Causes and Impacts *of* Tropical Widening

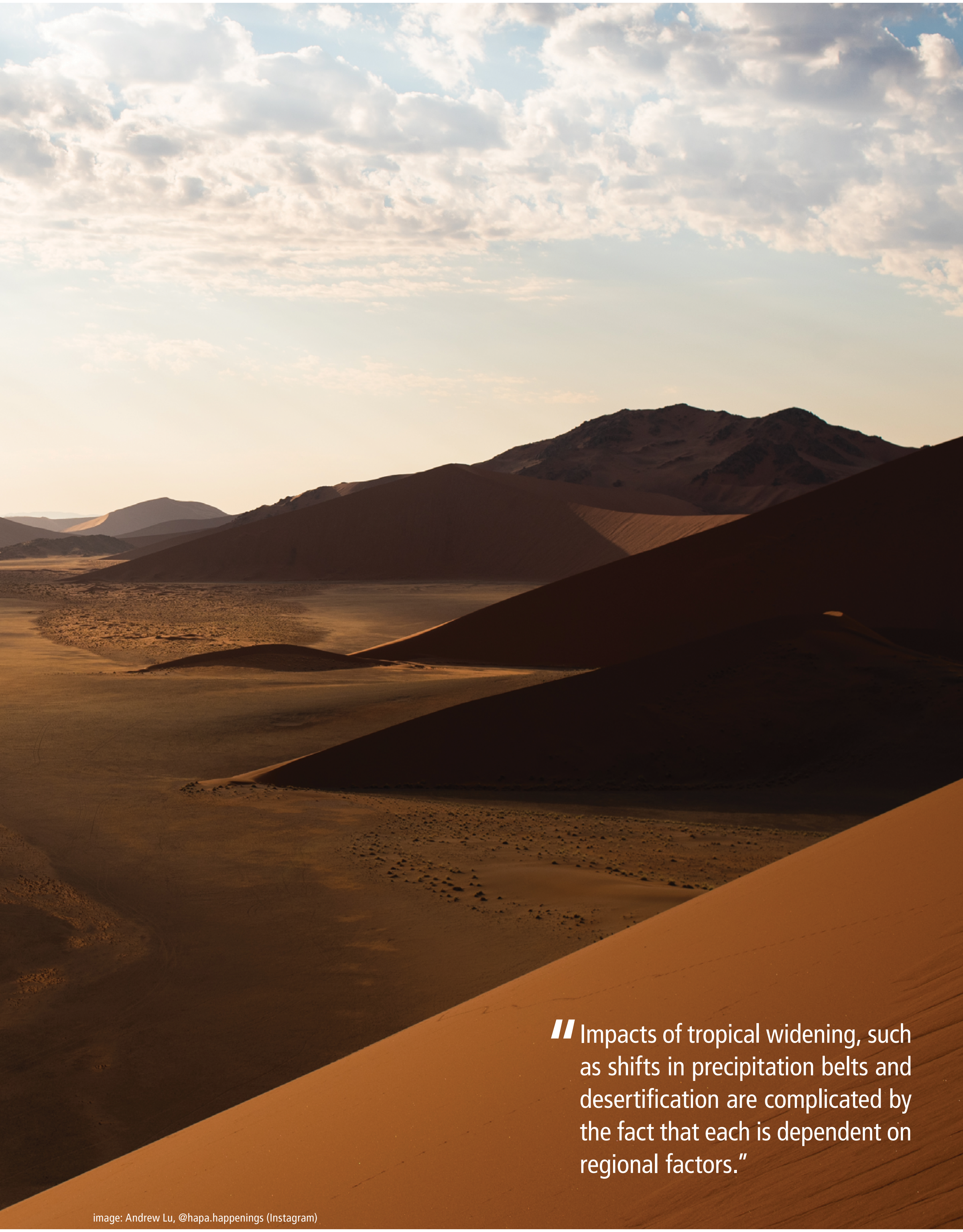

image: Andrew Lu, @hapa.happenings on Instagram

Adapted From "Tropical Widening: From Global Variations to Regional Impacts," by **Paul W. Staten** (Indiana University), **Kevin M. Grise, Sean M. Davis, Kristopher B. Karnauskas, Darryn W. Waugh, Amanda C. Maycock, Qiang Fu, Kerry Cook, Ori Adam, Isla R. Simpson, Robert J Allen, Karen Rosenlof, Gang Chen, Caroline C. Ummenhofer, Xiao-Wei Quan, James P. Kossin, Nicholas A. Davis,** and **Seok-Woo Son**. Published online in *BAMS*, June 2020. For the full, citable article, see DOI:10.1175/BAMS-D-19-0047.1.

