Tropical Width Impacts on the STratosphere (TWIST)

Abstract

Over the past ~5 years, the confusion regarding conflicting estimates of recent tropical widening based on different observational datasets (e.g. satellites, meteorological reanalyses) and climate model simulations has largely been resolved. Despite this recent progress, many new questions have emerged. One question in particular relates to the finding that there are two broad categories of tropical width metrics, referred to as "lower" and "upper" atmospheric metrics. While the "lower" atmospheric metrics co-vary with the Hadley cell edge, the "upper" metrics based on the subtropical jet and tropopause do not. The reason for the disconnect between "lower" and "upper" tropical edge metrics is currently unknown and is surprising given the expected connection between the tropospheric overturning circulation and subtropical jet.

The "upper" atmospheric category of metrics has been inadequately studied despite it being important for climate, since variability in the subtropical jet and tropopause characteristics affects transport and mixing of climatically important trace gases in the upper troposphere and lower stratosphere (UTLS), including water vapor and ozone. Indeed, satellite measurements indicate recent unexplained trends in lower stratospheric ozone and other trace gases, and changes in the regions of turbulent mixing near the subtropical jet have been implicated as a possible cause. The causes of such shifts in mixing zones are largely unexplained, and a major deficiency remains in our knowledge of the interrelationships between stratospheric transport and mixing, jet/tropopause properties, UTLS trace gas variability, and their relation to the tropospheric Hadley cells. The need to advance the fundamental understanding of these interrelationships motivates the proposed ISSI team.

Here we propose a project, TWIST (Tropical Width Impacts on the STratosphere), which tackles key research questions regarding the tropical width in the UTLS region. Specifically, the goals of TWIST are to: 1) identify robust satellite-observed metrics of tropical width in the UTLS region based on temperature structure and atmospheric composition, 2) characterize relationships between UTLS tropical width and tropospheric circulation, and 3) identify how these tropical width variations in the UTLS relate to variability and trends in trace gas concentrations and their impact on climate.

Background

The slow meridional overturning circulation of the stratosphere, commonly known as the Brewer-Dobson circulation [BDC, *Brewer*, 1949; *Dobson*, 1956], consists of upwelling air in the tropics and downwelling air at high latitudes that is driven by wave breaking in the stratosphere [*Butchart*, 2014]. The so-called "shallow branch" of the BDC (Fig. 1) in the lower stratosphere is driven by synoptic and planetary scale wave breaking in the subtropical lower stratosphere associated with the subtropical jet [STJ, *Birner and Bonisch*, 2011]. In addition to the shallow branch of the BDC that transports air poleward, there is a subtropical transport barrier region of reduced cross-latitudinal mixing associated with the STJ (Fig. 1). Both of these aspects of the stratospheric circulation play an important role in determining the distribution of radiatively active trace gases in the UTLS such as water vapor and ozone. Thus, stratospheric circulation changes can impact Earth's surface climate via their impact on the ozone layer and consequently on surface UV radiation levels [*Hegglin and Shepherd*, 2009], through stratosphere-troposphere exchange of ozone and related air quality issues [*Banerjee et al.*, 2016], and through direct radiative forcing due to changes in ozone and water vapor concentrations [*Banerjee et al.*, 2018; *Solomon et al.*, 2010].

A number of recent observational and modeling studies have identified increases in stratospheric tropical upwelling [*Butchart et al.*, 2006; *Fu et al.*, 2015; *Garcia and Randel*, 2008; *Li et al.*, 2008; *Lin and Fu*, 2013; *McLandress and Shepherd*, 2009], changes in stratospheric horizontal mixing [*Eichinger et al.*, 2019; *Garny et al.*, 2007], and shifts in the latitudes of the upwelling regions [*Stiller et al.*, 2017]. The cause of these changes is not known, but a leading hypothesis is that they are related to changes in the STJ caused by increases in greenhouse gases [*Garcia and Randel*, 2008].

