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Key Points:
- CESM-LE shows a robust Hadley cell expansion in the Southern Hemisphere, in the past and in the future
- The width of the Hadley cell is strongly correlated with $P - E = 0$ and the midlatitude jet
- The maximum tropopause slope, OLR, and the subtropical jet are not good metrics for Hadley cell width

Correspondence to:
A. Solomon,
as4638@columbia.edu

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Contrasting upper and lower atmospheric metrics of tropical expansion in the Southern Hemisphere

A. Solomon[1], L. M. Polvani[1,2], D. W. Waugh[3], and S. M. Davis[4]

[1]Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York, USA, [2]Department of Earth and Environmental Sciences, Lamont Doherty Earth Observatory, Palisades, New York, USA, [3]Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland, USA, [4]NOAA/ESRL/Chemical Sciences Division, and CIRES, University of Colorado Boulder, Boulder, Colorado, USA

Abstract Observational studies suggest that the tropics are expanding, but a wide range of expansion rates have been reported (from 0.2° to 2° of latitude per decade). This is due, in part, to the great variety of metrics used to define the tropical width. Here we ask whether these metrics are measuring tropical width consistently, focusing on the Southern Hemisphere, where the circulation is better approximated by the zonally symmetric component. Analyzing output from the Community Earth System Model (CESM) Large Ensemble Project, we show that tropical expansion robustly occurs in the model in response to forcings. In addition, we find that whereas the width of the Hadley circulation is strongly correlated with the midlatitude jet, from interannual to decadal time scales, it is essentially uncorrelated with upper atmospheric metrics, e.g., the maximum gradient of tropopause height, both in terms of variability and of response to forcings.

1. Introduction

The boundaries of the tropical belt, located near 30° in each hemisphere, are hot, dry regions containing most of the world's deserts. This is due to the dominance of subsiding air associated with the downwelling branch of the Hadley circulation. The location of this downwelling air is constantly varying, seasonally and interannually, due to cycles of insolation and the natural variability of the atmosphere. However, several recent studies have suggested the existence of a long-term trend toward widening of the tropical belt [*Seidel and Randel*, 2007; *Hu and Fu*, 2007; *Seidel et al.*, 2008]. Since any permanent changes in the width of the tropics would have profound implications for water resources in the adjacent regions where large populations currently live, it is important to understand what governs the variability (and trends) of the tropical width.

Birner et al. [2014] recently reviewed the observational evidence for the ongoing expansion of the tropics. Much of that evidence comes from satellite observations in the upper atmosphere, as the tropical belt can be defined by a number of pronounced features that can be remotely observed from space. For instance, compared to the subtropics, the tropical belt is characterized by lower concentrations of stratospheric ozone, higher outgoing longwave radiation (OLR), and a more elevated tropopause. Trends in these quantities since 1979, when the satellite record began, appear to suggest an expansion of the tropics, at a rate between 0.2° and 2° of latitude per decade, depending on the metric analyzed.

On the other hand the extent of the so-called "Hadley circulation," commonly defined from the zonally averaged meridional mass stream function, is a more traditional metric for the width of the tropical belt. The location where the mass stream function vanishes at 500 hPa, for instance, is a direct measure of the latitude of downwelling air at the edge of the Hadley circulation. How the more novel metrics based on satellite observations relate to this direct metric of the Hadley circulation is largely an open question.

Furthermore, a large number of additional metrics of the tropical width have appeared in the literature. Notably, the exhaustive compilation in *Davis and Rosenlof* [2012] has broadened the discussion to include more tropospheric metrics. For example, the latitudes of the subtropical and midlatitude jet streams can be thought of as dynamical boundaries segregating the tropical and polar climate zones. And, last but not least, the metric of possibly greatest relevance to surface climate: the latitude where precipitation is balanced by evaporation.

