Tropical widening: From global variations to regional impacts

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ABSTRACT

Over the past 15 years, numerous studies have suggested that the sinking branches of Earth's Hadley circulation and the associated subtropical dry zones have shifted poleward over the late 20th century and early 21st century. Early estimates of this tropical widening from satellite observations and reanalyses varied from 0.25˚ to 3˚ latitude per decade, while estimates from global climate models show widening at the lower end of the observed range.

In 2016, two working groups, the US Climate Variability and Predictability (CLIVAR) working group on the Changing Width of the Tropical Belt and the International Space Science Institute (ISSI) Tropical Width Diagnostics Intercomparison Project, were formed to synthesize current understanding of the magnitude, causes, and impacts of the recent tropical widening evident in observations.

These working groups concluded that the large rates of observed tropical widening noted by earlier studies resulted from their use of metrics that poorly capture changes in the Hadley circulation, or from the use of reanalyses that contained spurious trends. Accounting for these issues reduces the range of observed expansion rates to 0.25°–0.5˚ latitude decade^{-1}—within the range from model simulations. Models indicate that most of the recent Northern Hemisphere tropical widening is consistent with natural variability, whereas increasing greenhouse gases and decreasing stratospheric ozone likely played an important role in Southern Hemisphere widening. Whatever the cause or rate of expansion, understanding the regional impacts of tropical widening requires additional work, as different forcings can produce different regional patterns of widening.

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WHAT IS TROPICAL WIDENING?

Earth's tropics are characterized by a juxtaposition of extreme wet and extreme dry climates. These climates are linked by the Hadley circulation, which consists of moist ascent in the deep tropics, dry descent in the subtropics, and easterly trade winds associated with the equatorward return flow near the surface. In the mid–2000s, a series of studies began pointing out that the tropics (nominally defined as the zone between the Southern and Northern Hemisphere Hadley cell edges) appeared to be widening over the late twentieth and early twenty first centuries, with observed widening rates varying greatly by study—from 0.25˚ to 3° latitude per decade in the annual mean (see early review by Seidel et al., 2008). But in global climate models, forced tropical widening over 1979–2005 was only 0.1°–0.3° per decade (e.g., Johanson and Fu 2009; Hu et al., 2013). These studies raised a number of questions:

a) *What is the actual rate of tropical widening over recent decades?* Different datasets, methods, and time periods may yield different rates of tropical widening across studies. Are the various rates consistent, or are some methods or datasets error-prone? If the lower range of observational estimates (~0.25˚ latitude per decade) is correct, then there is no discrepancy between observed and modeled rates of tropical widening over recent decades. If the higher range of observational estimates (~3˚ latitude per decade) is correct, then this would indicate that global climate models may be missing some forcing or process crucial to the realistic simulation of recent tropical widening, or that the observed widening is caused by large natural climate variability—larger than what exists in models.

b) *What is the cause of the observed tropical widening?* Global climate models indicate that the Hadley circulation may widen as a result of greenhouse gas concentration increases,

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stratospheric ozone depletion, or anthropogenic aerosol pollution. However, the width of the Hadley circulation also varies with modes of natural variability, such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), making it difficult to discern whether or not the recent tropical widening is due to human activity. Additionally, the mechanisms by which anthropogenic forcing and natural variability affect the location of the Hadley cell edge are not yet fully understood.

c) *What are the impacts of tropical widening?* As the Hadley cell edges advance poleward, the distribution of surface winds changes, and subtropical dry zones may encroach upon moister midlatitude regions. Tropical widening is already suspected in producing surface and marine impacts around the globe. But as the spatial scale of interest shrinks, regional dynamics obscure the impacts of the global Hadley cell.

WORKING GROUP ACTIVITIES

The questions above were raised during an American Geophysical Union (AGU) Chapman Conference on “The Width of the Tropics: Climate Variations and Their Impacts” in 2015. Afterwards, to address these questions, two working groups were initiated: (1) the 19-member US CLIVAR working group on the Changing Width of the Tropical Belt (https://usclivar.org/working-groups/changing-width-tropical-belt-working-group), which operated from 2016 to 2019, and (2) the ISSI Tropical Width Diagnostics Intercomparison Project (http://www.issibern.ch/teams/twdip/), which operated from 2017 to 2018.

