitudinal dependence to exist in the regime boundaries. After computing the daily boundaries using the H03 method, these boundaries were then used to separate tropical and midlatitude regimes in each latitude band and come up with a latitudinally varying threshold for the subtropical front. As in H12, the daily timeseries have been averaged to create monthly mean timeseries.

Results and discussion

Replication of previous results

Because separating the meteorological regimes involves a complex algorithm, we first attempt to replicate the results from H12. Figure 1 shows the timeseries of NH subtropical front latitude taken from Fig. 5 of H12 (black line), as well as our implementation of the H12 methodology using the three TOMS data sets and the BODSCI data set.

The most valid comparison between H12 and our replication should be with the TOMS data sets, because they were used by H12 along with the no longer available TOVS_NEURAL to fill in data gaps in the 1990s between the Nimbus-7 and Earthprobe records. Our implementation with TOMS generally reproduces the absolute value and seasonality of H12, particularly during winter, but with significant differences during the summer months. Overall, the H12 values are much farther equatorward during summer than ours. The reason for this is that ozone regime boundaries in the Hudson methodology are extremely sensitive to the polar vortex identification. The size of the polar vortex area masked out impacts not only the ozone boundary values for the polar-midlatitude boundary but also the midlatitude-tropical boundary which is used to identify the latitude of the subtropical front.

The sensitivity to polar vortex masking is shown in Fig. 2, which shows the tropical width time series from the BODSCI data using three methods of identifying the polar vortex, overlaid with the time series from H12. The first method is the Nash method, which is the same method used in Fig. 1 (orange line). The second method identifies the vortex boundary using a PV threshold on the 550 K isentrope. The PV threshold is defined as the median value of PV within the upper second percentile of PV gradients within the NH. This definition reflects our attempt at implementing a robust and objective vortex identification that follows the ambiguous definition offered in H12, namely the "PV value associated with the maximum gradient in PV". The third definition is the same as the second, except that when the PV threshold falls below 40 PVU no vortex is defined. The third definition addresses the fact that for most of the year, the polar vortex does not exist, which is not taken into account by the second definition. As can be seen in Fig. 2, the second method goes much farther south, due to the area masked as "vortex" growing to encompass most of the NH. Since the three ozone regimes are still being defined within an area that is smaller, and the TCO gradients are relatively weak in summer, the TCO boundary values end up being strongly perturbed from their climatological first-guess values. This results in the latitudinal edges being displaced equatorward until they reach the minimum value allowed by the H12 definition (i.e., 25°

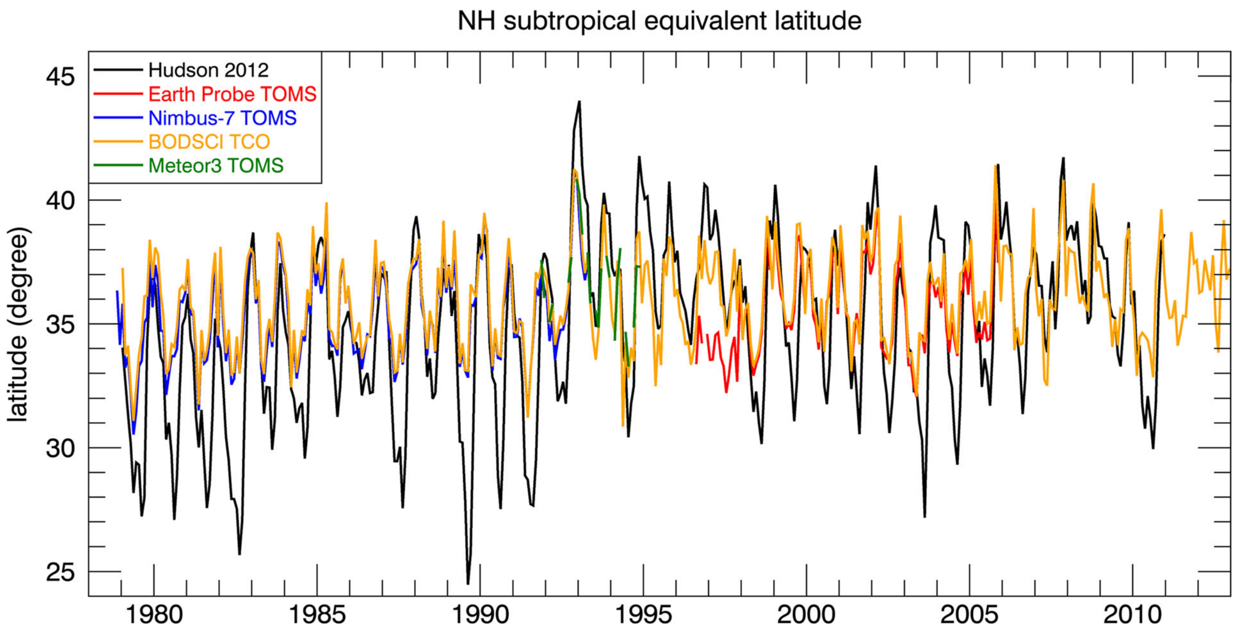

Fig. 1 Timeseries of total column ozone-based subtropical front equivalent latitude in the Northern Hemisphere from five different data sources. Calculations from Hudson 2012 are in black, and the colored lines are our calculations from four different TCO data sets

N). The third definition attempts to mitigate this unphysical growth of the vortex by setting a minimum PV threshold to use for the masking. In all cases, during wintertime when the vortex is present, the three methods are in relatively close agreement.