Furthermore, recent satellite observational studies have suggested that lower stratospheric ozone continues to decline despite the start of ozone recovery in the upper stratosphere following the phasing out of ozone depleting substances under the Montreal Protocol [*Ball et al.*, 2018; *Ball et* *al.*, 2019]. Several studies have pointed towards changes in stratospheric circulation and mixing as the explanation, but models have produced widely varying results in their attempts to simulate the recent past [*Ball et al.*, 2018; *Chipperfield et al.*, 2018; *Wargan et al.*, 2018]. Changes in the strength of air upwelling into the tropical lower stratosphere and changes in the rate of transport and mixing from tropics to high latitudes could be contributors to these observed changes in lower stratospheric ozone. These changes may in turn be related to changes in "upper" tropical width metrics (see below). A detailed examination of observationally based metrics along with dynamical studies using global models is needed. Below, we provide an overview of tropical width in order to motivate the proposed ISSI study.

Tropical width overview

A significant body of literature has grown over the past decade showing evidence of changes in the zonal-mean atmospheric circulation including the position and strength of the Hadley cell and the jet streams [e.g., *Birner et al.*, 2014; *Lucas et al.*, 2014; *Staten et al.*, 2018, and references therein]. A number of these studies identified poleward movement in the tropical-extratropical boundary; a phenomenon that has been referred to as "tropical widening" [*Seidel et al.*, 2008].

If the tropical belt expands, there will be dramatic shifts in regional surface climates in the subtropics, particularly precipitation, with important societal and ecological consequences [*Heffernan*, 2016]. In addition to potentially adverse impacts related to shifts in the subtropical dry zones and changes in mid-latitude droughts, tropical widening will also alter the spatial distribution of mid-latitude winds, driving changes in ocean salinity and circulation, ocean uptake of carbon dioxide, and ocean-cryosphere interactions [*Roemmich et al.*, 2007; *Waugh et al.*, 2013].

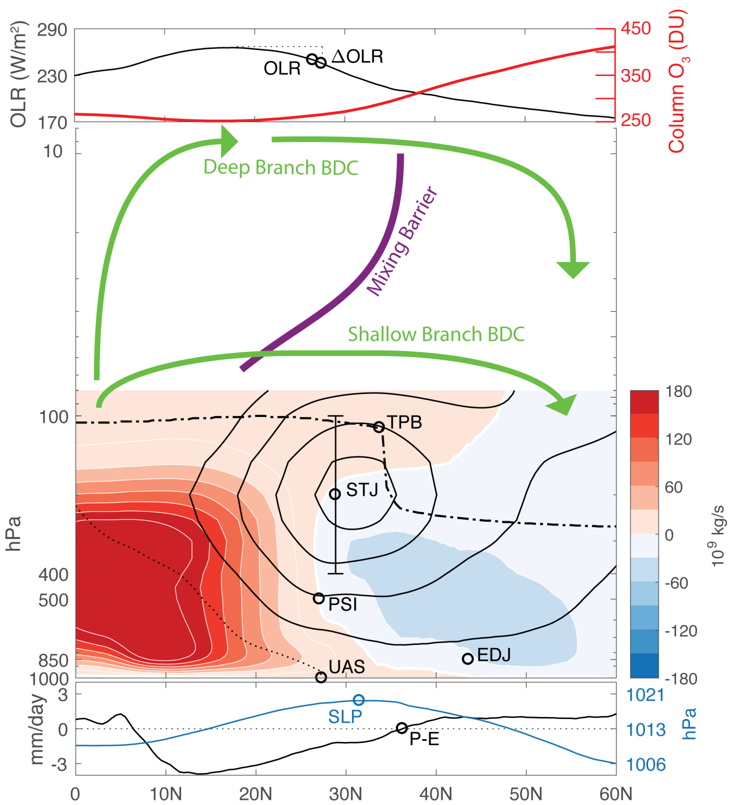

Figure 1. A subset of the metrics used to define the tropical edge latitude in satellite observations and reanalyses, adapted from *Waugh et al.* [2018]. (top) outgoing longwave radiation and total column ozone; (middle) schematic of Brewer-Dobson circulation transport and mixing barriers, zonal winds (black contours; zero: dotted curve), meridional streamfunction (color shading), and tropopause (dot–dashed curve); and (bottom) sea level pressure (blue) and P-E (black). Based on MERRA-2 for February 2002.

