IMPLICATIONS OF HADLEY CELL EXPANSION FOR NORTH AMERICAN DROUGHT

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Abstract

Numerous observational studies have found that the Hadley cells are expanding poleward in both the Northern and Southern Hemispheres, and modeling studies suggest that such expansion is likely to continue throughout this century as a result of global warming. This has led to concerns that the subtropical dry zones may also shift poleward. However, while most studies have focused on zonal-mean precipitation changes, relatively little work has been done on the zonal asymmetries of the impacts of Hadley cell expansion. In this study, I consider these regional asymmetries, and the possibility that they may be associated with shifts of the subtropical high-pressure systems. I find that zonal (east-west) shifts of the subtropical highs—which are not captured by the zonal-mean Hadley cell definition—are in fact more important for precipitation trends in North America than their meridional (north-south) shifts, suggesting that Hadley cell metrics are missing important information.

Introduction

The Hadley cells—atmospheric overturning circulations in which air rises near the equator and sinks around 30^oN and 30^oS—dominate the earth's tropical and subtropical climates. The subsiding branches, in particular, are responsible for the existence of the subtropical high-pressure systems and the subtropical dry zones near 30^o latitude in each hemisphere which contain many of the world's deserts.

Climate models predict that global warming will drive a poleward expansion of the Hadley cells over the 21^{st} century (Lu et al., 2007; Gastineau et al., 2008; Hu et al., 2013; Vallis et al., 2015). Numerous observational studies have found that the Hadley cells are in fact already expanding poleward, though it is not clear whether this is due to global warming, ozone depletion, air pollution, or natural fluctuations in the climate system (Fu et al., 2006; Hu & Fu, 2007; Seidel & Randel, 2007; Seidel et al., 2008; Davis & Rosenlof, 2012; Birner et al., 2014; Lucas et al., 2014). Regardless of the cause, the prospect of poleward expansion has raised concerns about increased drought potential on the poleward margins of the subtropical dry zones (Scheff & Frierson, 2012; Feng & Fu, 2013).

A number of recent studies have found that Hadley cell expansion is in fact associated with drying of the subtropical regions (Lu et al., 2007; Kang & Polvani, 2011; Lau & Kim, 2015; Grise & Polvani, 2016). However, most of this work has focused on the zonal mean, and only a few studies have attempted to identify the particular regions that are most susceptible to drying due to Hadley cell expansion (Cai et al., 2012; Cai & Cowan, 2013), and the associated shifts in the subtropical highs (Li et al, 2011; Li et al, 2012). My previous study (Schmidt & Grise, 2017) concluded that widening of the Hadley cells is in fact associated with increased sea level pressure (SLP) and reduced precipitation in certain regions. However, these effects are zonally asymmetric, with the strongest changes occurring over the oceans and on the western sides of continents.

Figure 1 (similar to Figures 3 and 4 from Schmidt & Grise, 2017) shows the precipitation anomalies associated with short-term poleward shifts of the Northern Hemisphere Hadley cell boundary in both observations (left) and global climate models (right). The observational data used here is an average of the Global Precipitation Climatology Project (GPCP; Adler et al., 2003) and the Climate Prediction Center Merged Analysis of