In addition to the differences between H12 and our implementation during summer months that are caused by vortex identification differences, there is an apparent jump in the H12 latitude in 1992 near the end of the Nimbus-7 TOMS data set. Moreover, at this time, there is also a jump

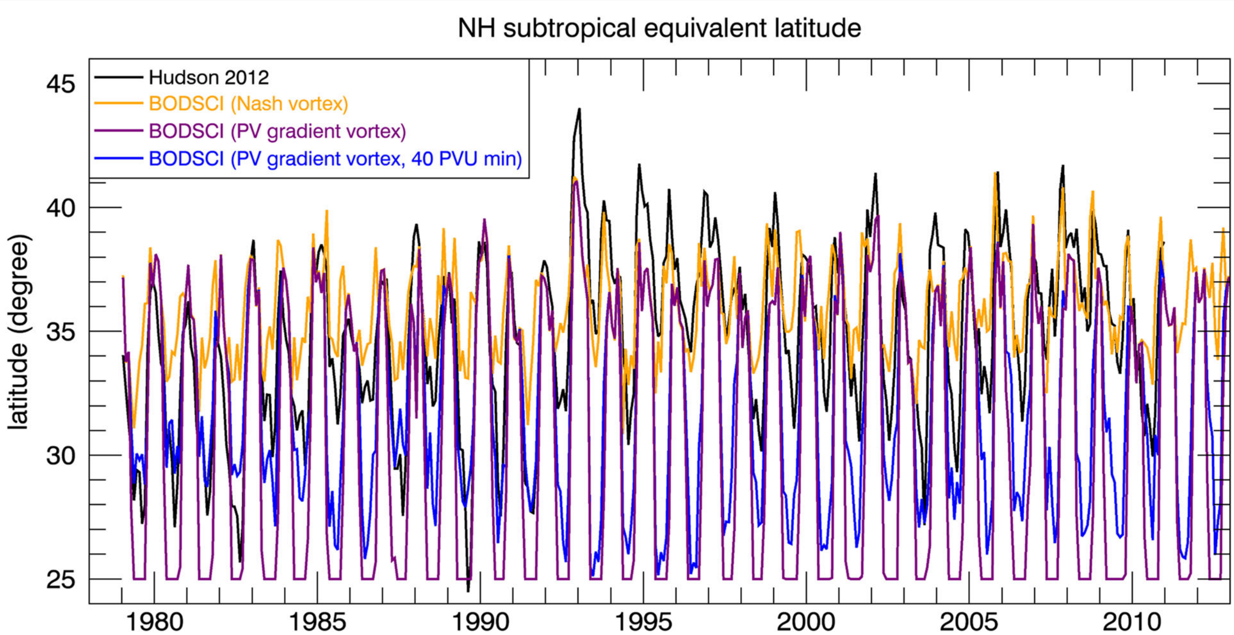

Fig. 2 NH tropical width sensitivity to polar vortex masking. Calculations from Hudson 2012 are in black, and the colored lines show the NH subtropical edge latitude computed from three different vortex identification algorithms

of several degrees in the difference between our Nimbus-7 TOMS timeseries and H12 in 1992. Before this time, our timeseries calculated using Nimbus-7 TOMS TCO generally agrees well with the H12 estimates. After this time, the H12 timeseries is significantly offset poleward of ours by several degrees of latitude, particularly during summer months.

Similar to the comparison with the Nimbus-7 TOMS calculations, there is a jump in the difference between H12 and BODSCI estimates around 1992, with the H12 timeseries moving several degrees poleward of the BODSCI estimates after that time. Overall, our implementation using the BODSCI data agrees very well with that using TOMS, which is expected given that TOMS data are included in the merged BODSCI product. However, the similarity between our implementation of the H12 method using both the raw (unadjusted) TOMS data and the homogenized BODSCI data suggests that the jump is not substantially impacted by data merging in the construction of the BODSCI data set and could be an as-yet unidentified artifact in the data used by H12. As previously noted, H12 used a TOVS data set that is no longer available to fill in some of the data gaps in the 1990s during the transition between TOMS instruments, so it is not possible for us to directly assess the potential impact of data inhomogeneities in their study. Rather, in the next section, we investigate the significance and impact of the jump in the 1990s, and its effect on long-term trends derived in H12.