Given the ways by which changes in the width of the tropics could impact society, it is important to quantify any significant changes that have occurred and to understand their causes and impacts. In the past decade, tropical widening estimates – based on satellite observations, *in situ* measurements, and meteorological reanalyses – spanned an order of magnitude, ranging from a tenth of a degree to several degrees latitude per decade [*Davis and Rosenlof*, 2012]. Because these tropical widening estimates were computed from a wide variety of metrics and data sources (Fig. 1), and from different time periods, it was not clear to what extent the large range of estimates in the literature represented differing physics or some deeper problem in constraining past changes. Furthermore, early analyses suggested that observed tropical widening was greater than predicted by climate model simulations [*Johanson and Fu*, 2009], which called into question both our understanding of past changes and the ability to simulate future changes.

These large disagreements and the associated uncertainty surrounding past tropical width changes were the prime motivator of the ISSI Tropical Width Diagnostics Intercomparison Project (TWDIP) that began in 2016 and ended in 2018. The primary goal of TWDIP was to understand the different model- and observation-based metrics used to estimate tropical widening, in order to better constrain past changes and provide clarity on what metrics constitute a robust measure of the tropics. To understand the context for TWIST, a brief overview of tropical width metrics is given below.

At the most fundamental level, tropical width metrics are intended to quantify the latitudes of the poleward boundaries of the Hadley cells. The Hadley cells are thermally direct overturning circulations in the latitude-height plane, with air rising near the equator, flowing poleward at upper levels, sinking in the subtropics, and flowing back toward the equator near the surface. The most direct metric of the Hadley cell edges is given by the latitude where the direction of rotation of the mean meridional circulation changes sign (PSI, Fig. 1). Related to the Hadley cell and more relevant to surface climate impacts is the location where precipitation (P) equals evaporation (E) on the poleward edge of the Hadley cell (P-E, Fig. 1). Other surface-focused metrics include the sea-level pressure maximum (SLP) and the surface wind transition from easterlies to westerlies (UAS).

Neglecting the influence of eddies, the STJ cores would coincide with the Hadley cell edges. Several studies have thus used satellite-based UTLS temperature measurements as a measure of the STJ [*Fu et al.*, 2006; *Fu and Lin*, 2011], and others have used winds from reanalyses [e.g., *Archer and Caldeira*, 2008; *Strong and Davis*, 2007]. Associated with the STJ is an abrupt drop in tropopause height between the tropics and mid-latitudes, which has also been used to demarcate the tropical edge [*Birner*, 2010; *Davis and Birner*, 2013; *Davis and Rosenlof*, 2012; *Seidel and Randel*, 2007]. Tropopause metrics have been derived with temperature data from reanalyses, radiosondes, and Global Navigation System Satellite Radio Occultation (GNSS-RO) signals [*Davis and Birner*, 2013].

To avoid reliance on reanalysis fields that are constrained by observational input but susceptible to unphysical jumps [*Fujiwara et al.*, 2017; *Long et al.*, 2017], studies have also estimated tropical width and widening from satellite observations that are nominally measuring some aspect of the Hadley cell, tropopause, and/or STJ. Examples include outgoing longwave radiation [OLR, *Hu and Fu*, 2007], the location of clouds and precipitation [*Bender et al.*, 2012; *Feng and Fu*, 2013; *Zhou et al.*, 2011], the region of ‘‘tropical’’-like low total column ozone amount [*Hudson et al.*, 2006; *Hudson*, 2012], and latitudinal gradients in stratospheric water vapor and methane concentration fields [*Rosenlof*, 2002].