In the mid-2000s, a series of studies began pointing out that the tropics appeared to be widening over the late twentieth and early twenty-first centuries. The observed increase, in the annual mean distance between the Southern and Northern Hemisphere Hadley cell edges, varied greatly by study—from 0.25° to 3° latitude per decade. By comparison, global climate models (GCMs) simulated only 0.1°–0.3° per decade of widening over 1979–2005.

These studies raised a number of questions. What is the actual rate of tropical widening over recent decades? What is the cause of the observed tropical widening? What are the impacts of tropical widening?

Different datasets, methods, and time periods may explain discrepancies among studies. Are there significant differences between observed and modeled rates of tropical widening? If the lower range of observational estimates (~0.25° latitude per decade) is correct, then there is no discrepancy. If the higher range of observational estimates (~3° latitude per decade) is correct, then GCMs may be missing some forcing or process crucial to the realistic simulation of recent tropical



"Impacts of tropical widening, such as shifts in precipitation belts and desertification are complicated by the fact that each is dependent on regional factors."

image: Andrew Lu, @hapa.happenings (Instagram) widening, or natural climate variability is greater than what exists in models.

GCMs indicate that the Hadley circulation may widen as a result of greenhouse gas concentration increases, stratospheric ozone depletion, or anthropogenic aerosol pollution. However, the Hadley circulation can also widen on decadal timescales in association with modes of natural variability, such as the El Niño–Southern Oscillation and the Pacific decadal oscillation (PDO). The mechanisms by which anthropogenic forcing and natural variability affect the location of the Hadley cell edge are not yet fully understood.

Two working groups were initiated to address these questions: the 19-member U.S. Climate Variability and Predictability (CLIVAR) working group on the Changing Width of the Tropical Belt (2016 to 2019) and the International Space Science Institute (ISSI) Tropical Width Diagnostics Intercomparison Project (2017 to 2018).

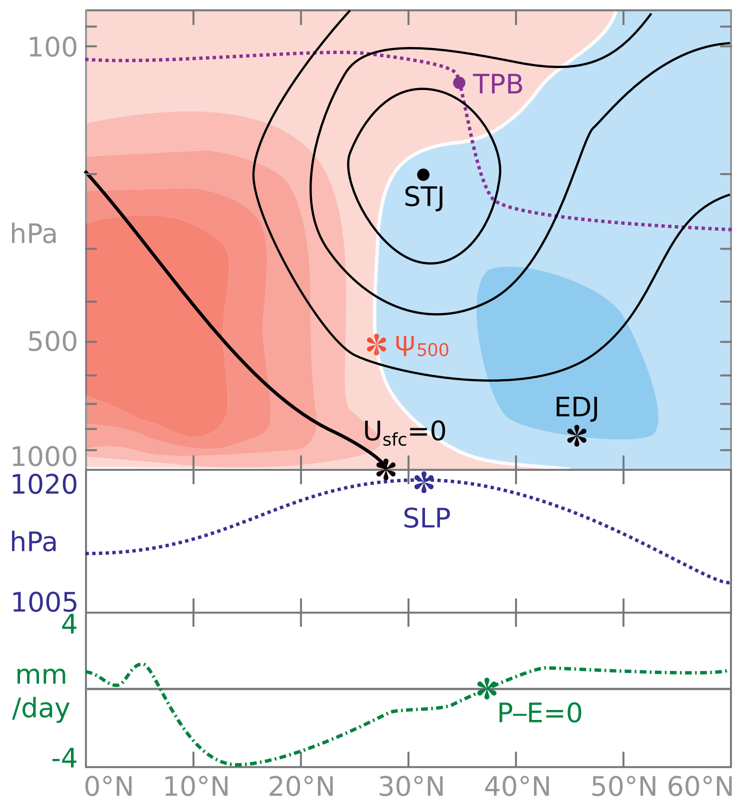
Findings of the working groups

The U.S. CLIVAR and ISSI working groups evaluated how various metrics for the width of the tropics 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, especially in the Southern Hemisphere, where the flow is more zonally symmetric.