The goals of the US CLIVAR working group were three-fold:

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1. Catalog, compare, and reconcile various methods ("metrics") used to define tropical width (addressing questions a above; the 14-member ISSI working group worked concurrently on this first goal),

2. Distinguish whether the recent tropical widening was caused primarily by anthropogenic emissions or natural variability (addressing question b above), and

3. Diagnose the regional impacts of tropical widening (addressing question c above).

In the remainder of this article, we summarize the key findings and recommendations from these working group activities.

Objective 1: Catalog, compare, and reconcile various metrics of tropical width

The US CLIVAR and ISSI working groups provided the first synthesis of how various metrics for the width of the tropics (as illustrated in Figure 1) compare to one another in terms of interannual variations and trends. A key finding is that the subtropical sea-level-pressure (SLP) maximum, the subtropical transition between surface easterlies and westerlies ($U_{sfc} = 0$), and the subtropical transition from net evaporation to net precipitation (P–E=0) all closely capture variability in the zero-crossing of the 500 hPa mass streamfunction (Ψ_{500})—the conventional, dynamical definition of the Hadley cell edge (see Waugh et al., 2018). This is particularly true in the Southern Hemisphere, where the flow is more zonally symmetric. These metrics are marked with asterisks in Figure 1. In contrast, tropical width metrics that focus on the upper troposphere or on the stratosphere, such as the tropical tropopause break (TPB), the subtropical jet latitude (STJ), or meridional gradients in outgoing longwave radiation, show only moderate agreement

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with each other and generally poor agreement with the Hadley cell edge. Additionally, methodological concerns were raised about other previously used metrics, such as column ozone gradients, as they may be unreliable metrics of tropical width (Davis et al., 2018). A detailed intercomparison of tropical width metrics for the annual mean and for different seasons can be found in the working groups' summary paper by Waugh et al. (2018).

Why is there a general lack of correlation between the upper tropospheric and lower tropospheric metrics of tropical width shown in Fig. 1? Davis and Birner (2017) reconcile the difference as follows. The moderate correlations between the TPB and STJ metrics follow from zonal wind in the free troposphere being in thermal wind balance away from the Equator. In contrast, the zonal wind at the surface is constrained by the momentum transport into or out of the vertical column above, and consequently the metrics most strongly tied to the near-surface branch of the Hadley circulation (SLP, $U_{sfc} = 0$, P–E=0, Ψ_{500}) are closely related to momentum transport within the atmosphere (Grise et al., 2019).

Focusing on the lower tropospheric metrics, the working groups found that modeled and observed widening rates in recent decades are broadly similar (≤ 0.5° per decade), once internal variability is accounted for (Grise et al., 2018) and the most recent generation of reanalyses are used (Davis & Davis, 2018).

To help to standardize metric calculations for future studies, working group members created the Tropical-width Diagnostics ("TropD") software package (Adam et al., 2018). TropD provides a flexible, well-documented, numerically-consistent set of methods for calculating tropical-width metrics. It is available in Python and MATLAB, and includes pre-calculated metrics from several widely used datasets (including four modern reanalyses) for quick

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validation, or as research-ready time-series (publicly available at https://doi.org/10.5281/zenodo.1157043).

Objective 2: Distinguish forced change from natural variability

The second goal of the US CLIVAR working group was to distinguish the roles of anthropogenic forcing and natural variability in tropical expansion observed in recent decades. To this end, the working group conducted a comprehensive multi-model analysis (Grise et al., 2019), and concluded that global climate models driven by changes in radiative forcing (greenhouse gases, stratospheric ozone, aerosols) over the 20th and 21st century simulate an expansion of the tropics that is large enough to emerge from natural variability (see also Quan et al. 2018). However, models suggest that the poleward shift of the tropical edge in the Southern Hemisphere should be 2–3x greater than that in the Northern Hemisphere, even when forced by increasing greenhouse gases alone (e.g. Watt-Meyer et al., 2019). Consequently, in the annual mean, forced tropical expansion in the Southern Hemisphere may begin to emerge from natural variability in the coming decades, whereas it may not in the Northern Hemisphere until the end of the century (Fig. 2, compare black and blue lines). Over the late 20th century, the development of the Antarctic ozone hole also acted to pull the Southern Hemisphere tropical edge poleward during austral summer (DJF). Thus, because of the ozone hole, it is likely that forced tropical expansion in the Southern Hemisphere has already emerged from natural variability during the DJF season (Thomas et al. 2015; Min & Son, 2013).

