A Tropical Width Diagnostics Intercomparison Project

Abstract

Many important features of Earth's large-scale atmospheric circulation are connected to the width of the "tropical belt", including the locations of the subtropical dry zones and midlatitude jet streams. These phenomena exert a strong influence on regional surface climates in both hemispheres, and even small changes in their position can thus have important societal and ecological consequences. It is therefore crucial to understand whether there have been changes in the width of the tropical belt over the recent past, and, if so, what factors have contributed to these changes.

There is growing evidence that "tropical widening" has occurred over the past ~40 years. However, there is an order of magnitude disagreement among published rates of tropical widening, which range from a few tenths up to several degrees latitude per decade. It is unclear whether this large range reflects differing physical aspects of the atmosphere, the use of different methodologies to define the tropical belt, or the use of different observational datasets (e.g. satellite, in situ datasets, meteorological reanalyses) and time periods. Furthermore, even the median of the historical tropical widening estimates exceeds the tropical widening rates predicted by global climate model (GCM) simulations of the recent past, which calls into question the basic understanding of this phenomenon.

These outstanding issues motivated a recent American Geophysical Union Chapman Conference on "The Width of the Tropics: Climate Variations and Their Impacts" in 2015 [*Davis et al.*, in press]. A key recommendation from the meeting is that the interrelationships between the diverse array of tropical width metrics used in the literature need to be better understood in order to explain the discrepancy among past tropical widening estimates and to provide clarity regarding future projections. The proposed ISSI team will fulfill this goal by conducting the first systematic intercomparison of tropical width diagnostics.

In the first phase of this project we will identify the set of tropical width diagnostics and GCM simulations that will provide the basis of the intercomparison. Because tropical width diagnostics have been computed from disparate data sources including radiosonde measurements, satellite observations, and meteorological reanalyses, we will perform a new set of GCM simulations with the specialized output necessary to compute and robustly compare all previously used and proposed diagnostics. These simulations will provide a self-consistent data source for analysis, and will include as output the information necessary to simulate diagnostics based on satellite measurements.

The second phase of the project will center on comparing climatological position, seasonality, interannual variability, and correlation among the tropical width metrics using the GCM simulations. A key outcome of this activity will be to clarify which tropical width metrics are closely related and which are not, with a focus on interpreting the relationships in the context of the physical processes they represent. The ISSI team will produce a review paper aimed at the broader climate science community that describes the robustness and interpretation of tropical width diagnostics for studies of atmospheric circulation changes. The recommended metrics will be applied to reanalyses and satellite observations, and made available to the scientific community for model evaluation and other studies.

Background

The past decade has witnessed increasing scientific focus on detailed aspects of tropical climate at and above the Earth's surface, specifically on the location of the boundary between the tropical and extratropical zones. A growing body of literature addresses the possibility of changes in the position and strength of the Hadley cell, jet streams, and zonal-mean atmospheric circulation [e.g., *Birner et al.*, 2014; *Lucas et al.*, 2014 and references therein]. A number of studies have identified poleward movement in the tropical-extratropical boundary;

this phenomenon has been referred to as "tropical widening" or "expansion of the tropical belt" [*Seidel et al.*, 2008].

An expanded tropical belt could cause dramatic changes in surface climate, particularly precipitation, and have 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 may also relate to shifts in mid-latitude winds that can drive changes in ocean circulation, ocean uptake of carbon dioxide, and ocean-cryosphere interactions [*Roemmich et al.*, 2007; *Waugh et al.*, 2013].

Given the potential implications of changes in the width of the tropics for societies, it is important to quantify any changes that have occurred. In the past decade or so, a large range of estimates for tropical widening has been published. Values ranging from a few tenths and up to several degrees latitude per decade have been estimated using a variety of physical diagnostics applied to multiple data sets including satellite observations, in situ measurements, and meteorological reanalyses (see Fig. 1).

These large disagreements and the associated uncertainty surrounding past tropical width changes are the prime motivator of this proposed ISSI team project. Even the median observed tropical widening estimates are well above the range predicted by global climate model (GCM) simulations [e.g., *Davis and Rosenlof*, 2012; *Johanson and Fu*, 2009], which calls into question the ability of these models to simulate future changes. It is therefore critical to understand the sources of the current spread in estimates of tropical widening.