Trend and breakpoint analysis of tropical width timeseries

In this section, we compare our trends to H12 and assess the significance of the apparent jump in the 1990s in the H12 data. We perform linear trend fits to the anomaly timeseries in each hemisphere and provide 95% confidence intervals on the trend after accounting for lag-1 autocorrelation of the residuals (Santer et al. 2000). Between 1979 and 2010, H12 found poleward movement of the subtropical front of 3.7° ± 0.3° in the NH and 6.5° ± 0.2° in the SH, which is equivalent to a global tropical widening rate of 3.2° ± 0.1° per decade. We performed an independent trend analysis on the H12 data and found very similar trends in each hemisphere (see Table 1), but with much larger uncertainty estimates (~ 1° per decade). The reason that our values are larger is mostly due to us accounting for autocorrelation and quoting a 95% confidence interval (CI) rather than a 1σ estimate. For example, for the global mean trend, we compute a 1σ trend uncertainty of 0.2°, which is similar to that found in H12 but a factor of 5 less than our 95% CI estimate.

Table 1 Tropical widening trends from the H12 method (° latitude per decade)

O_3 data	H12	H12	H12	BODSCI
	published values	our trend calculation	with breakpoint removed	
NH	1.2 ± 0.1	1.3 ± 0.9	−0.061 ± 0.7	0.34 ± 0.2
SH	2.0 ± 0.1	2.1 ± 1.3	0.93 ± 1.1	
Global	3.2 ± 0.1	3.3 ± 2.1	0.87 ± 1.6	

To investigate whether or not the potential jump in the 1990s is significant and how it impacts the derived long-term trends, we use the two-phase regression model described by Lund and Reeves (2002). Briefly, this model tests each data point in a timeseries as a potential undocumented changepoint by doing a linear least-squares fit on either side of the changepoint and compares the reduction in sum-of-square errors (SSE) relative to the case of fitting a single line for the entire timeseries. The SSE reduction is quantified using an F statistic, and an undocumented changepoint is said to occur at the maximum value of F if it is greater than a critical value of F (see, e.g., Lund and Reeves 2002, Table 1).

Figure 3 shows the anomaly of the H12 timeseries (i.e., with the seasonal cycle removed) in both hemispheres, as well as our results from the NH using the BODSCI data. As can be seen in this figure, the H12 timeseries contain strong trends in both hemispheres (solid lines), whereas our analysis of the BODSCI calculations in the NH shows very little trend in comparison. The changepoint analysis identifies a statistically significant breakpoint in the H12 timeseries in both hemispheres in the same year and month, July 1992. For the BODSCI NH timeseries, no statistically significant breakpoint is found.

To assess the impact of the breakpoint in the H12 timeseries on trends, we remove its effect by subtracting the latitudinal offset at the breakpoint (i.e., the difference between the dashed lines in Fig. 3a, at July 1992) from the latter portion of the timeseries, and then compute the linear trends on this "corrected" timeseries (Fig. 3b). After removing the breakpoints in the H12 timeseries, the trends in both hemispheres are significantly reduced (see Table 1) and the difference from our NH trend using BODSCI timeseries is not statistically significant (based on the confidence interval method described in Santer et al. 2000). The global tropical widening rate is reduced by more than a factor of three, from over 3° per decade and statistically significant to less than 1° per decade and not statistically significant. It is worth noting that with or without breakpoint removal, the SH trends are greater than those in the NH, in line with many previous studies suggesting the Antarctic stratospheric ozone depletion is one of the main drivers of tropical width changes and that ozone depletion has its greatest impact on the SH tropical width (Polvani et al. 2011; Waugh et al. 2015).

Given that the objective breakpoint analysis reveals a breakpoint at the same date (July 1992) in both

