Prospectus for a US CLIVAR Working Group:
Changing Width of the Tropical Belt

1. Motivation

The tropics are a fundamental climate zone on Earth, characterized by a band of deep convective storms along the Equator, known as the Intertropical Convergence Zone (ITCZ), and bounded by arid regions in the subtropics of each hemisphere, such as the African and Australian deserts. Together, the moist and dry regions of the tropics represent surface manifestations of the Hadley circulation, the mean meridional circulation in the tropical troposphere with ascent near the Equator, poleward flow in the tropical upper troposphere, and descent in the subtropics of each hemisphere. The boundaries of the Hadley circulation are not stationary but rather vary in time. In fact, recent evidence has shown that the tropics have expanded over the last several decades, pushing the boundaries of the Hadley circulation and the associated subtropical dry zones further poleward in each hemisphere (e.g., Seidel et al., 2008; Fung and Fu, 2013; Birner et al., 2014). If such a climate shift were to continue over the 21st century as projected by climate models (e.g., Lu et al., 2007; Johanson and Fu, 2009; Hu et al., 2013), it could have substantial impacts on the water resources of ecosystems and human population centers at the poleward edges of the current subtropical dry zones (Sherwood and Fu, 2014), including regions of the southern United States.

Current theories explain the location of the poleward boundaries of the Hadley circulation using either a combination of angular momentum and energy conservation arguments (Schneider, 1977; Held and Hou, 1980; Lindzen and Hou, 1988), or instability arguments involving baroclinic eddies (Held, 2000; Walker and Schneider, 2006). These theories suggest that the Hadley cell is likely to widen in a warmer climate, as the tropics become more moist, and the tropical atmosphere becomes accordingly more stable (Frierson et al., 2007). Idealized numerical simulations spanning a range of climates agree that, in climates similar to that of the present day, a warming climate should result in a wider tropical belt (Korty and Schneider, 2008; Levine and Schneider, 2011; Levine and Schneider, 2015). More sophisticated and comprehensive general circulation models and earth system models also generally project a widening of the global Hadley circulation in global warming scenarios (Lu et al., 2007; Hu et al., 2013).

A number of papers from the last decade have provided observational evidence that the tropics have expanded in the last ~3 decades (e.g., Hudson et al., 2006; Seidel and Randel, 2007; Hu and Fu, 2007; Seidel et al., 2008), possibly at a higher rate than that predicted by climate models (Johanson and Fu, 2009; Quan et al., 2013). However, the interpretation of these results is complicated by the fact that individual studies use different metrics for the width of the tropics, which results in trends ranging from a near-zero change in the width of the tropics to up to a 2 degree latitude tropical expansion per decade (e.g., Birner, 2010; Davis and Rosenlof, 2012; Birner et al., 2014). Additionally, it remains unclear whether the observed trends in the width of the tropics are due to increasing greenhouse gas levels, or are merely a signature of natural variability in the ocean-atmosphere general circulation, such as the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

To address these issues, as well as the societal and ecological impacts of an expanding tropical belt, an American Geophysical Union (AGU) Chapman Conference was held in Sante Fe, New Mexico on 27-31 July 2015. This conference brought together atmospheric and oceanic dynamicists, as well as observational scientists and hydrologists. New insights emerged that called into question the prevailing view about the nature and causes of changes in the width of the tropics. Key conclusions of this meeting (in our interpretation) were as follows:

- Recent observed estimates of the expansion of the tropics vary widely, ranging from 0.25 to 3 degrees latitude per decade (Davis and Rosenlof, 2012), depending on the time period, the instrument or dataset, and the metric used to measure edge of the tropics (Davis and Birner, 2013; Lucas et al., 2014). The sheer number of metrics is notable. It was recommended that a group be convened to write a peer-reviewed journal article to document what each metric physically represents about the edge of the tropics, to explore how the metrics relate to one another, and to recommend a smaller subset of metrics to be used, consistently and reproducibly, in future studies.
- The causes of variability in the width of the tropics on decadal timescales remain highly uncertain. Prior to this meeting, the prevailing viewpoint was that recent variability in the width of the tropics was the direct result of anthropogenic forcing. While the roles of stratospheric ozone depletion in the Southern Hemisphere (Waugh et al., 2015) and aerosols in the Northern Hemisphere (Allen et al., 2014) were noted, the overall consensus of this meeting was that natural variability dominated tropical widening over the past several decades, primarily through modes of coupled atmosphere-ocean variability such as ENSO (Monteiro et al., 2015) or the PDO (Allen et al., 2014). As a result of this shift in viewpoint, future research was recommended to address the role of coupled atmosphere-ocean variability in the width of the tropical belt, and how changes in the Hadley circulation might feed back on the general circulation of the ocean.
- Results from Cook (2003), Karnauskas and Ummenhofer (2014), and Lucas and Nguyen (2015) have called into question the merit of examining the traditional zonal-mean view of the Hadley circulation for local impacts. Karnauskas and Ummenhofer (2014) noted, for example, that a Hadley cell-like overturning circulation is not typically present at all longitudes in the tropics, but rather is confined to longitude bands in eastern subtropical ocean basins, where there are large land-sea temperature contrasts. It remains unclear whether the recent observed widening of the tropics is focused in these particular longitude bands, or is more global in its extent. It was recommended that a better connection be made between the zonal-mean expansion of the Hadley circulation and changes in the regional circulations of the tropical and subtropical zones.