Recent progress in understanding tropical width

Starting in 2016, ISSI TWDIP group members published a series of papers [*Davis and Birner*, 2017; *Solomon et al.*, 2016; *Waugh et al.*, 2018] suggesting that tropical width metrics could be loosely divided into two groups—one that correlates well with the Hadley cell edge (so-called "lower" metrics), and one that relates more to the STJ and tropopause ("upper" metrics). It is now clear that the mixing of the different types of metrics has been one of the dominant contributors to the large range of tropical widening estimates [*Waugh et al.*, 2018]. In our ISSI-supported review paper, the range of tropical widening trends has thus been narrowed substantially, from ~0.1 – 3° latitude decade^{-1} in the early 2010's to ~0.5° decade^{-1} [*Staten et al.*, 2018]. ISSI TWDIP work has also convincingly demonstrated that the previously noted model-observational discrepancy in tropical widening rates resulted largely from natural climate variability [*Grise et al.*, 2019].

In addition to identifying robust tropical width definitions and solving several outstanding issues related to tropical widening, TWDIP created the freely available open source TropD software package [https://zenodo.org/record/1157044, *Adam et al.*, 2018]. TropD includes well-documented code for computing tropical width diagnostics from gridded model output, and includes a set of validation data with which users can verify their own calculations.

Although TWDIP answered a number of important questions regarding recent tropical widening, it also identified several major new questions surrounding the interpretation of the STJ/tropopause metrics. Namely, if these metrics don't co-vary with the Hadley cell edges, what drives them? To what extent are they related to or indicative of the stratospheric circulation and processes occurring in the UTLS rather than near the surface? How will the STJ/tropopause metrics vary with climate change, and what are the potential feedbacks? How might these features impact the distribution of climatically important trace gases in the stratosphere?

Proposed Work

Given the importance of stratospheric ozone and water vapor for climate and health, it is critical to understand the interaction between stratospheric dynamics and changes in the tropospheric circulation that may be driving changes in these species. To address these issues, the ISSI TWIST project will focus on 3 scientific topics:

1. Identifying robust satellite-observed metrics of tropical width in the UTLS

There have been a number of ways of defining the tropical width using STJ and tropopause proxies from both satellite observations and meteorological reanalyses. Here, we seek to define new satellite-observed metrics of tropical width that relate to circulation in the upper troposphere and lower stratosphere (UTLS). This work will include a broad analysis of the stratospheric circulation encompassing tropical upwelling strength, tropical-midlatitude mixing strength, the location of the maximum meridional tracer gradients between the tropics and higher latitudes, and the turnaround latitudes of the stratospheric circulation, where the mean-meridional stratospheric circulation reverses from upward to downward, hearkening back to work done in one of the first papers on tropical widening [*Rosenlof*, 2002].

This work will involve analysis of satellite constituent data from multiple sources, including SF_6 and CO_2 as a proxy for age-of-air [*Ray et al.*, 2014], with the hope of establishing how these types of satellite measurements can be leveraged as a metric for stratospheric circulation change. It will also involve analyzing latitudinal gradients in ozone, as done in several previous studies [*Davis et al.*, 2018; *Hudson*, 2012], and will consider other relevant species measured by satellite that exhibit changes with the length of time spent in the stratosphere. Ultimately, we want to understand how the stratospheric "tropical pipe" region connects to the STJ/tropopause and tropospheric circulation by identifying sharp gradients in satellite-measured trace species.

We will also consider variations in temperature structure in this region, as they are well observed by satellites. One key question is whether the decades-long satellite tropical width metrics based on UTLS temperature from the Microwave Sounding Unit (MSU) and Advanced MSU (AMSU) are reflective of STJ variability or are more related to other measures and causes of stratospheric variability. Also, we will examine Global Navigation Satellite System Radio Occultation (GNSS-RO) temperature and wind data both for tropopause studies and for STJ characterization using balanced winds derived from GNSS-RO [*Davis and Birner*, 2016; *Verkhoglyadova et al.*, 2014]. A key question we want to answer is how these various satellite-observed UTLS metrics relate to one another, and how they relate to the previously used "upper" and "lower" metrics identified by the work done as part of ISSI TWDIP. Modeling work will come into play here as well, in that we want to identify what the forcers are for change in the "upper" metrics and what the connections are between the "lower" and "upper" metrics.