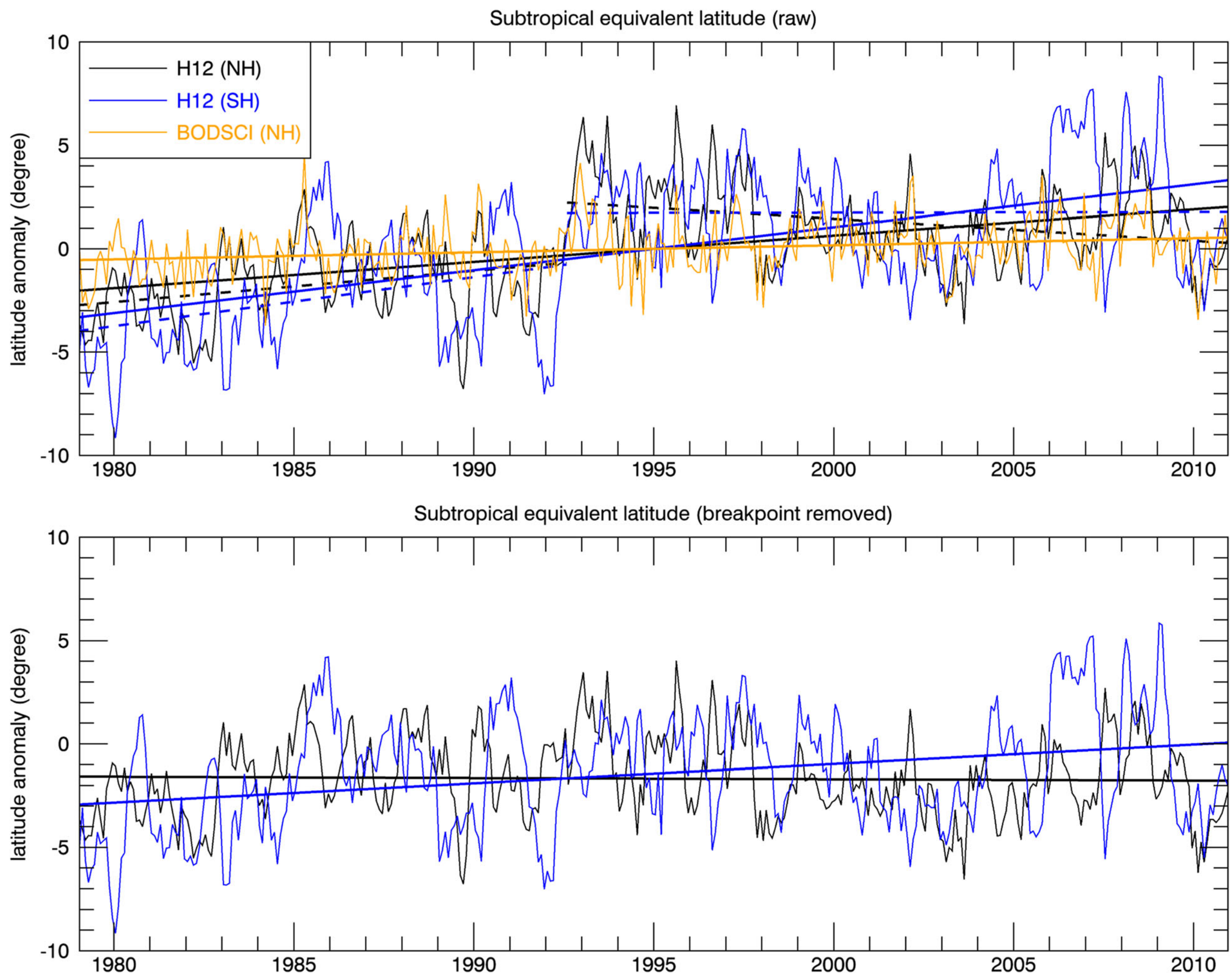

Fig. 3 Top panel: Timeseries analysis illustrating an undocumented changepoint in the Hudson 2012 metric (black, blue lines) and our implementation using the BODSCI TCO data (yellow line). Lower panel: the reconstructed timeseries with breakpoint removed

hemispheres in the H12 timeseries, and not in our implementation of the H12 method using the BODSCI TCO data, we hypothesize that the H12 result was impacted by a spurious change related to data merging. Although Nimbus-7 operated until May 1993, it is possible that H12 made the transition to TOVS TCO before the end of the Nimbus-7 lifetime.

Relation to other tropical width metrics

In this section, we investigate how the H12 tropical width metric relates to other tropical width metrics by comparing its seasonality and interannual variability with tropical width calculated over the same time period from the ERA-Interim reanalysis (Dee et al. 2011). The metrics here are a subset of the metrics documented in Adam et al. (2018), and the reader is referred to the discussion there for more thorough definitions. Briefly, we use the poleward edge of the subtropical dry zone, defined by the latitude where zonal mean precipitation equals evaporation ($P - E = 0$); the poleward edge of the Hadley cell, defined as the zero-crossing of the mean meridional streamfunction at 500 hPa ($\psi_{500} = 0$); the subtropical jet (STJ), defined as the maximum of the mass-weighted wind in the 400–100 hPa layer with the surface wind removed; the subtropical tropopause break, defined by the maximum meridional gradient of the tropopause height; and the eddy-driven jet (EDJ), defined as the latitude of maximum wind on the 850 hPa surface. Although the EDJ is not technically a marker of the “tropics”, it has been shown to be well correlated with the position of the Hadley cell. Of these metrics, the so-called “lower” metrics (P-E, ψ_{500}, and EDJ) have been demonstrated to correlate well with one another, whereas the so-called “upper metrics” (STJ and tropopause) are not well correlated with the lower metrics (Davis and Birner 2017; Solomon et al. 2016). Here, we include the upper metrics because there are physical reasons that they may be related to the stratospheric ozone distribution.

Seasonality

If they are measuring similar phenomena, tropical edge latitudes should have similar seasonal cycles. For example, one might expect that TCO- and tropopause-based tropical width metrics would closely follow one another, based on the physical relation between the tropopause height and total column ozone.

Although the reanalysis tropical edge latitudes shown in Fig. 4 have different mean values and different amplitudes in their seasonal cycles, in both hemispheres, they move poleward during summer months and equatorward during winter months. In the SH, the H12 metric roughly follows the seasonal progression of the reanalysis metrics, albeit with a much smaller amplitude than most other metrics. In contrast, in the NH, the H12 metric (and our computation using BODSCI TCO data) is most poleward during winter and most equatorward during summer. Thus, it is out of phase with the rest of the metrics.