Factors responsible for the recent observed tropical expansion can also be identified by examining the spatial pattern of the circulation trends (Grise et al., 2018; Kim et al., 2017; Staten

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et al., 2019). Anthropogenic forcings may all widen the tropics, but they also produce regional patterns of widening that differ from those driven by natural variability. In most seasons, observed trends more closely resemble the patterns associated with the PDO than anthropogenic forcing.

Overall, the working group concluded that greenhouse gas forcing and stratospheric ozone depletion both expanded the tropics in the Southern Hemisphere in recent decades, and that both internal atmospheric variability and the recent phase change of the PDO widened the tropics in both hemispheres (especially in the Northern Hemisphere). The role of aerosols in tropical expansion is difficult to determine, as aerosol processes remain uncertain in climate models.

Objective 3: Diagnose regional impacts of tropical widening

The third goal of the US CLIVAR working group was to describe the local impacts of tropical widening. Two related, quantifiable questions may be asked: (i) "Where do the tropics widen?", and (ii) "What are the surface impacts of tropical widening?"

Determining where the tropics widen (question i) requires a regional tropical width metric. Several zonal mean metrics (e.g., subtropical sea-level pressure) can also be applied regionally, and shifts in these metrics are often interpreted in the context of a global Hadley circulation. The stream function definition of the Hadley cell edge metric (which traditionally is only defined in the zonal mean) has also recently been generalized to the regional scale (Staten et al., 2019). Both approaches reveal that zonal mean widening does not imply a widening at all longitudes. For example, the Southeastern United States, though in the subtropical belt, is

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removed from the prototypical Hadley cell-wise circulation (Staten et al. 2019); there, shifts in the North Atlantic Subtropical High modulate large-scale precipitation patterns (Schmidt and Grise, 2019).

The surface impacts of tropical widening (question ii) remain poorly understood and likely vary substantially by region. Hypothesized surface impacts, such as changes in tropical cyclogenesis, altered marine productivity, shifts in precipitation belts, desertification, and wildfires are each dependent on regional factors beyond the width of the tropical circulation. Although some hydrological changes can be explained by a uniform tropical expansion on top of spatially varying meridional gradients in precipitation and evaporation (e.g. Norris et al., 2019), many of the other possible impacts are likely more influenced by regional dynamical changes (stationary waves, monsoons, etc.) than a widening of the global-scale Hadley circulation.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future challenges include understanding tropical widening in the context of a changing global circulation. In this article, we have used the term "tropical width" to denote the width of the Hadley circulation and its attendant subtropical dry belts. But changes in the width and position of the inter-tropical convergence zone (Kang & Lu, 2012; Watt-Meyer et al., 2019), and the extent, duration, and intensity of monsoons in the deep tropics are also crucially important (Lau & Kim, 2015; Wang et al., 2017). On the poleward side, changes in midlatitude weather systems may have even larger hydrological impacts than simultaneous changes in tropical width (Diaz & Bradley, 2004; Scheff & Frierson, 2012).

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Tropical widening is also tied to changes in the ocean circulation beneath (Doney & Karnauskas, 2014; Schneider et al., 2014) and the upper troposphere and stratosphere above. These connections need to be pursued in the future. In fact, a newly formed ISSI working group on Tropical Width Impacts on the Stratosphere (TWIST; http://www.issibern.ch/teams/twist/) aims to address related questions, such as: How do tropical widening metrics relate to stratospheric processes such as the Brewer-Dobson circulation? How might tropical widening impact stratospheric chemistry (e.g. the ozone layer)? And how might stratospheric changes in turn impact the troposphere?

The mechanisms underpinning tropical widening are a topic of ongoing study. Subtropical static stability is often cited as a major factor in Hadley cell widening, owing largely to its role in baroclinic instability. Subtropical static stability has been shown to increase in lock-step with CO_2-induced warming (see Chemke and Polvani, 2019), while other terms, such as eddy phase speed and tropical tropopause height, play at best a minor role in expanding the Hadley circulation. This narrows the list of possible mechanisms behind tropical widening in a warming world, but more work is needed to analyze the mechanisms triggered by other forcings, such as stratospheric ozone depletion. Furthermore, while tropical stability is fairly constant from west to east, land-sea contrasts and topography produce stationary waves, preferred storm track regions, and subtropical high-pressure centers. The zonal mean framework is thus insufficient for understanding impacts in a given region.