2. Characterizing relationships between UTLS tropical width and circulation

Because the "upper" tropical width metrics are defined using variables in the upper troposphere and lower stratosphere (e.g., upper tropospheric winds), their changes may relate more to changes in the lower stratosphere than in the troposphere [*Lin et al.*, 2015]. Following the methodology set out [*Waugh et al.*, 2018] and using metrics from the TropD software, we will investigate potential correlations between the upper metrics (tropopause/STJ/OLR/ozone) and the stratospheric circulation.

We will also investigate how the newly identified UTLS metrics relate to tropospheric circulation. Recent work suggests that STJ strength (rather than latitude) covaries with the Hadley cell edges [*Menzel et al.*, submitted]. Additional work in progress by members of our team suggests that the STJ position possibly varies with Hadley cell overturning strength. We seek to clarify these relationships, and also consider how they relate to other UTLS metrics. Additionally, we will further clarify the relation between UTLS metrics and the height of the tropopause, which is well measured by the GNSS constellation of satellites. We want to know if these relationships identified for the STJ hold for tropopause parameters.

3. Identifying how tropical width variations in the UTLS relate to variability and trends in trace gas concentrations

We seek to understand how the UTLS metrics relate to the distribution of trace gases, particularly ozone and water vapor. The idea here is to investigate the extent to which the recent variability/trends in lower stratospheric ozone can be explained by variations in STJ strength and the associated BDC and mixing pathways. So far, studies attempting to understand STJ-related variability and their role in driving variability/trends in trace gases have relied heavily on models. Here, we plan to use tropical width metrics derived from the 20+ years record of climate-quality GNSS-RO and MSU/AMSU data in conjunction with the long-term satellite records of stratospheric water vapor and ozone put together by members of our team [*Davis et al.*, 2016]. This is novel in that there are no existing observational studies showing the relevant changes in dynamics to explain the observed ozone changes.

What added value does ISSI and/or ISSI-BJ provide for the implementation of the team activity?

ISSI support of this project will allow a diverse group of scientists, including those with expertise in theory, modeling, and satellite data analysis, to interface in order to meet the stated objectives of this proposal. This project will build upon the outcomes of the previous ISSI TWDIP team, as all but one of the members of the current team were also members of the ISSI TWDIP team. The previous ISSI TWDIP meetings proved extremely valuable because we were able to work as a small group, rather than merely presenting work as is typically done at scientific conferences.

List of confirmed members

Sean M. Davis (Team Leader, NOAA ESRL, USA), Marta Abalos (Universidad Complutense de Madrid, Spain), Thomas Birner (Univ. of Munich, Germany), Nicholas Davis (NCAR, USA), Qiang Fu (Univ. of Washington, USA), Hella Garny (DLR IPA, Germany), Amanda Maycock (Univ. of Leeds, UK), Alison Ming (British Antarctic Survey, UK), Karen H. Rosenlof (NOAA ESRL, USA), Seok Woo Son (Seoul Natl. Univ., S. Korea), Gabriele Stiller (KIT, Germany), Darryn Waugh (Johns Hopkins Univ., USA)

Schedule of the project

We plan two 5-day meetings in Bern. All team participants have indicated a willingness and ability to travel to these meetings. Before the first meeting, participants will update reanalysis STJ/tropopause tropical width timeseries, compute candidate UTLS tropical width timeseries, and do preliminary work to understand the dynamics/composition relationships. The meeting will include overview presentations of existing work related to the main themes. The majority of the time will be reserved for discussing the details of gaps in our knowledge, and coming up with a research plan for the first year. A plan for analysis of satellite and model output data will be agreed upon during the first meeting.