As discussed in the "Results and discussion" section, the NH edge latitudes are very sensitive to the vortex masking, which impacts the iteratively determined thresholds for the subtropical front. To see the impact of the iterative process, we also computed the ozone-based tropical width using just the first guess of the subtropical front threshold (i.e., from Fig. 3 of Hudson et al. 2003). Interestingly, the tropical width based on this first guess shows the correct seasonality in the NH, which means that some aspect of the vortex masking or iterative procedure causes the seasonality of the full method to be out of phase. It is possible that a simplified TCO-based tropical edge metric could be defined based on such a seasonally varying fixed TCO threshold, but in such a case chemically induced ozone

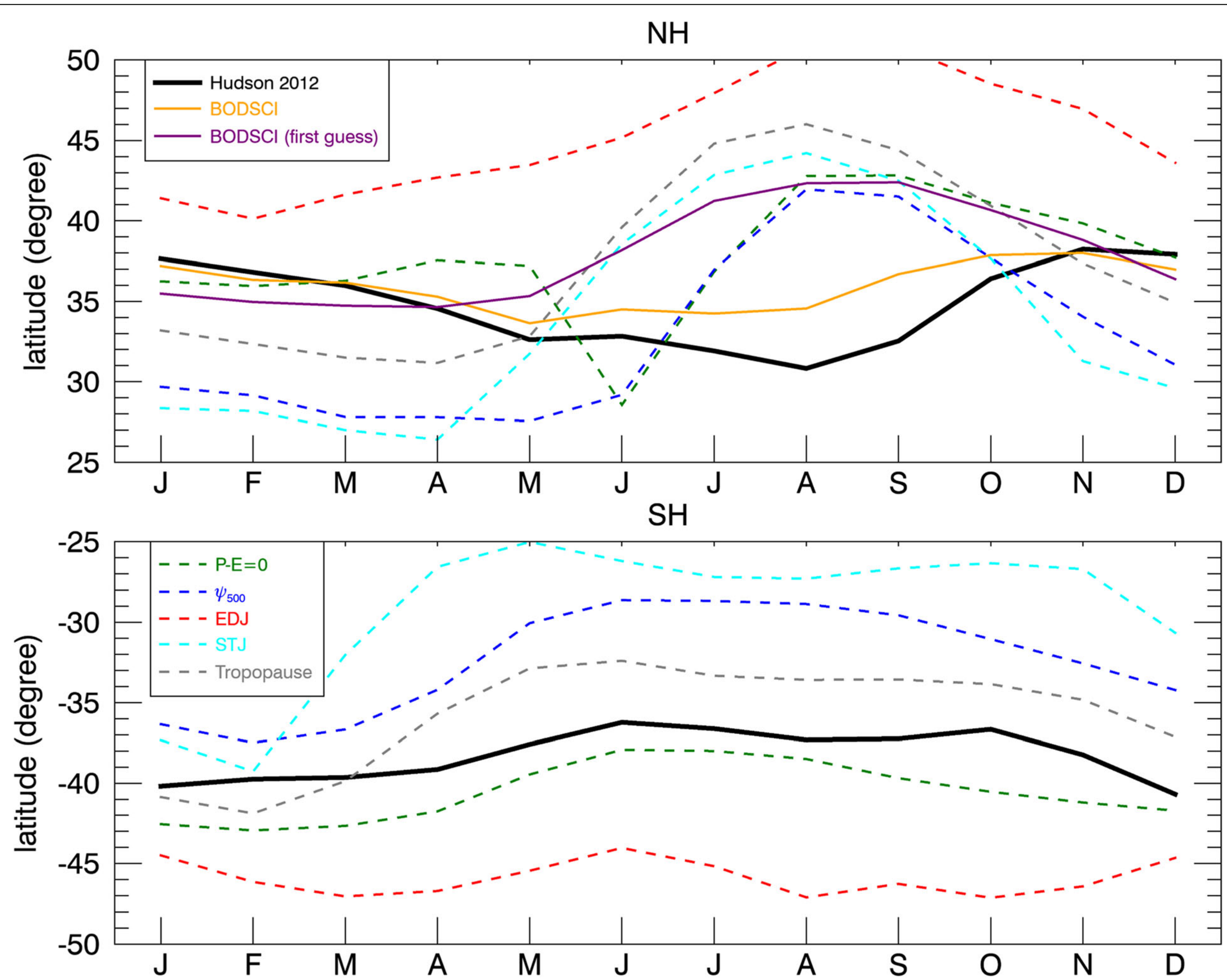

Fig. 4 Seasonal cycle of tropical width metrics from TCO data (solid lines) and ERA-Interim reanalysis (dashed lines) over their common time period (1979–2010). The EDJ metric has been shifted 5° equatorward in the SH

depletion (that is unrelated to dynamical changes) would cause poleward movement of the subtropical front.