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FIGURES

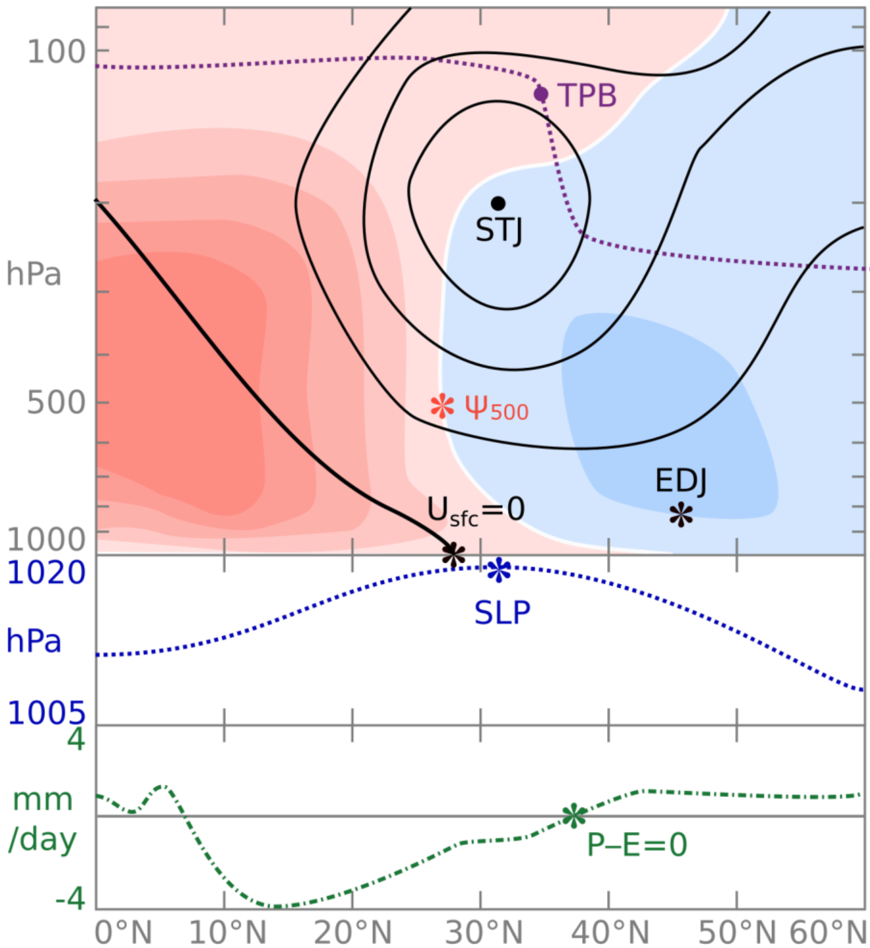

Figure 1. Schematic representation of commonly used zonal mean tropical width metrics (along with the eddy-driven jet, or EDJ), and the fields from which they are derived, as a function of latitude (and pressure in the top panel). The top pane depicts the Hadley cell (red shading), the Ferrel cell (blue shading), zonal mean zonal winds (black contours, with the thick contour representing the zero isotach), and the lapse-rate tropopause (purple dotted line). The middle and bottom panels depict the zonal mean sea level pressure (blue dotted curve) and precipitation-minus-evaporation (green dash-dotted curve). The circulation metrics are marked with colors corresponding to their underlying field (e.g., black for the fields derived from the zonal wind).