Given this profusion of metrics, the aim of this paper is to explore the relationships among them, in order to determine which of them vary in concert, and which are meaningfully able to capture the natural and forced variations in the Hadley cell. The metrics fall naturally into two distinct groups: upper atmospheric (e.g., relating to tropopause height) and more tropospheric or near surface ones (e.g., precipitation metrics as well as the latitude of the eddy-driven jet). For simplicity, we confine our study to the Southern Hemisphere, where the time-mean flow is more zonally symmetric. Analyzing model output from the latest Community Earth System Model's Large Ensemble Project (CESM-LE) [*Kay et al.*, 2015], which provides a long control integration in addition to a 40-member ensemble of runs from 1920 to 2080, we find that while a robust tropical expansion in the model clearly emerges from the natural variability over decadal timescales, upper atmospheric metrics correlate very poorly (and mostly negatively) with the width of the Hadley cell and appear to poorly describe Hadley circulation expansion.

2. Methods

To keep the task manageable and avoid unnecessary duplication, we have opted to consider the following seven metrics, which we give acronyms and simple definitions:

OLR	the latitude where the outgoing longwave radiation OLR equals 250 W m^{-2};
T_p	the latitude of the largest gradient in tropopause pressure;
SL	the latitude of maximum zonal wind, averaged 400–100 hPa, north of 45°S;
PSI	the latitude where the zonal mean mass stream function at 500 hPa vanishes;
BL	the latitude of maximum zonal wind, averaged 900–50 hPa, south of 45°S;
L	the latitude of maximum zonal wind at 850 hPa, in the Southern Hemisphere;
$P - E$	the latitude where precipitation (P) equals evaporation (E), so $P - E = 0$.

These metrics offer a representative sample of the set studied in *Davis and Rosenlof* [2012] and include both dynamical and thermodynamical quantities. The dynamical metrics capture the locations of three zonal jets: SL for the Subtropical jet Latitude, BL for the Barotropic jet Latitude, and L for the Latitude of maximum near-surface winds. The meridional circulation metric is called PSI because Ψ is conventionally used for the mass stream function. For each metric, the variable of interest is interpolated to a resolution of 0.01° in order to determine latitudes at a finer scale than the somewhat coarse, approximately 1°, resolution of the model. Maxima are fit to a quadratic polynomial; metrics based on a threshold (OLR, PSI, and $P - E$) are linearly interpolated.

For all these metrics, in addition to annual mean values, we also consider decadal means: these are of greater interest for quantifying climate change [*Solomon and Polvani*, 2016], as the responses to anthropogenic forcings are typically much smaller than the large year-to-year variability in these metrics.

The model data used here consist of monthly mean, zonal mean fields from the CESM-LE, documented by *Kay et al.* [2015]. First an 1800 year long preindustrial (PI) control integration is used to investigate the covariability of the different tropical width metrics on interannual and decadal time scales. Second, an ensemble of 40 coupled integrations, from 1920 to 2080 (with historical forcings prior to 2005 and RCP8.5 scenario forcings afterwards), is analyzed, to explore whether the responses of the same metrics to anthropogenic forcings are correlated. This large ensemble permits an assessment of forced changes, taking into consideration the uncertainty associated with natural variability.

For the recent past (i.e., the last few decades) the CESM-LE model results are contrasted with atmospheric reanalyses, to provide evidence that the relationships seen in CESM-LE are reflected in recent observations. Since reanalyses differ from one another, we evaluated three: the National Center for Environmental Prediction-National Center for Atmospheric Research reanalysis (NCEP) [*Kalnay et al.*, 1996], the European Centre for Medium-Range Weather Forecasts Interim reanalysis (ERA) [*Simmons et al.*, 2007], and the Japanese Climate Data Assimilation System (JRA-25) [*Onogi et al.*, 2007].

3. Results

3.1. Climatology

The seasonal diagrams presented in Figure 1 show the climatological location of each metric in the meridional plane for December–February (DJF) (left) and June–August (JJA) (right) in the CESM-LE PI control. In Figure 1 (bottom row), the mass stream function (colored contours) shows the southern branch of the Hadley cell in