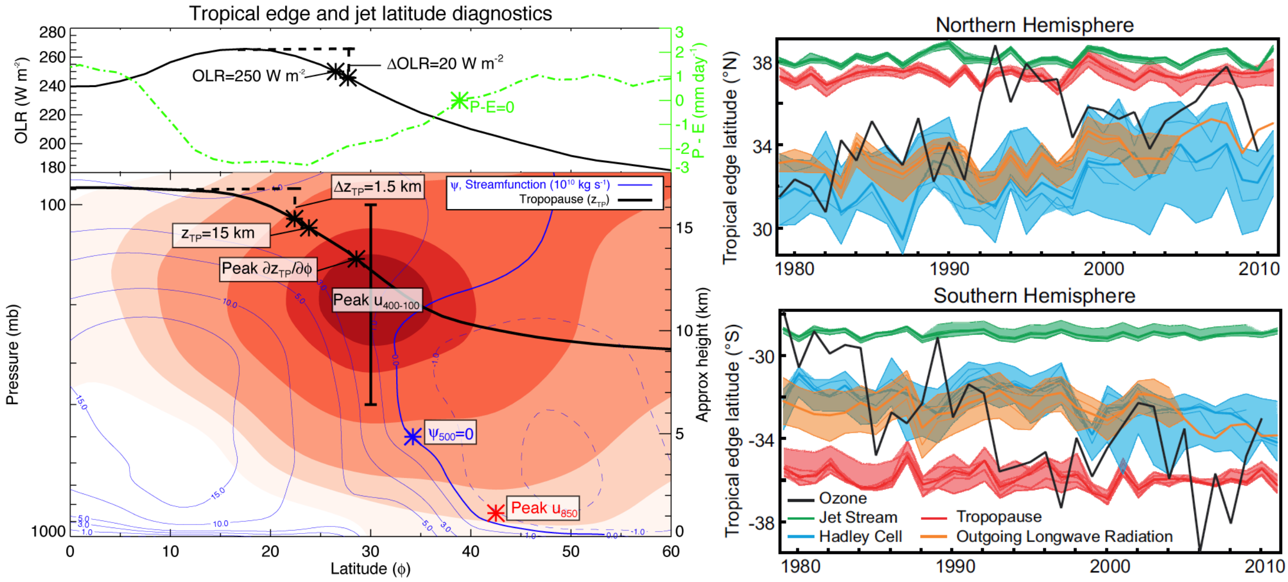

Figure 1. (Left) A subset of the metrics used to define the tropical edge latitude in satellite observations and reanalyses, from Davis and Rosenlof [2012]. (Right) Example tropical edge latitude timeseries, from the IPCC AR5 [Fig 2.40, Hartmann et al., 2013], as reproduced in Birner et al. [2014]. Different colors are different metrics, thin lines represent individual datasets, and thick lines are the median over all datasets.

A major barrier to understanding tropical widening uncertainties is that the tropical belt has been defined using a myriad of metrics (a subset of which are shown in Fig. 1), and not all metrics can be applied to the same observational data sets. A brief discussion of these metrics is given here in order to further motivate the proposed study.

Most tropical width metrics relate directly or indirectly to the poleward boundary of the Hadley cell. The Hadley cell is a thermally direct overturning circulation 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 tropical edge latitudes of the Hadley cell measure the boundaries in each hemisphere between the tropical and extratropical circulations. Numerous studies have defined these latitudes using the zero crossing of the mean meridional streamfunction (ψ_{500}=0, see blue asterisk and lines in Fig. 1), which denotes the location where the sense of overturning of the circulation changes. Although this definition is conceptually straightforward, the zero-crossing latitudes have been defined in several different ways, including at a single level in the troposphere [typically 500 hPa, *Frierson et al.*, 2007; *Lu et al.*, 2007] and averaged over a vertical layer [*Davis and Birner*, 2013; *Stachnik and Schumacher*, 2011]. Furthermore, there are currently ~10 global reanalyses, which in general contain differing amounts of tropical widening [*Davis and Rosenlof*, 2012].

One key drawback of ψ is that it can only be calculated from a well-defined wind field provided from a global model (i.e., from a reanalysis or GCM). Because of this, satellite observation-based studies have used other quantities associated with the Hadley cell edges, such as outgoing longwave radiation [*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 the distribution of stratospheric water vapor/methane concentrations [*Rosenlof*, 2002].