Interannual variations

In addition to assessing the seasonality of the H12 metric in comparison to other tropical width metrics, we also consider whether H12 correlates well with the other tropical width metrics on interannual timescales. The idea being tested is that if a pair of metrics are measuring the same physical quantity, they should both be anomalously poleward or equatorward in step with one another. This type of analysis was used to identify the set of "upper" and "lower" tropical width metrics discussed above (Davis and Birner 2017; Solomon et al. 2016; Waugh et al. 2018). Here, we reproduce the results of those previous studies but add in the Hudson 2012 metric in order to identify whether the ozone-based tropical edge correlates with either of these categories of metrics.

Figure 5 shows the correlations between detrended monthly mean tropical width anomalies for all combinations of metrics in each hemisphere, including both reanalysis tropical width metrics from ERA-Interim computed using the Tropical Width Diagnostics package (TropD, Adam et al. 2018) and the uncorrected H12 timeseries, the H12 timeseries with breakpoints removed, and our implementation of the H12 method in the NH data from the BODSCI TCO data. This table shows that the H12 metrics are generally not well

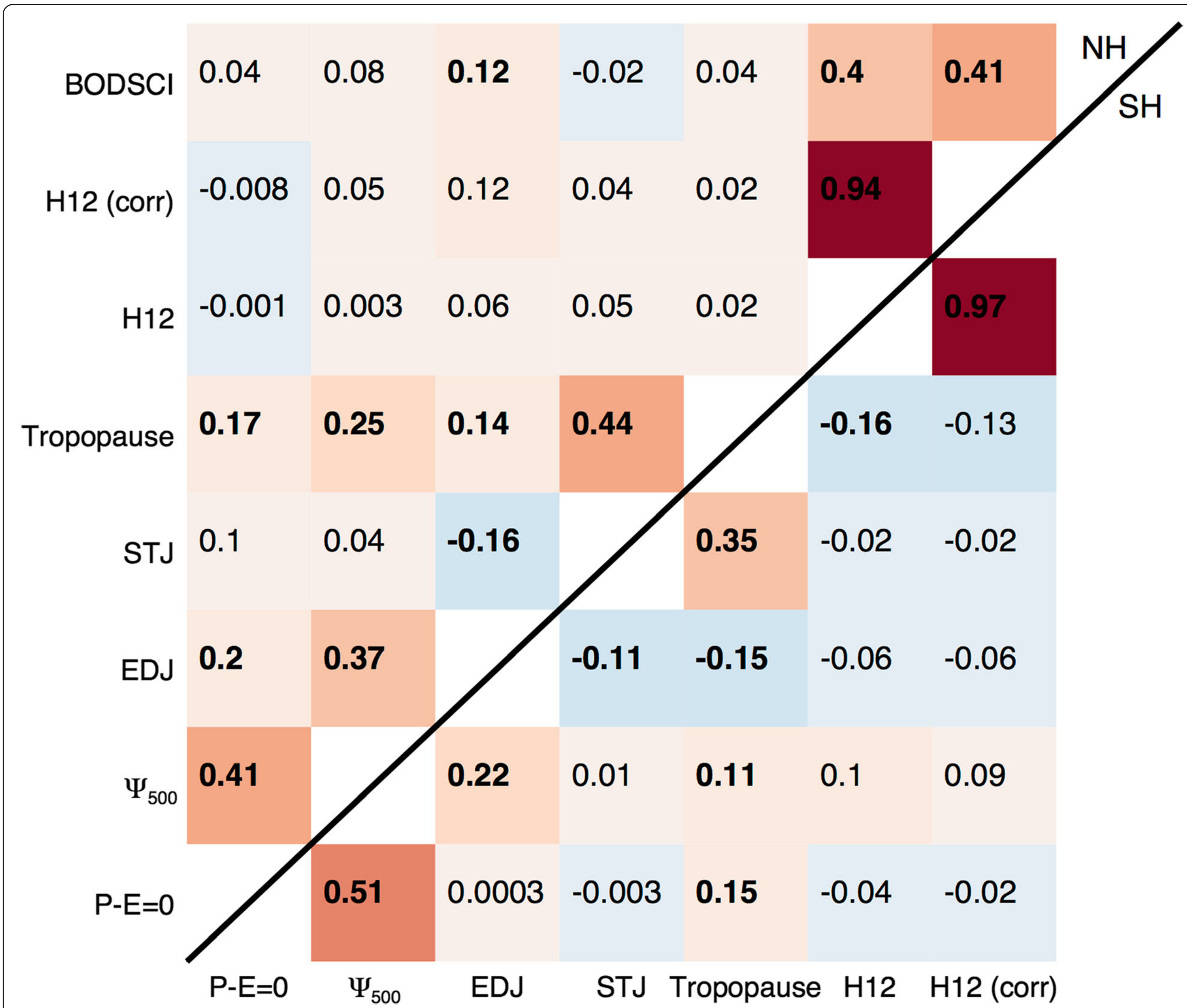

Fig. 5 Correlation coefficients between pairs of detrended monthly mean tropical width metric anomalies (1979–2010) from ERA-Interim reanalysis, calculations from Hudson 2012 (both raw and corrected versions), and our implementation of the Hudson 2012 method using BODSCI TCO data, color-coded by the value. The upper left is NH and the lower right is SH. Statistically significant correlations, taking into account autocorrelation of the timeseries, are shown in bold

correlated with any of the reanalysis tropical width metrics. The only statistically significant correlation is between the ozone metric and the EDJ in the NH, but the magnitude of this correlation is quite small. It is also worth noting that although many of the correlations within the reanalysis metrics are quite low, this is expected given the different categories that have been identified by previous studies.