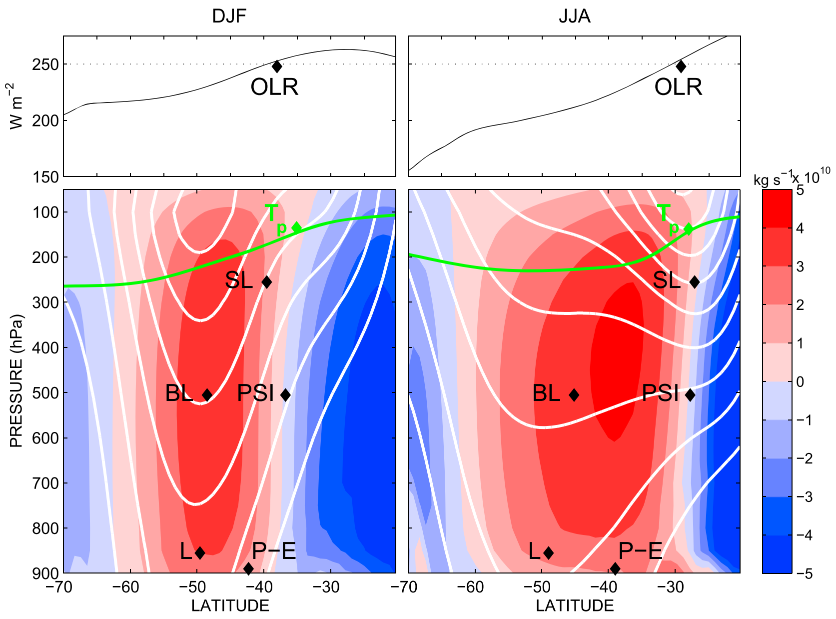

Figure 1. (bottom row) Seasonal mean mass stream function (shading) for (left column) DJF and (right column) JJA from PI control, the contour interval is 10^{10} (kg s^{-1}). The zonal wind is overlain in white contours, the contour interval is 5 (m s^{-1}). The green curve shows the height of the tropopause at each latitude. (top row) The outgoing longwave radiation in units of W m^{-2}. The location for each tropical width metric (OLR, T_p, SL, PSI, BL, L, $P-E$) is labeled (see text for definitions of each metric).

blue and the Ferrel cell in red: the PSI metric is at the boundary between the two cells. The white contours show the zonal wind, with the eddy-driven jet (L) near the surface, the barotropic jet (BL) in the midtroposphere, and the subtropical jet (SL) in the upper troposphere at lower latitudes. The green curve shows the height of the tropopause, and the location of it largest slope T_p is indicated. Figure 1 (top row) shows the OLR as a function of latitude and the threshold value of 250 W m^{-2}.

From the figure, one can cluster these seven metrics into two groups: OLR, SL, and T_p in the upper atmosphere and the others in the middle and lower troposphere. It is interesting to note that the upper atmospheric metrics are all located at latitudes quite similar to PSI, i.e., in the subtropics. In contrast, $P-E$, BL, and L are considerably farther south, into the midlatitudes. As shown below, however, it would be simplistic to conclude

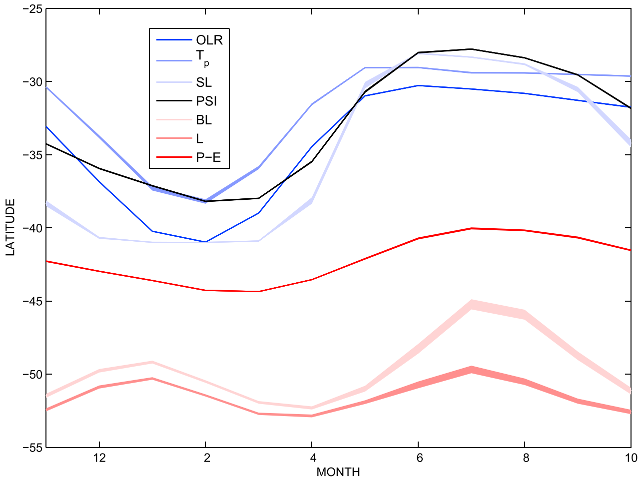

Figure 2. Seasonal cycle of each tropical width metric in the PI control plotted as a function of month. Contour thickness is twice the standard error ($\sigma/\sqrt{(180)}$) for the t distribution of the 180 nonoverlapping decadal mean values, calculated from the respective standard deviations σ of each metric.