Neglecting the influence of extratropical eddies, Hadley cell properties (e.g., width) are primarily determined by the rotation rate of the planet and the equator-to-pole temperature contrast [*Schneider*, 2006], and under this assumption the subtropical jet cores would mark the Hadley cell edges (red contours in Fig. 1). Several studies have thus used the subtropical jet location as a tropical edge diagnostic. Satellite-based temperature measurements have been used [*Fu et al.*, 2006; *Fu and Lin*, 2011], as have reanalysis winds [e.g., *Archer and Caldeira*, 2008; *Strong and Davis*, 2007]. Additionally, the location of the subtropical ridge has been used to identify tropical widening in surface pressure observations [*Choi et al.*, 2014].

Associated with the subtropical jet, the edge latitudes of the tropical belt may also be determined through the subtropical tropopause break — a large and abrupt drop in tropopause height between the tropical and mid-latitude tropopause [*Birner*, 2010; *Davis and Birner*, 2013; *Davis and Rosenlof*, 2012; *Seidel and Randel*, 2007; see black line in Fig. 1]. As with the streamfunction diagnostic, the tropopause metrics are primarily derived from reanalysis fields. Thus, a related satellite-based metric has been used based on the latitude of maximum tropospheric dry bulk stability from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) GPS radio occultation data [*Davis and Birner*, 2013].

Given the myriad of ways the tropical belt has been defined, it is not clear whether the large range of tropical widening estimates from ~0.1 – 3° latitude decade^{-1} over the last several decades reflects the differing physical properties measured by different definitions of the tropical belt edge location (e.g., definitions based on surface vs. upper-air parameters), subtle differences among methodologies, differences among datasets, or the difference between the hemispheres, seasons, and time periods studied.

The large uncertainties surrounding the magnitude of past tropical width changes raise issues for attributing changes to potential anthropogenic drivers, which could include increases in well-mixed greenhouse gases [*Lu et al.*, 2009], increases in tropospheric pollution such as ozone and black carbon [*Allen et al.*, 2012], and stratospheric ozone depletion [*Polvani et al.*, 2011; *Son et al.*, 2010]. Additionally, unforced internal variability from the ocean and atmosphere may be an important factor operating on decadal scales [*Adam et al.*, 2014; *Garfinkel et al.*, 2015]. These drivers are diverse in their spatial/seasonal heterogeneity and contrasting in their expected future evolution, so they may have distinctive seasonal and hemispheric impacts on different tropical edge metrics. The poor understanding around the relative magnitude of forced and unforced variations in tropical width over the recent past poses a significant limitation for making projections of future changes.

With these numerous uncertainties surrounding tropical widening as a backdrop, an American Geophysical Union Chapman Conference on "The Width of the Tropics: Climate Variations and their Impacts" was convened in July 2015 [*Davis et al.*, in press]. A key recommendation arising from discussions at the meeting was that the interrelationships between tropical width diagnostics need to be better understood in order to explain the large range of past tropical widening estimates, to explain why they are apparently greater than expectations from GCM simulations, and to provide clarity regarding future projections.

At the meeting, a group of interested parties was formed with the purpose of addressing the tropical width diagnostics issue through an intercomparison using GCM output, in order to facilitate a diagnostics intercomparison from a self-consistent data source. This ISSI project constitutes the expansion of that group into a formal intercomparison project. The project will consist of two phases, which are outlined below.

Phase 1: Identifying the metrics and model simulations

As discussed above, there are numerous methods and data sources from which the tropical edge latitudes may be computed. In the first phase of this project, we will identify a comprehensive set of tropical width diagnostics, including those that have been previously computed from satellite data, radiosonde data, and reanalyses. Additionally, we will consider novel atmospheric composition-based diagnostics of tropical width [e.g., based on ozone concentration or long-lived atmospheric tracers, *Palazzi et al.*, 2011] that might be applied to existing or future satellite measurements for the purpose of measuring tropical widening independently of reanalyses, which can be subject to artificial discontinuities and unreliable long-term trends.

We will then identify the GCM model output that is needed in order to compute these metrics. For some metrics, identifying the necessary output is a trivial task. For other metrics, such as those based on satellite measurements, this task is not trivial because it involves emulating complex weighting functions and orbital sampling patterns.

After identifying the diagnostics and the model output necessary to compute them, we will decide upon the GCM simulations to be performed. Our team includes members with expertise in a number of models, including the German EMAC model (Garny), the NCAR CESM/WACCM model (Davis), the NASA GEOSCCM model (Waugh), and the UK Met Office's HadGEM model (Maycock). Team members have indicated their ability to leverage existing computing allocations to devote to proposed simulations, data storage, and data sharing.