Overall, the out-of-phase seasonal cycle of the H12 NH metric and the lack of apparent relation to the tropopause height suggests that some methodological detail in the H12 formulation is problematic.

Conclusions

Total column ozone varies with latitude, in part due to tropopause height differences between the tropics and midlatitudes. This physical relation was used by H12 to identify the tropical edge latitudes, or subtropical fronts, and compute their variations in time. The H12 method is rather complicated, involving both polar vortex boundary identification and masking using daily isentropic PV data, and two separate iterative processes for determining the subtropical front TCO thresholds as a function of latitude from daily TCO data. Using this method, H12 found tropical widening over the 1979–2010 of greater than 3° latitude per decade (both hemispheres combined). This tropical widening rate is significantly larger than those published in previous studies. For example, Davis and Rosenlof (2012) considered a number of different tropical edge diagnostics and mostly found trends of less than 1° per decade. A more recent study has reduced this range even further, to ~ 0.1°–0.5° per decade (Staten et al. 2018). To put these numbers in perspective, even tropical widening rates of 1° per decade are outside the range of trends predicted by historical simulations of the twentieth century in models (Grise et al. 2018; Johanson and Fu 2009). Thus, if the extreme tropical widening found in H12 is correct it suggests a major deficiency in the representation of tropical widening in models.

In order to reassess the H12 results, we replicated their methodology in the NH with both the original TOMS data used by H12 and the new homogenized BODSCI TCO data set. Overall, we were able to reproduce the general features of the H12 results, although we noted a large sensitivity to the polar vortex identification process. Furthermore, we found that the H12 tropical width timeseries in each hemisphere contained a statistically significant breakpoint in July 1992, around the end of the lifetime of the Nimbus-7 TOMS instrument when H12 switched to using TOVS data. Our replication of H12 in the NH with the TOMS and BODSCI data does not contain this breakpoint, so we conclude that the breakpoint is a spurious jump, likely associated with data inhomogeneities in the H12 analysis. We then correct for the breakpoint by applying an objective methodology to the H12 timeseries and recompute the tropical widening rates. The resulting global widening rate is less than 1° per decade and is statistically insignificant. In the NH, the H12 widening rate with the breakpoint removed is statistically insignificant and is not statistically different than the small significant trend (0.34 ± 0.2° per decade) we compute based on the

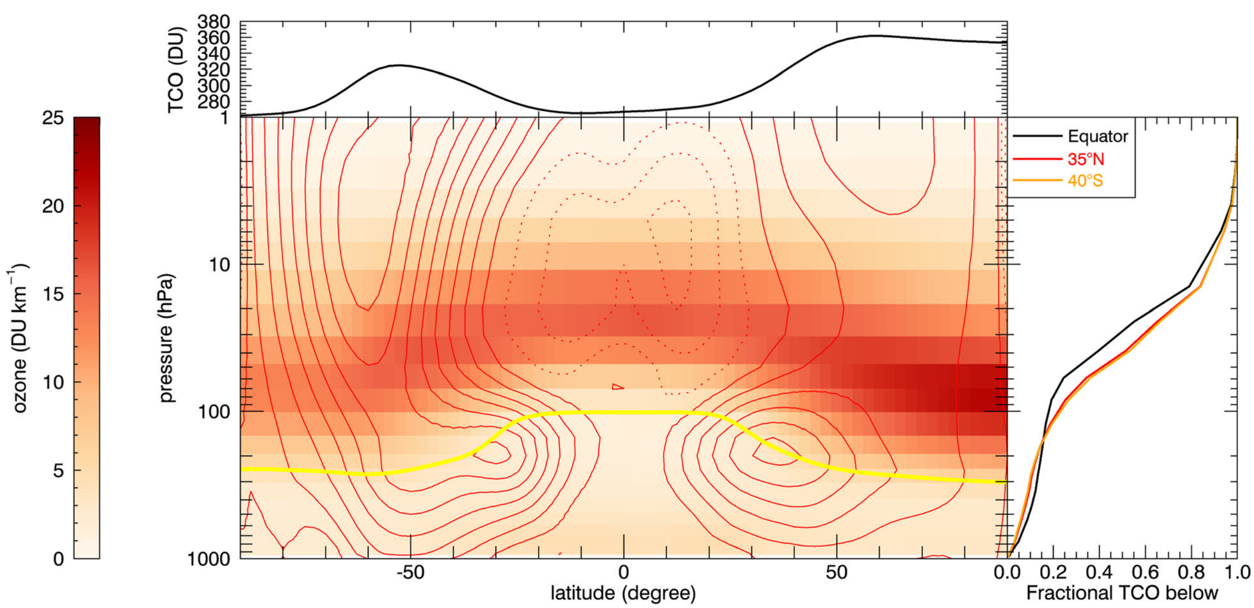

Fig. 6 Climatological ozone distribution (1979–2010) from the ERA-Interim reanalysis, along with the tropopause (yellow line). The right panel shows the fraction of the total column ozone below the given height at three different latitudes