2. Objectives, Tasks, Timeline

To implement the recommendations from the recent AGU Chapman conference, we propose to establish a three-year US CLIVAR Working Group on the Changing Width of the Tropical Belt. The objectives for the proposed working group are as follows:

Objective #1: *Provide guidance on which metrics are most appropriate to quantify key impacts of the changing width of the tropical belt.* To do this, we will assess and synthesize knowledge from numerous studies that have used different metrics, time periods, and model forcing scenarios to document the expansion of the tropics. Our rationale for this objective arises from the lack of consensus achieved during discussions at the Chapman Conference. We expect that a selection of standard or accepted definitions and metrics may assist in the communication of tropical width changes to the broader scientific community. This objective directly addresses the US CLIVAR science goal to "better quantify uncertainty in the observations, simulations, predictions, and projections of climate variability and change", and the mission of the US CLIVAR POS panel to "develop syntheses of critical climate parameters."

Objective #2: *Identify how anthropogenic forcing and natural atmosphere-ocean variability contribute uniquely to decadal timescale changes in the width of the tropical belt.* A key theme of the recent Chapman Conference was the difficulty of separating the roles of natural variability (particularly from coupled atmosphere-ocean variability, such as ENSO and the PDO) and anthropogenic forcing in recent trends in the width of the tropical belt. Kang et al. (2013) have previously identified coupled atmosphere-ocean variability as a key source of uncertainty in future tropical circulation trends. Furthermore, the tropical oceanic overturning circulation is integrally linked with the atmospheric Hadley circulation (Clement, 2006), as the circulations mirror each other through an Ekman force balance (Schneider et al., 2014). Understanding the interplay between atmosphere-ocean coupling and the varying width of the tropics requires a joint team of atmospheric scientists and oceanographers to provide novel insights into past observed climate variability and future climate model projections. This objective directly addresses the US CLIVAR science goals to 1) "understand the role of the oceans in observed climate variability on different timescales" and 2) "improve the development and evaluation of climate simulations and predictions." This objective also serves the mission of the US CLIVAR PSMI panel to "reduce uncertainties in the general circulation models used for climate variability prediction and climate change projections through an improved understanding and representation of the physical processes governing climate and its variation." Finally, this objective is directly relevant to the US CLIVAR Research Challenge concerning decadal variability and predictability.

Objective #3: *Address how the global-scale widening of the tropics is manifested through regional-scale impacts.* During the recent Chapman Conference, a general consensus was reached that the impacts of climate variability and change are experienced locally, but it was not generally agreed that the traditional zonal-mean view of the Hadley circulation was at all meaningful in terms of impacts. Understanding the relevance of global-scale Hadley circulation changes to regional-scale impacts in the subtropics is critical to communicating the impacts of the expanding tropics to policy makers. This objective directly addresses the US CLIVAR science goal to "understand the processes that contribute to climate variability and change in the past, present, and future," and the mission of the US CLIVAR POS panel to "improve understanding of climate variations in the past, present, and future." This objective also serves the mission of the US CLIVAR PPAI panel, with its focus on predictions and interfacing with the applications, operations, and decision-making community.

Objective #4: *Coordinate effort with other international programs (e. g., SPARC DynVar, WCRP Grand Challenge on Clouds, Circulation, and Climate Sensitivity, GEWEX Hydroclimatology Panel), and inform funding agencies of where research initiatives are needed to advance understanding.* We recognize that the proposed working group is one of many groups with strong interest in past and future changes in the tropical atmospheric and oceanic general circulation, and that our efforts will be most effective inasmuch as they leverage interconnections with existing research communities. As such, we have suggested members of this working group with a diverse range of expertise, to help build bridges across distinct research communities interested in the impacts of global-scale tropical circulation changes. This objective directly addresses the US CLIVAR science goal to "collaborate with research and operational communities that develop and use climate information," and the mission of the US CLIVAR PPAI panel to "foster improved practices in the provision, validation and uses of climate information and forecasts through coordinated participation within the U.S. and international climate science and applications communities."