In contrast, metrics focusing on the upper troposphere or on the stratosphere [e.g., tropical tropopause break (TPB); subtropical jet latitude (STJ)] show only moderate agreement with each other and generally poor agreement with the Hadley cell edge. One study found that 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. The zonal wind at the surface, however, is constrained by the momentum transport into or out of the vertical column above. Consequently the metrics most strongly tied to the near-surface branch of the Hadley circulation are closely related to momentum transport within the atmosphere.

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 and the most recent reanalyses are used. Working group members created the Tropical-width Diagnostics software package, which provides a flexible, well-documented, numerically consistent set of methods for calculating tropical-width metrics.

To distinguish the roles of anthropogenic forcing and natural variability in the recent



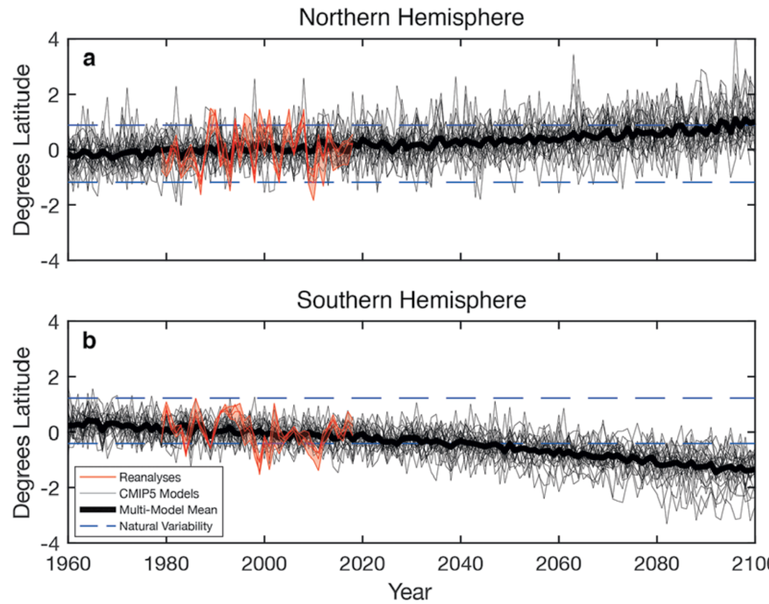
Schematic representation of commonly used zonal mean tropical width metrics (along with the eddy-driven jet, or EDJ), and the fields from which they are derived, as a function of latitude (and pressure in the top panel). The top panel depicts the Hadley cell (red shading), the Ferrel cell (blue shading), 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 SLP (blue dotted curve) and P – E (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). Metrics that are strongly correlated with the Hadley cell edge latitude are marked with an asterisk—others are marked with a dot. Adapted from Waugh et al. (2018).

tropical expansion, the U.S. CLIVAR working group conducted a comprehensive multimodel analysis. They concluded that GCMs, driven by changes in radiative forcing (by greenhouse gases, stratospheric ozone, and aerosols), simulate an expansion of the tropics large enough to emerge from natural variability during the 21st century. However, models suggest that the tropical edge shifted 2–3 times further poleward in the Southern Hemisphere than in the Northern Hemisphere. Consequently, in the annual mean, forced tropical expansion in the Southern Hemisphere may begin to emerge from natural variability in the coming decades, but not until late in this century in the Northern Hemisphere. Over the late twentieth century, the Antarctic ozone hole pulled the Southern Hemisphere tropical edge poleward during austral summer. Thus, forced tropical expansion in the Southern Hemisphere likely has already emerged from natural variability during this season.

The regional patterns of widening produced by anthropogenic forcings differ from those driven by natural variability. In most seasons, observed trends more closely resemble the patterns associated with the Pacific Decadal Oscillation (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, while internal atmospheric variability and the recent phase change of the PDO widened the tropics in both hemispheres.

Zonal mean widening does not imply a widening at all longitudes. For example, large-scale precipitation patterns in the southeastern United States, though in the subtropical belt, are modulated by the North Atlantic subtropical high. Determining where the tropics widen therefore requires a regional tropical width metric. Several zonal mean metrics (e.g., subtropical sea level pressure) and the streamfunction definition of the Hadley cell edge can also be applied regionally.