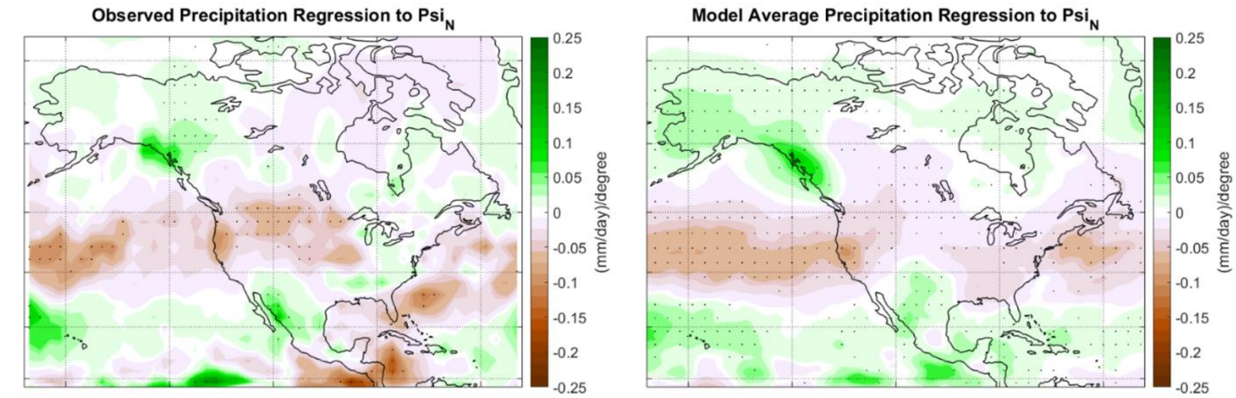

Figure 1. (left) Precipitation anomalies associated with a 1^o poleward shift of the Hadley cell boundary (the latitude where the mean meridional streamfunction at 500 hPa (Ψ'_{500}) = 0), using ERA-Interim reanalysis data (Dee et al., 2011) for the Hadley cell width and the average of two data sets for precipitation (GPCP and CMAP). The El Niño-Southern Oscillation has been removed (see Schmidt & Grise, 2017). **(right)** As at left, but using data from sstClim runs of CMIP5 global climate models (Taylor et al., 2012), in which case sea surface temperatures are prescribed to a control climatology. The regression pattern has been averaged over 15 models. Stippling indicates (left) statistical significance at the 0.95 level, or (right) agreement of at least 80% of models on the sign of the regression. (Adapted from Schmidt & Grise, 2017)

Precipitation (CMAP; Xie & Arkin, 1997) data sets, and the models come from Phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al, 2012). What this figure shows is that widening of the Northern Hemisphere Hadley cell is in fact associated with drying in some land regions (see the brown areas), and that climate models reasonably reproduce the observed pattern.

However, the drying and increased SLP are concentrated in certain regions. Aside from demonstrating the existence of zonal asymmetries in the *effects* of Hadley cell expansion, this may hint at a zonally asymmetric *cause* of the drying. Specifically, the subsiding air in the Hadley cells is itself not zonally symmetric, but tends to be split into semi-permanent subtropical high-pressure systems. These subtropical highs are centered over the oceans, and can be fairly distinct from each other, especially in summer. They will likely shift poleward with the Hadley cells (since the definition of the Hadley cells includes the highs in an averaged sense) but they can also move in more complex ways: they may shift meridionally, but independently of each other, and they may shift zonally. Neither of these modes would be captured by Hadley cell metrics.

The fact that the regions of drying and increased SLP coincide fairly well with the poleward edges of the current subtropical highs suggests that these highs represent a promising avenue for research. The goal of this project is (1) to determine the sensitivity of local SLP and precipitation to the zonal and meridional shifts of these high-pressure systems, as well as to their strengths, and (2) to determine which of these three measures is most important for driving long-term trends in SLP and precipitation.

Data and Methods

I will consider the North Pacific Subtropical High (NPSH) and North Atlantic Subtropical High (NASH). For each high, I will define three metrics: the longitude and latitude of its center, and its strength. The center is defined by the centroid of the $P > 1020\ mb$ region, and the strength is defined by the basin-wide mean sea level pressure.

I use data from the Community Earth System Model Large Ensemble project (CESM-LENS; Kay et al., 2015), which includes 40 runs of the CESM model from 1920 to 2100, using historical values of greenhouse gas concentrations and other forcings up to 2005, and the hypothetical Representative Concentration Pathway (RCP) 8.5