Beyond the required output variables and their spatial/temporal properties, there are a number of details regarding the simulations that will be decided at the first meeting, such as whether or not to run time-slice simulations vs. transient simulations, coupled vs. atmosphere-only simulations, historical vs. future simulations, single forcing (e.g., GHG only, stratospheric ozone depletion only) vs. multiple forcings, free-running vs. specified dynamics, etc. Other choices will include which models to run or whether only one model should be run, and whether or not ensemble runs need to be performed. Also, it will be decided whether or not an existing set of model runs could provide the foundation for an analysis (e.g., the NCAR CESM large ensemble or CMIP5 runs) on which only a subset of metrics are analyzed. If so, additional simulations could be performed in order to complement the existing set of runs.

Phase 2: Analysis of GCM output and observations

At the first meeting, the diagnostics will be settled upon and GCM simulations planned. After this meeting, the GCM simulations will be performed and members of the team will compute the tropical edge latitude diagnostics. These same diagnostics will be applied to existing reanalyses and satellite observations, leveraging previous work that has been performed by members of the team. We expect to create a shared database of tropical edge latitude timeseries for analysis.

Team members will analyze correlations between the diagnostics as a function of season and hemisphere in order to identify which of those diagnostics are related and which are not, and to clarify their physical meaning. Our team will also be able to attribute past changes to individual drivers and unforced variability using data from the targeted GCM simulations. We will also attempt to resolve the wide range of decadal-scale trends reported in the literature by intercomparing trends from all the metrics and datasets used, and assessing the robustness of previously used methodologies.

One expected outcome of this meeting is a set of recommendations regarding the use of tropical width diagnostics, which will form the basis for a review paper that we will write. These recommendations may be applicable to other aspects of Earth's circulation (e.g., mid-latitude jets, the stratospheric Brewer-Dobson circulation), and will support complementary efforts of a recently formed U.S. CLIVAR working group (led by two ISSI team members, Staten and Grise) to understand the causes and regional impacts of tropical widening. Additionally, we will make our observational diagnostics, model diagnostics, and model output available to the scientific community for model evaluation and other studies.

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

Comprehensively and systematically intercomparing existing tropical width diagnostics is desirable but beyond the abilities of a single researcher with limited time. This project therefore inherently lends itself to a group activity. In addition to providing a central location and comfortable meeting facilities, ISSI support of this project will provide the opportunity for a diverse group of scientists, including those involved in otherwise disparate fields such as theory, modeling, and satellite data analysis, to interface in order to meet the stated objectives of this proposal.

List of confirmed members

Sean M. Davis (Team Leader, NOAA ESRL, USA), Ori Adam (ETH, Switzerland), Thomas Birner (Colorado State Univ., USA), Qiang Fu (Univ. of Washington, USA), Hella Garny (DLR IPA, Germany), Kevin Grise (Univ. of Virginia, USA), Amanda Maycock (Leeds Univ., UK), Karen H. Rosenlof (NOAA ESRL, USA) Seok Woo Son (Seoul Natl. Univ., S. Korea), Paul Staten (Indiana Univ., USA), 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, a list of diagnostics will be compiled and potential existing GCM simulations will be identified. The meeting will include overview presentations of the diagnostics and potentially existing GCM simulations for analysis. The majority of the time will be reserved for discussing the details of the diagnostics and necessary GCM simulations. A plan for the GCM simulations, division of labor for computing width diagnostics, and data sharing plan will be agreed upon during the first meeting.

Before the second meeting, the GCM simulations will be completed, and the diagnostics computed and collated into a dataset for sharing among team members. Members will conduct analyses of the simulations and make presentations on their findings at the second meeting. At this meeting we will distill the analysis of team members into a set of findings and recommendations that will form the basis of a review paper and other publications.

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 this activity to spur the writing of a review paper that will focus on 1) documentation of which tropical width metrics are related to one another, and which ones aren't, and 2) recommendations for a subset of tropical width diagnostics that are most robust and best capture the multiple physical processes occurring in the atmosphere. We also expect additional publications written by team members addressing methodology issues focused on specific classes of width metrics (e.g., focusing on satellite OLR-based estimates only, or satellite constituent measurements), and on novel metrics based on satellite constituent measurements. Finally, we plan to share our model output, as well as the tropical width diagnostics computed from models, the available satellite observations, and reanalyses. These data will support ongoing community activities.

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