Hypothesized surface impacts of tropical widening, such as changes in tropical cyclogenesis, altered marine productivity, shifts in precipitation belts, frequency and intensity of monsoons, desertification, and wildfires, are complicated by the fact that each is dependent on regional factors beyond the width of the tropical circulation. Many of the other possible impacts are likely more influenced by regional dynamical changes than a widening of the global-scale Hadley circulation.



Historical vs modeled poleward expansion of the annual mean Hadley cell edge (based on the 500-hPa mass streamfunction), 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 JRA-55 reanalyses. Simulation time series (gray curves) and the multimodel 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 Hadley cell edge) from preindustrial simulations, and are hence not symmetric about the 1981–2010 average. Adapted from Staten et al. (2018).

Recommendations for future research

Future challenges include understanding tropical widening not only in the context of the Hadley circulation but also in terms of the width and position of the intertropical convergence zone. On the poleward side, changes in midlatitude weather systems may have even larger hydrological impacts than simultaneous changes in tropical width. Tropical widening is also tied to changes in the ocean circulation below and the upper troposphere and stratosphere above. These connections need to be pursued in the future. Finally, more work is needed to understand the dynamical mechanisms underpinning tropical widening.

BAMS: What would you like readers to learn from this article?

Kevin Grise (University of Virginia): *Attribution of atmospheric circulation trends on the relatively short timescale of the global satellite record (1979-present) is extremely challenging. While increasing greenhouse gases play a role, there are many other important factors—stratospheric ozone depletion, aerosols, coupled atmosphere-ocean variability, internal atmospheric variability, etc.*

Paul Staten (Indiana University): *I hope our BAMS article inspires people to take a second, closer look at tropical expansion. I think that, for a few years, it was easy to get the impression that the issue of climate change causing observed tropical expansion was case-closed; we had the observations, we had the theory, and we had the simulations, and they all agreed—mostly.*

BAMS: What reopens the case, so to speak?

PS: *We've learned that natural sea surface temperature variations can have a large influence on tropical width for decades at a time. But there is still theoretical work to be done to understand why different parts of the tropical and subtropical atmosphere expand or shift the way they do in response to climate variability and change. And of course there is much work to do to answer the question, "I live in such-and-such a city. What does a widening Hadley cell mean for me?"*

BAMS: When did you become interested in tropical expansion?

PS: *As a graduate student. My advisor, Thomas Reichler, was among the first scientists to demonstrate tropical expansion, and I was excited to contribute to the discussion.*

KG: *Likewise, when I was in graduate school. Several studies were published that concluded that there may be a discrepancy between observed and modeled trends in Hadley cell expansion. I always found this problem to be interesting, so I attended the AGU Chapman Conference in 2015 on this subject. The discussions at that meeting stimulated the working group efforts that are summarized in this article.*

BAMS: What has surprised you in researching the widening?

PS: *One surprise for me in performing the tropical widening work is how many ways there are to think of tropical expansion—and even of the tropics themselves. We like to think of the tropics as a continuous (if not straight west-to-east) overturning circulation. But at some longitudes, such a thermally direct circulation doesn't even exist—and even where such a circulation does exist, there's no guarantee that the tropics will widen there the same way it does in other places.*

KG: *First, I think a lot of people are surprised that the position of the subtropical jet stream and the Hadley cell edge do not closely co-vary with one another, especially because these features are commonly linked to one another in textbooks. Second, a lot of people are surprised that, according to climate models, increasing greenhouse gases do not lead to comparable rates of Hadley cell expansion in the Northern and Southern Hemispheres. Why the Southern Hemisphere circulation trends are substantially larger remains a topic for future study.*

BAMS: What was the biggest challenge you encountered while doing this work?

PS: *This interaction between regional and global scales illustrates the biggest challenge in understanding the tropics: the interconnectedness of the earth's general circulation. Tropical expansion usually occurs hand-in-hand with shifts in the extratropical storm tracks. In fact, at some longitudes and seasons this storm track shift may be a better way to describe a shift in weather patterns than tropical expansion. At other longitudes, the circulation changes may be better thought of as a change in a monsoon pattern. In a sense, all work on jet shifts and monsoon circulations is related to tropical widening.*

KG: *Inconsistent methodologies to define the edge of the Hadley circulation made it very challenging to compare conclusions from previous studies. The Tropical Width Diagnostics (TropD) software code package that was developed as part of this work will hopefully help to alleviate this issue in future studies.*