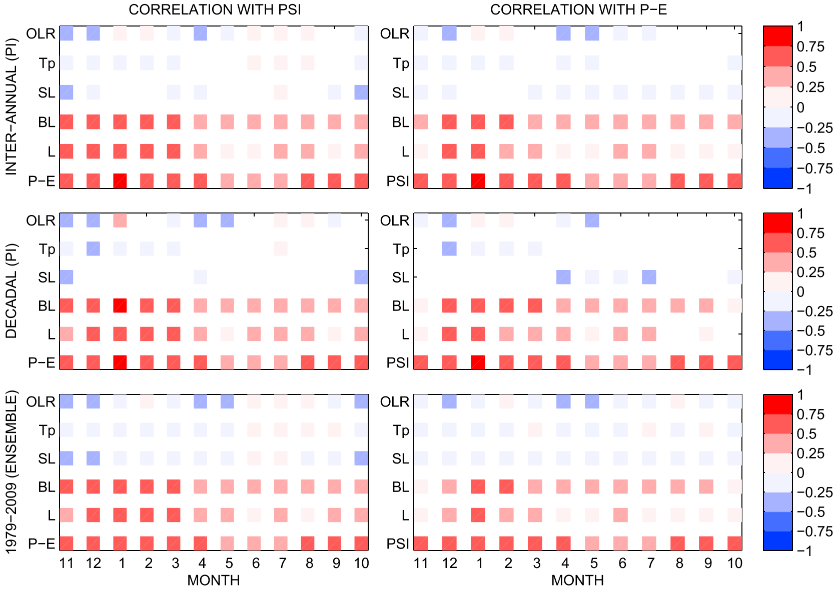

Figure 3. Cross correlations between tropical width metrics for each month. (top row) Interannual correlations from the CESM-LE PI control. (middle row) Decadal correlations calculated from the 180 nonoverlapping decadal mean values in the PI control. (bottom row) Interannual correlations over the period 1979–2009, averaged across the 40 member ensemble. (left column) Correlations with PSI. (right columns) Correlations with $P-E$. All colored values are all significant at the 95% level (i.e., white indicates lack of a significant correlation).

from this fact that the upper tropospheric metrics are more relevant for capturing the variability and trends of the mean meridional circulation.

The full seasonal cycle for each metric, as computed from the CESM-LE PI control run, is plotted in Figure 2. PSI and the upper atmospheric metrics (blue) remain within 10° of one another throughout the year. Although $P-E$ is located somewhat farther south, it does exhibit a similar seasonal cycle to PSI, with a poleward migration in summer and a more equatorward location in the winter. The midlatitude jet metrics (BL and L) have a different seasonal cycle, with an equatorward migration in both solstice seasons. It is also clear that the midlatitude jet maximum L is located more than 10° to the south of PSI throughout the year.

3.2. Correlations

To understand how the natural variability of these metrics relate to one another, we analyze the cross correlations for each metric, separately for each month. One might naively expect that metrics located closer to one another, or with a more similar seasonal cycle, would also be more highly correlated. As we now show, that is not the case.

Figure 3 (left column) shows the correlations for each metric with PSI and Figure 3 (right column) the correlations with $P-E$. These correlations are computed in three different ways: interannual correlations from the PI control run in Figure 3 (top row), interdecadal correlations from the PI control run in Figure 3 (middle row) (calculated from 180 nonoverlapping decadal means), and interannual correlations averaged over the 40-member historical runs over the period 1979–2009 in Figure 3 (bottom row), for comparison with renalyses.

First, note the strong similarity across all panels, indicating that these correlations are very robust. Second, in Figure 3 we see that the strongest correlation is found between $P-E$ and PSI: it is significant in every month of the year and exceeds 0.55 from August to April in all cases. This has been reported previously [*Lu et al.*, 2007; *Polvani et al.*, 2011b; *Quan et al.*, 2014] and confirms that PSI, the traditional metric of the Hadley circulation [*Hu and Fu*, 2007] can be used to assess the variability of the latitudinal width of the hydrological cycle in the subtropics in austral summer.