Before the second meeting, the analyses will be undertaken and rough drafts of manuscripts (one for each theme) will be prepared before the meeting. Group members will make presentations on their findings at the second meeting. At this meeting we will finalize the writing and a work plan for any remaining analyses to be completed shortly after the meeting.

Facilities required

We will need a meeting room for the team with internet access and a projector for presentations. We will also need a website and associated IT support.

Financial support requested

We request hotel and per diem for 12 team members plus two additional young scientists that we hope to add to the team at a later date in accordance with the proposal guidelines. Per diem will be needed for approximately 6 days for each participant for each of two meetings, and travel support for either the team leader or a designated participant.

Expected output

We expect that this activity will result in three team papers that will address the major themes related to new observational metrics of stratospheric tropical width, how they relate to tropospheric and stratospheric circulation, and how they relate to observed stratospheric composition changes. We also expect additional publications written by team members on more technical topics related to the major themes. Finally, we plan to share any relevant model output and analyses generated by the group. These data will support ongoing community activities, including the WMO ozone and IPCC assessments. The TropD software package that we created as part of ISSI TWDIP has been widely used in the community, and we expect that any relevant new metrics identified as part of this group will be added to an updated version of TropD.

The work of this group will improve upon the previous efforts at characterizing tropical width by leveraging the experience of ISSI TWDIP. As the relation between the “upper” and “lower” metrics is currently unknown, this group should be able to make a significant advance in the field by leveraging the opportunity provided by ISSI to bring together a diverse group of scientists spanning the fields of theory, modeling, and satellite observations.

References (* indicates ISSI team member authorship on paper)

*Adam, O., et al. (2018), The TropD software package (v1): standardized methods for calculating tropical-width diagnostics, *Geosci Model Dev*, *11*(10), 4339-4357.

Archer, C. L., and K. Caldeira (2008), Historical trends in the jet streams, *Geophys Res Lett*, *35*(8), L08803.

*Ball, W. T., et al. (2018), Evidence for a continuous decline in lower stratospheric ozone offsetting ozone layer recovery, *Atmos Chem Phys*, *18*(2), 1379-1394.

*Ball, W. T., et al. (2019), Stratospheric ozone trends for 1985–2018: sensitivity to recent large variability, *Atmos. Chem. Phys. Discuss.*, *2019*, 1-27.

*Banerjee, A., et al. (2016), Drivers of changes in stratospheric and tropospheric ozone between year 2000 and 2100, *Atmos Chem Phys*, *16*(5), 2727-2746.

*Banerjee, A., et al. (2018), Chemical and climatic drivers of radiative forcing due to changes in stratospheric and tropospheric ozone over the 21st century, *Atmos Chem Phys*, *18*(4), 2899-2911.

Bender, F. A. M., et al. (2012), Changes in extratropical storm track cloudiness 1983-2008: observational support for a poleward shift, *Clim Dynam*, *38*(9-10), 2037-2053.

*Birner, T. (2010), Recent widening of the tropical belt from global tropopause statistics: Sensitivities, *Journal of Geophysical Research-Atmospheres*, *115*(D23).

*Birner, T., and H. Bonisch (2011), Residual circulation trajectories and transit times into the extratropical lowermost stratosphere, *Atmos Chem Phys*, *11*(2), 817-827.

*Birner, T., et al. (2014), The changing width of Earth's tropical belt, *Phys Today*, *67*(12), 38-44.

Brewer, A. W. (1949), Evidence for a World Circulation Provided by the Measurements of Helium and Water Vapour Distribution in the Stratosphere, *Quarterly Journal of the Royal Meteorological Society*, *75*(326), 351-363.

Butchart, N., et al. (2006), Simulations of anthropogenic change in the strength of the Brewer-Dobson circulation, *Clim Dynam*, *27*(7-8), 727-741.