To accomplish the above objectives, the working group will complete the following tasks:

1) Publish a peer-reviewed journal article to provide the community with a comprehensive assessment of tropical width metrics and to recommend a subset of metrics to be used by subsequent studies (to better aid in comparison among studies across the published literature).
2) Compare and contrast the impacts of anthropogenic forcing and coupled atmosphere-ocean variability on decadal variability in tropical width. Synthesize our understanding of coupling between tropical width and sea surface temperatures.
3) Inform linkages between global-scale circulation changes and the regional-scale circulation changes most relevant for impacts, setting the stage for a session at the AGU Fall Meeting on global and regional impacts of tropical circulation change.

The tasks will be completed according to the following timeline:

- Year 1: Plan and schedule working group activities, review previous research, and identify strategies for working group research initiatives.
- Year 2: Research, assess and synthesize research findings, and begin to draft peer-reviewed journal articles to summarize working group findings.
- Year 3: Finalize research and journal articles, hold session at AGU Fall Meeting, report results to CLIVAR, and propose future work.

3. Publications and Outreach

The publications resulting from the activities of the proposed working group will include:
1) A paper that provides a comprehensive assessment of tropical width metrics and that recommends a subset of metrics to be used by subsequent studies
2) A paper that reviews how various types of coupled atmosphere-ocean variability are linked to the width of the tropical belt
3) A paper that investigates linkages between global-scale tropical circulation changes and regional-scale impacts (summarizing the results of the AGU session held on this topic)

The outreach of the working group will include presentations to US CLIVAR, articles in the US CLIVAR Variations newsletter, and special sessions at the AGU or American Meteorological Society annual meetings.

4. Reporting Plan

As listed above, the objectives of the proposed working group are highly relevant to the science goals of US CLIVAR, as well as to the missions of the three US CLIVAR panels (POS, PSMI, and PPAI). Several members of the PSMI panel recommended the idea for this working group, and we propose to report our progress to both the POS and PSMI panels and seek their advice and support. We also propose to report on our progress at the annual US CLIVAR summit and panel meetings, as appropriate.

5. Leadership and Suggested Membership

Paul Staten (Indiana University) and Kevin Grise (University of Virginia) will serve as co-chairs of the proposed working group and were responsible for the development of this prospectus. The co-chairs have expertise in atmospheric and climate dynamics, and use both observations and global climate model experiments to understand the atmospheric general circulation, its variability, and its response to anthropogenic forcing.

We propose to have a working group membership with diverse expertise, including members with specialties in atmospheric dynamics, ocean dynamics, atmosphere-ocean interaction, global climate, regional climate, monsoons, observational analysis, and climate modeling. We also propose a healthy mix of scientists at different career stages, to maximize community involvement and networking/mentoring opportunities. Suggested members along with their affiliations and areas of expertise are listed below:

- *Ori Adam (ETH Zurich): Energetic constraints of the tropical circulation
- Robert Allen (California-Riverside): Aerosols and oceanic variability
- Thomas Birner (Colorado State): Troposphere-stratosphere interactions
- Gang Chen (UCLA): Atmospheric dynamics, regional impacts
- Kerry Cook (University of Texas): Regional climate change impacts
- Sean Davis (NOAA): Stratospheric ozone and water vapor variability
- Qiang Fu (University of Washington): Remote sensing and radiative transfer
- Kevin Grise (University of Virginia): Atmospheric circulation variability and change
- Kristopher Karnauskas (Univ. of Colorado): Simulated regional Hadley circulations
- *James Kossin (NOAA, Univ. of Wisconsin): Hurricanes and climate variability
- *Chris Lucas (Bureau of Meteorology, Australia): Tropical width observations
- *Amanda Maycock (University of Leeds): Troposphere-stratosphere interactions, chemistry coupling
- *Timothy Merlis (McGill University): Ocean-atmosphere general circulation, tropical meteorology
- *Xiao-Wei Quan (Univ. of Colorado, NOAA): Rainfall variability and hydrological impacts
- *Karen Rosenlof (NOAA): Stratospheric dynamics and composition
- Isla Simpson (NCAR): Linkage of global-scale and regional-scale climate change
- Paul Staten (Indiana University): Atmospheric dynamics
- Caroline Ummenhofer (Woods Hole): Rainfall variability and hydrological impacts
- Darryn Waugh (Johns Hopkins): Circulation widening and stratospheric ozone

  * Indicates a contributing member

6. Resource Requirements

The proposed working group will meet once per year for 2-3 days and will hold monthly teleconferences. Specifically, we request funding for:

- Travel support for two annual working group meetings
- Publication charges for the three journal articles detailed above

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