Third, and most importantly, Figure 3 reveals that BL and L exhibit positive correlations with PSI and $P-E$, and these correlations are particularly strong in the summer months (a finding originally reported by *Kang and Polvani* [2011]). In stark contrast, it is clear that the upper atmospheric metrics have very small and predominantly negative correlations with PSI and $P-E$.

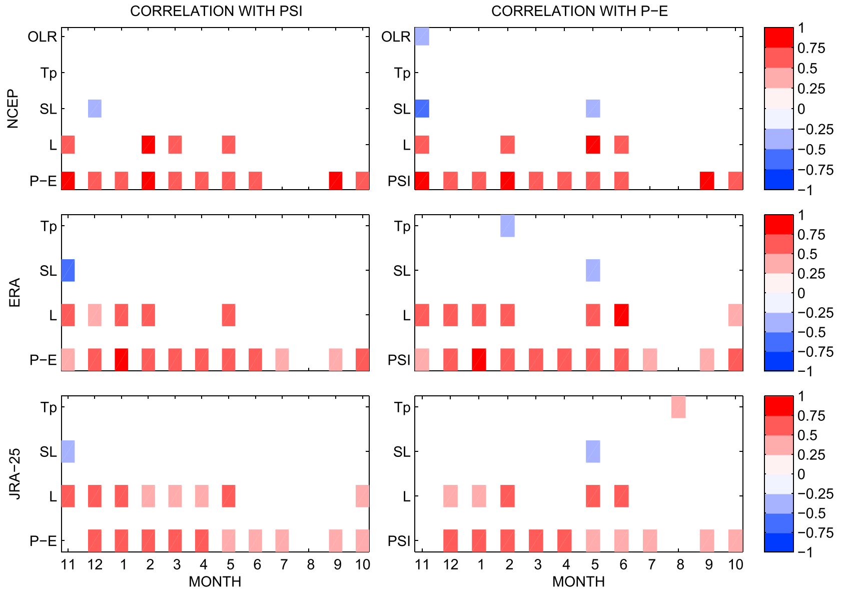

Figure 4. As in Figure 4 (bottom row), for the available tropical width metrics as computed by *Davis and Rosenlof* [2012]. (top row) NCEP. (middle row) ERA. (bottom row) JRA-25. All correlations are interannual, over the period 1979–2009.

This fact, which constitutes the key finding of our paper, is confirmed in the reanalyses we have examined, as illustrated in Figure 4. Not all metrics are available for all reanalyses, so we simply report here all the ones available from *Davis and Rosenlof* [2012], for the period 1979–2009 which was used for that study. Figure 4 (top row) shows six of our seven metrics (*Davis and Rosenlof* [2012] did not evaluate BL) calculated from NCEP, revealing a similar pattern of correlations to the CESM-LE model. Although OLR was not evaluated for ERA (Figure 4, middle row) and JRA-25 (Figure 4, bottom row), these two reanalyses also show weak and negative correlations of both upper atmospheric metrics with PSI and $P - E$ and large and positive correlations with the midlatitude jet.