Butchart, N. (2014), The Brewer-Dobson circulation, *Rev Geophys*, *52*(2), 157-184.

Chipperfield, M. P., et al. (2018), On the Cause of Recent Variations in Lower Stratospheric Ozone, *Geophysical Research Letters*, *45*(11), 5718-5726.

*Davis, N., and T. Birner (2016), Climate Model Biases in the Width of the Tropical Belt, *Journal of Climate*, *29*(5), 1935-1954.

*Davis, N., and T. Birner (2017), On the Discrepancies in Tropical Belt Expansion between Reanalyses and Climate Models and among Tropical Belt Width Metrics, *Journal of Climate*, *30*(4), 1211-1231.

*Davis, N. A., and T. Birner (2013), Seasonal to multidecadal variability of the width of the tropical belt, *J Geophys Res-Atmos*, *118*(14), 7773-7787.

*Davis, S. M., and K. H. Rosenlof (2012), A Multidiagnostic Intercomparison of Tropical-Width Time Series Using Reanalyses and Satellite Observations, *Journal of Climate*, *25*(4), 1061-1078.

*Davis, S. M., et al. (2016), The Stratospheric Water and Ozone Satellite Homogenized (SWOOSH) database: a long-term database for climate studies, *Earth Syst Sci Data*, *8*(2), 461-490.

*Davis, S. M., et al. (2018), Revisiting ozone measurements as an indicator of tropical width, *Prog Earth Planet Sc*, *5*.

Dobson, G. M. B. (1956), Origin and Distribution of the Polyatomic Molecules in the Atmosphere, *Proc R Soc Lon Ser-A*, *236*(1205), 187-193.

*Eichinger, R., et al. (2019), The influence of mixing on the stratospheric age of air changes in the 21st century, *Atmos Chem Phys*, *19*(2), 921-940.

*Feng, S., and Q. Fu (2013), Expansion of global drylands under a warming climate, *Atmos Chem Phys*, *13*(19), 10081-10094.

*Fu, Q., et al. (2006), Enhanced mid-latitude tropospheric warming in satellite measurements, *Science*, *312*(5777), 1179-1179.

*Fu, Q., and P. Lin (2011), Poleward Shift of Subtropical Jets Inferred from Satellite-Observed Lower-Stratospheric Temperatures, *Journal of Climate*, *24*(21), 5597-5603.

*Fu, Q., et al. (2015), Observational evidence of strengthening of the Brewer-Dobson circulation since 1980, *J Geophys Res-Atmos*, *120*(19), 10214-10228.

*Fujiwara, M., et al. (2017), Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, *Atmos Chem Phys*, *17*(2), 1417-1452.

Garcia, R. R., and W. J. Randel (2008), Acceleration of the Brewer-Dobson circulation due to increases in greenhouse gases, *J Atmos Sci*, *65*(8), 2731-2739.

*Garny, H., et al. (2007), Trends and variability in stratospheric mixing: 1979-2005, *Atmos Chem Phys*, *7*(21), 5611-5624.

*Grise, K. M., et al. (2019), Recent Tropical Expansion: Natural Variability or Forced Response?, *Journal of Climate*, *32*(5), 1551-1571.

Heffernan, O. (2016), The Mystery of the Expanding Tropics, *Nature*, *530*(7588), 21-23.

Hegglin, M. I., and T. G. Shepherd (2009), Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux, *Nature Geoscience*, *2*(10), 687-691.

*Hu, Y., and Q. Fu (2007), Observed poleward expansion of the Hadley circulation since 1979, *Atmos Chem Phys*, *7*(19), 5229-5236.

Hudson, R. D., et al. (2006), The total ozone field separated into meteorological regimes - Part II: Northern Hemisphere mid-latitude total ozone trends, *Atmos Chem Phys*, *6*, 5183-5191.

Hudson, R. D. (2012), Measurements of the movement of the jet streams at mid-latitudes, in the Northern and Southern Hemispheres, 1979 to 2010, *Atmos Chem Phys*, *12*(16), 7797-7808.