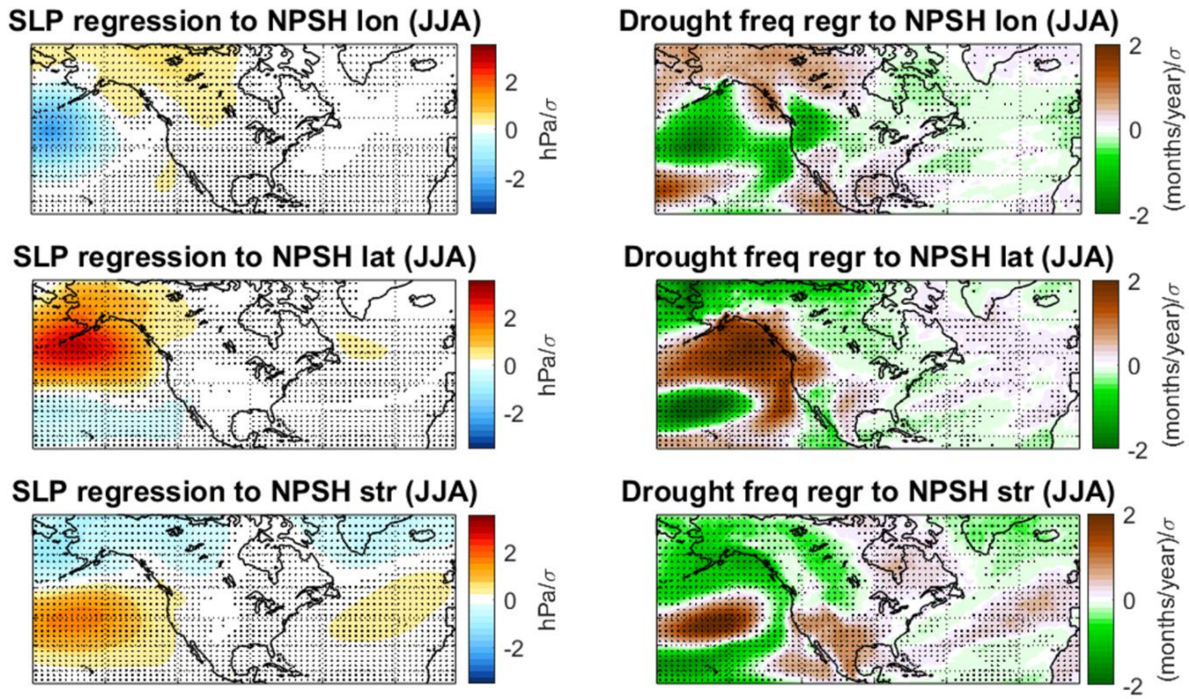

Figure 2. (left) Sea level pressure regressions to the longitude, latitude, and strength of the North Pacific Subtropical High for the JJA season using data from the CESM uncoupled control run. **(right)** Regressions of drought frequency to the same indices as at left. Drought is defined here in terms of months with less than 75% of climatological mean precipitation. Note that these patterns represent the change in SLP (left) or in number of drought months per year (right) associated with a one-standard-deviation shift of each subtropical high index.

emissions scenario after 2005 (Meinshausen et al., 2011). The 40 ensemble members use the same forcings but slightly different initial conditions—at the level of round-off error—in order to quantify the range of internal variability in the climate system. Using this ensemble, I can compute trends in the subtropical high metrics for all 40 members to determine whether they have consistent signs, and in so doing, compare the trends with the internal variability.

CESM-LENS also includes a 2600-year atmosphere-only control run, in which sea surface temperatures are fixed to a climatology, with preindustrial greenhouse gas concentrations. By construction, this run does not include the effects of coupled ocean-atmosphere oscillations such as the El Niño-Southern Oscillation (ENSO), a common confounding variable. Using this control run, I compute regression slopes of local SLP and drought frequency onto the various subtropical high metrics, separately for the December-February (DJF) and June-August (JJA) seasons. This shows the spatial pattern of SLP or drought sensitivity to the subtropical highs. To compute the trends in SLP and precipitation attributable to subtropical high shifts, I multiply these patterns by the ensemble-mean trends in the respective subtropical high metrics.

Comparison of these CESM regression patterns with the multi-model mean from CMIP5 models shows that these patterns are not strongly dependent on the particular choice of model (not shown).

I also use observational data for comparison with the model results. I use monthly-mean SLP data from five reanalyses: (1) European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis data set (ERA-Interim; Dee et al., 2011), (2) NCEP Climate Forecast System Reanalysis (CFSR; Saha et al., 2010), (3) Japanese 55-year reanalysis (JRA-55; Kobayashi et al., 2015), (4) NASA Modern-Era Retrospective analysis for Research and Application Version 2 (MERRA-2; Gelaro et al., 2017), and 5) NCEP-DOE