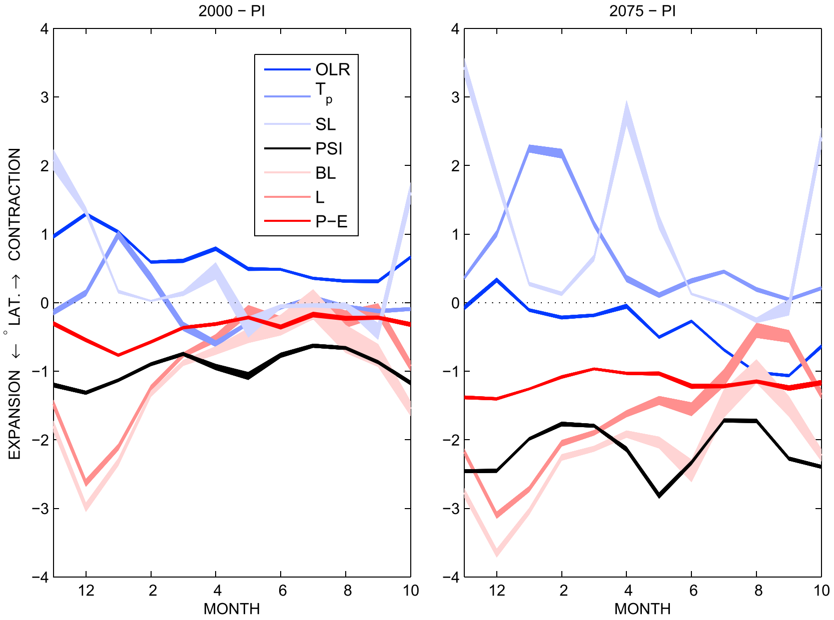

Figure 5. Latitudinal changes in each tropical width metric, calculated from the 40-member ensemble. The envelope around each curve shows the 95% confidence interval, for the Welch's *t* test using 180-decadal means from the PI control and the ensemble of 40-decadal means for each metric. (left) Changes in the decade centered on the year 2000 relative to the PI control climatology. (right) Changes between the decade centered on the year 2075 and the PI control.

3.3. Trends

Finally, we examine how long-term trends in the various metrics relate to one another. For this we return to the CESM-LE model output, so as to compute trends across many decades (trends over the short observational period are very noisy). We consider two periods: from the past (PI control) to the present (the decade 1996–2005, simply labeled 2000) and from the past to the future (the decade 2071–2080, labeled 2075). For each metric, these trends are shown, respectively, in Figures 5 (left) and 5 (right)as a function of month; the envelopes around each curve indicate the 95% confidence interval (obtained from the PI control and the 40-member ensemble). As we found for the correlations presented above, the trends of these upper atmospheric metrics are quite different from trends of tropospheric metrics, for both the present and the future.

Looking at the past (Figure 5, left), note first that the poleward shifts of PSI and $P - E$ are statistically significant in each month, although the change in $P - E$ is considerably smaller in magnitude. Over the same period, a large and significant poleward shift of the midlatitude jet (BL and L) is seen in all seasons except JJA. In contrast, the upper atmospheric metrics (in blue) show little significant change except for a contraction, in some fall-winter months. In particular, OLR shifts equatorward in each month over the historical period in the model.

As for future trends (Figure 5, right), one sees that the poleward shift of PSI nearly doubles during the 21st century in this model, and the predicted future poleward shift of $P - E$ is actually larger in most months than the historical shift. Together with these, the future shifts of both BL and L become significant throughout the year and continue to exhibit a pronounced seasonality with larger changes in DJF than JJA, as shown in *Solomon and Polvani* [2016]. Although a significant tropical expansion emerges for OLR in some months (May through October), neither of the other upper atmospheric changes (blue) indicate a clear expansion of the tropics in the future.

4. Discussion

How can we reconcile our findings of poor correlations between upper atmospheric metrics and the width of the Hadley cell with several recent observational studies that have reported tropical expansion based on trends in the upper atmosphere? For one, the pioneering study of *Hudson et al.* [2006] was focused on the Northern Hemisphere and relied on trends in ozone column amounts. As such it cannot be immediately compared to our Southern Hemisphere focused study; in addition, it is quite possible that due to stratospheric ozone depletion and tropospheric ozone trends, those reported trends may be reflecting processes that are unrelated to the key mechanism driving tropical width variability. Another frequently cited study, the brief report of *Fu et al.* [2006], using satellite measurements of temperature, spanned only a couple of decades (1979–2005): these include the large El Niños of 1982/1983 and 1997/1998, which could bias the results. Finally, the early study of *Seidel and Randel* [2007], based on in situ observations, proposed a new tropopause height-based metric, but that method has been shown to be somewhat unreliable, and highly sensitive to threshold choices [*Birner*, 2010]. More crucially, however, none of these early studies actually evaluated the correlation between the variability in the proposed upper tropospheric metrics and the width of the Hadley cell as defined by the extent of the mean meridional stream function (PSI), which cannot be directly observed at present.