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Metrics that are strongly correlated with the HC edge latitude are marked with an asterisk—others with a dot. Adapted from Waugh et al., (2018)

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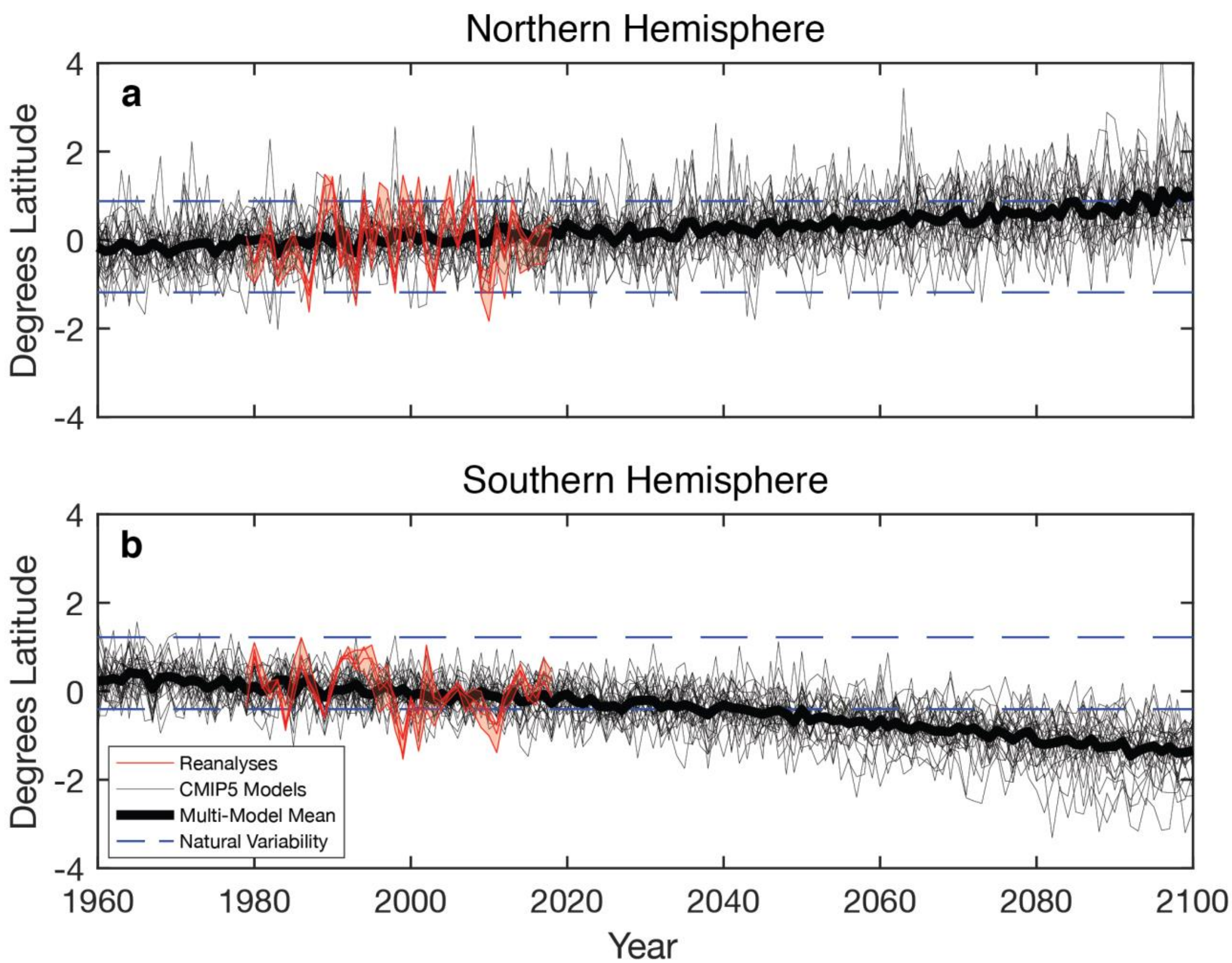

Figure 2. Historical versus modeled poleward expansion of the annual mean Hadley cell (HC) edge (based on the 500 hPa mass stream function), relative to the 1981–2010 average. Observed estimates (red curves) and the corresponding envelope (red shading between the red curves) are drawn from the ERA-Interim, MERRA2, CFSR, and JRA55 reanalyses. Simulation time series (gray curves) and the multi-model ensemble mean (thick black curves) come from historical (1960–2005) and RCP8.5 (2006–2100) experiments from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Blue dashed lines provide a measure of natural climate variability (i.e., the mean ± 2 standard deviations of the HC edge) from pre-industrial simulations, and are hence not symmetric about the 1981–2010 average. (adapted from Staten et al. 2018)

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