*Johanson, C. M., and Q. Fu (2009), Hadley Cell Widening: Model Simulations versus Observations, *J Climate*, *22*(10), 2713-2725.

Li, F., et al. (2008), The strength of the Brewer-Dobson circulation in a changing climate: Coupled chemistry-climate model simulations, *Journal of Climate*, *21*(1), 40-57.

*Lin, P., and Q. Fu (2013), Changes in various branches of the Brewer-Dobson circulation from an ensemble of chemistry climate models, *J Geophys Res-Atmos*, *118*(1), 73-84.

Lin, P., et al. (2015), Tropical climate change control of the lower stratospheric circulation, *Geophysical Research Letters*, *42*(3), 941-948.

*Long, C. S., et al. (2017), Climatology and interannual variability of dynamic variables in multiple reanalyses evaluated by the SPARC Reanalysis Intercomparison Project (S-RIP), *Atmos Chem Phys*, *17*(23), 14593-14629.

Lucas, C., et al. (2014), The expanding tropics: a critical assessment of the observational and modeling studies, *Wires Clim Change*, *5*(1), 89-112.

McLandress, C., and T. G. Shepherd (2009), Simulated Anthropogenic Changes in the Brewer-Dobson Circulation, Including Its Extension to High Latitudes, *Journal of Climate*, *22*(6), 1516-1540.

*Menzel, M. E., et al. (submitted), Relationships between the Hadley Cell and Subtropical Jet, *J Climate*.

*Ray, E. A., et al. (2014), Improving stratospheric transport trend analysis based on SF6 and CO2 measurements, *J Geophys Res-Atmos*, *119*(24), 14110-14128.

Roemmich, D., et al. (2007), Decadal spinup of the South Pacific subtropical gyre, *J Phys Oceanogr*, *37*(2), 162-173.

*Rosenlof, K. H. (2002), Transport changes inferred from HALOE water and methane measurements, *J Meteorol Soc Jpn*, *80*(4B), 831-848.

Seidel, D. J., and W. J. Randel (2007), Recent widening of the tropical belt: Evidence from tropopause observations, *J Geophys Res-Atmos*, *112*(D20), D20113.

*Seidel, D. J., et al. (2008), Widening of the tropical belt in a changing climate, *Nat Geosci*, *1*(1), 21-24.

*Solomon, A., et al. (2016), Contrasting upper and lower atmospheric metrics of tropical expansion in the Southern Hemisphere, *Geophys Res Lett*, *43*(19), 10496-10503.

*Solomon, S., et al. (2010), Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming, *Science*, *327*(5970), 1219-1223.

*Staten, P. W., et al. (2018), Re-examining tropical expansion, *Nature Climate Change*, *8*(9), 768-775.

*Stiller, G. P., et al. (2017), Shift of subtropical transport barriers explains observed hemispheric asymmetry of decadal trends of age of air, *Atmos Chem Phys*, *17*(18), 11177-11192.

Strong, C., and R. E. Davis (2007), Winter jet stream trends over the Northern Hemisphere, *Q J Roy Meteor Soc*, *133*(629), 2109-2115.

Verkhoglyadova, O. P., et al. (2014), Estimation of Winds from GPS Radio Occultations, *J Atmos Ocean Tech*, *31*(11), 2451-2461.

Wargan, K., et al. (2018), Recent Decline in Extratropical Lower Stratospheric Ozone Attributed to Circulation Changes, *Geophysical Research Letters*, *45*(10), 5166-5176.

*Waugh, D. W., et al. (2013), Recent Changes in the Ventilation of the Southern Oceans, *Science*, *339*(6119), 568-570.

*Waugh, D. W., et al. (2018), Revisiting the Relationship among Metrics of Tropical Expansion, *Journal of Climate*, *31*(18), 7565-7581.

Zhou, Y. P., et al. (2011), Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data, *J Geophys Res-Atmos*, *116*.