BODSCI data. Thus, we conclude that the large tropical widening trends (i.e., > 1° per decade) reported by H12 were a result of unphysical data jumps. Because the H12 methodology was not documented in H12 and enough detail for us to produce tropical width timeseries in the SH, it is not possible to say definitively what the global tropical widening rate is from this method when applied to the BODSCI data.

In addition to assessing data quality issues in the H12 timeseries, we also assessed the robustness of the H12 method by comparing its seasonality and interannual variability to a number of independent tropical edge latitude diagnostics. While the H12 method generally produces edge latitudes that are within the range of other metrics, both the seasonality and interannual variations indicate that it is not physically well related to other tropical width metrics. In the SH, the H12 seasonal cycle amplitude is smaller than the other metrics, and in the NH, the seasonal cycle is its out-of-phase with the other metrics (i.e., it goes poleward in summer and equatorward in winter). The lack of correlation with well-established tropical width metrics on interannual timescales supports our conclusion that the H12 TCO-based tropical width diagnostic is not a robust measure of tropical width.

One obvious question raised by this conclusion is why the TCO-based width diagnostic is not a good measure of the tropics, given the expected relationship between the tropopause height and total column ozone. One possibility lies in the recent finding that tropopause-based tropical width metrics are themselves not a robust indicator of Hadley cell width, or at least that they do not correlate well with metrics directly related to the Hadley Cell (Davis and Birner 2017; Solomon et al. 2016; Waugh et al. 2018). However, our analysis shows that the ozone-based tropical width metric is not well correlated with subtropical jet metrics, so this explanation is insufficient.

A better explanation for why TCO-based with diagnostics fail to capture the tropopause variability is that variations in TCO are relatively weakly driven by tropopause variability. For example, the fraction of TCO occurring below the overworld stratosphere (≥ 380 K potential temperature, or ~ 90 hPa) is only 15–20% (Fig. 6). Approximately 5–10% of TCO is below the extratropical tropopause (~ 300 hPa), meaning that the amount of ozone in the region that can be impacted by latitudinal variations in the tropopause break (i.e., between the extratropical tropopause and the overworld stratosphere) is only ~ 10%. Given that relatively small lever arm on TCO, it is perhaps unsurprising that defining tropical width based solely on TCO is problematic.

In summary, we have identified several problems with TCO-based tropical width. Broadly, these problems relate to the complex iterative algorithm employed previously, inhomogeneities in the TCO data, and the relatively small component of TCO variability that can be explained by latitudinal variations in the tropopause break. However, in principle, the strong meridional ozone gradient in the lower stratosphere should be a good marker of the location of the tropopause break. Given the potential temporal inhomogeneities in reanalysis fields, there is a justified desire for robust observationally based metrics of tropical width that do not rely on reanalysis output. It is possible that vertically resolved ozone measurements could be used to address this issue, although the duration and reliability of such measurements may be limited to the point that it is not possible to confidently use them for trend detection. Future studies aimed at the suitability of vertically resolved ozone measurements for tropical edge latitude identification should be able to clarify the extent to which existing measurements can be used for tropical widening studies.

Abbreviations

ATOVS: Advanced Tiros-N Operational Vertical Sounder; BODSCI: Bodeker Scientific merged total column ozone data set; EDJ: Eddy-driven jet; GOME: Global Ozone Monitoring Experiment; H03: Hudson et al. 2003; H06: Hudson et al. 2006; H12: Hudson 2012; NASA: National Aeronautics and Space Administration; NCEP-NCAR: National Centers for Environmental Prediction – National Center for Atmospheric Research; NH: Northern Hemisphere; NOAA: National Oceanic and Atmospheric Administration; OLR: Outgoing longwave radiation; OMI: Ozone monitoring instrument; PV: Potential vorticity; SH: Southern Hemisphere; SSE: Sum-of-square errors; STJ: Subtropical jet; TCO: Total column ozone; TOMS: Total ozone mapping spectrometer; TOVS: Tiros-N Operational Vertical Sounder; WOUDC: World Ozone and Ultraviolet Data Center

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Availability of data and materials

The ozone and reanalysis data used in this article were obtained from public data sources. Please contact the author for data requests related to the tropical width timeseries calculated from the ozone and reanalysis data.

Authors' contributions

KHR and SMD proposed the topic, conceived, and designed the study. BH implemented the TCO algorithm and assisted with the data analysis. All authors collaborated with the corresponding author in the construction of manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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