The situation is complicated by the fact that at a fundamental level, we simply do not know if metrics such as OLR = 250 W/m^2 or tropopause gradients should correlate with more traditional metrics of the zonally symmetric tropical circulation, since a solid theoretical understanding of the tropical circulation is lacking at present. The early theory of *Held and Hou* [1980] provided a relationship between the width of the Hadley cell and its height. But that theory proved inadequate to explain the variability of tropical width [*Walker and Schneider*, 2006]. Subsequent efforts to incorporate a role for atmospheric eddies into theories of tropical width have provided somewhat better qualitative agreement with modeling results [*Lu et al.*, 2007; *Frierson et al.*, 2007; *Kang and Lu*, 2012]. Yet no theory to date has been able to provide accurate, quantitative *predictions* for the variability of tropical width [*Walker and Schneider*, 2006; *Korty and Schneider*, 2008].

Another important unknown at present is that while modeling studies show historical expansion of the tropics, it remains uncertain to what degree it is anthropogenically forced. Early studies suggested that models were unable to capture the magnitude of the observed trends [*Hu and Fu*, 2007; *Johanson and Fu*, 2009]. But, as pointed out by *Garfinkel et al.* [2015], internal variability is very large and could have been responsible for a large fraction of the recently observed trends.

As to the forcings themselves, the situation is also rather complicated. Recent analyses of the Fifth Coupled Model Intercomparison Project (CMIP5) suggest that anthropogenic forcing has contributed to the expansion of the tropics [*Hu et al.*, 2013]. However, several different forcings may be acting at the same time. Increasing carbon dioxide [e.g., *Adam et al.*, 2014; *Nguyen et al.*, 2015] and decreasing stratospheric ozone [*Polvani et al.*, 2011a; *Min and Son*, 2013; *Waugh et al.*, 2015] are likely to be major contributors in the Southern Hemisphere, but aerosols and tropospheric ozone may also affect the width of the Hadley cell [*Allen et al.*, 2014]. The relative importance of these different forcings depends on which season, time period, and hemisphere is being considered, so that it is very difficult to make a general statement.

5. Conclusions

Owing to its clear societal importance, the question of whether the tropical belt has been expanding and the potential causes for that expansion have been the subject of a number of recent studies. These have relied on a wide variety of metrics to quantify the expansion, leading a broad and confusing array [*Davis and Rosenlof*, 2012]. The point of this paper has been to seek some clarity and ask which of the many metrics that have appeared in the literature should actually be expected to covary with the width of the Hadley circulation and the edge of the dry zones. Only those metrics can be meaningfully used to capture the changing width of the tropics, on a variety of time scales.

We have here answered that question by exploiting the CESM-LE project, validated by reanalyses. The CESM-LE model allows us to establish correlations among metrics with robust statistics (a very long control and a large ensemble of past and future runs). Focusing on differences in decadal means, we find that robust widening trends of the Hadley cell clearly emerge from the internal variability in the model, both from PI to present and from present into the future. This allows us to then examine and contrast individual metrics of tropical expansion.

What emerges from our analysis is that in the Southern Hemisphere at least, the threshold OLR = 250 W/m^2, tropopause gradients and the upper tropospheric subtropical jet correlate very poorly, and mostly negatively, with the width of the mean meridional circulation and the $P - E = 0$ latitude. This suggests that those metrics and similar ones discussed in *Davis and Rosenlof* [2012] may not be meaningful proxies for the more traditional metrics of Hadley cell expansion interannually, interdecadally, and even multidecadally. As such they need to be used with caution, and their covariability with the width of the Hadley cell needs to be demonstrated, on a range of time scales, before they are proposed as indicators of trends in the width of the tropics.

Looking forward, one would want to repeat the analysis performed here for the Northern Hemisphere, to see whether the conclusions we have reached generalize to a situation which is complicated by the less zonally symmetric character of the circulation (e.g., the presence of continents and longitudinally confined storm tracks). And, of course, we recognize that a study using a single model, even if validated from reanalyses, is far from sufficient to solidly establish a result. Repeating a similar analysis with a different model, especially one with a better resolved stratosphere (or at least with more levels around the tropopause), would be an important next step in corroborating the findings reported here.

Acknowledgments
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