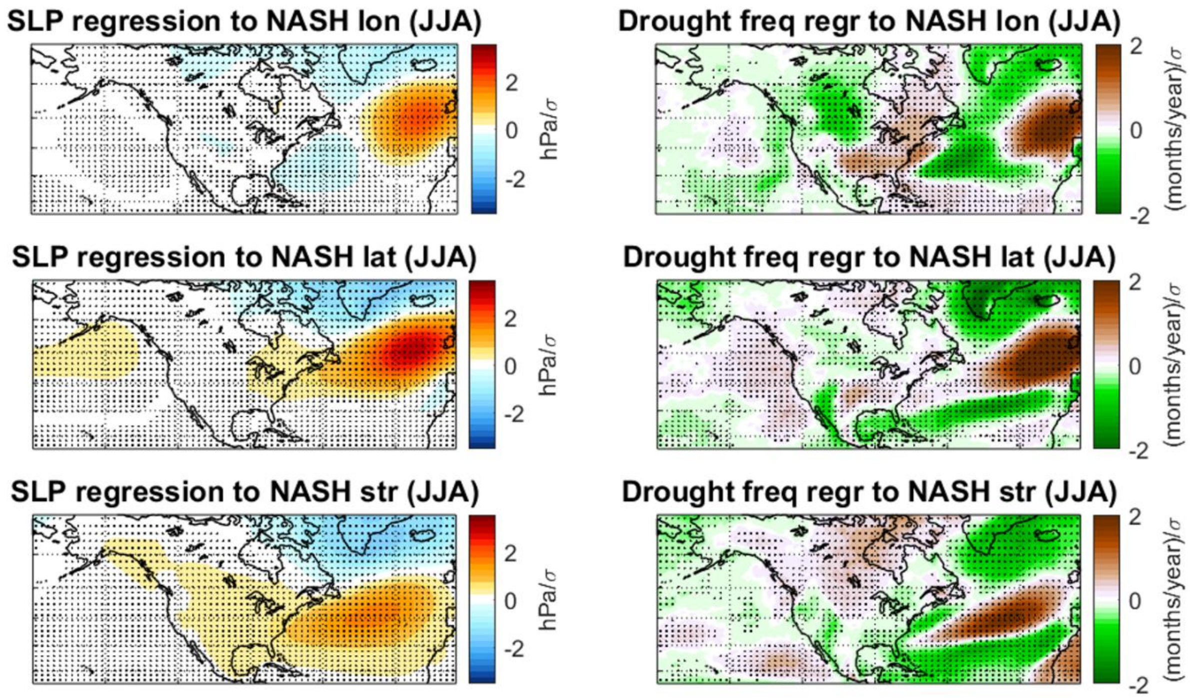

Figure 3. As in Figure 2, but for the North Atlantic Subtropical High.

Reanalysis 2 (Kanamitsu et al., 2002). I also examine gridded monthly SLP observations from the Hadley Centre SLP data set (HadSLP2r; Allan & Ansell, 2006). The time period over which all six data sets overlap is January 1980 – December 2010. Reanalysis data is not the optimal source for information on precipitation, so for that field I instead use monthly-mean data from the GPCP and CMAP data sets, which incorporate both ground-based and satellite estimates of precipitation.

For parts of the analysis, I will consider the frequency of meteorological droughts, defined here as months in which total monthly precipitation at a particular location is less than 75% of the climatological mean from the same location.

Results

The regressions of local SLP and drought frequency to the three subtropical high metrics are shown, for the JJA season, in Figures 2 and 3. For the NPSH longitude, the pattern is a rough dipole, with decreased pressure and decreased drought frequency near the Aleutian Islands, and increased pressure and drought frequency in northwestern North America for increases in longitude (Fig. 2, top row). For the NPSH latitude, I find a simpler north-south dipole pattern, in which SLP and drought frequency both increase in a given region whenever the high shifts into that region (Fig. 2, middle row). Strengthening of the NPSH is associated with increased pressure and decreased precipitation near the center of the high (Fig. 2, bottom row).

For the NASH longitude, I again find a northeast-southwest dipole in both SLP and drought frequency regressions (Fig. 3, top row). The latitude pattern is a dipole with increased SLP and drying in the region of the Azores, and the reverse in the region of Iceland and Greenland (Fig. 3, middle row). This pattern is approximately replicated by the regressions of SLP and drought frequency to the strength of the NASH (Fig. 3, bottom row).

All of these patterns extend across the North American continent to various degrees, though they are often more complex over land than over the oceans. Some of the more complex features of these patterns are likely due to moisture advection associated with the wind anomalies.

Note that shifts of each high have little impact on the other ocean basin, emphasizing the need to consider both separately. Note also that the sensitivity of local climate to each of the three metrics is of similar magnitude. That is, zonal shifts and changes in strength are approximately as important as meridional shifts, though only the latter would be included in the computation of Hadley cell width. This demonstrates the need to consider the subtropical highs separately in order to understand their impacts on North American climate. The patterns for the DJF season are similar to those described here, but somewhat stronger and in some cases slightly more zonally symmetric (not shown). Regression patterns computed from observations and reanalysis products are remarkably similar to these model results (not shown).

Note that the patterns in Figures 2 and 3 show only the regressions of SLP and drought frequency to monthly changes in subtropical high indices in a control run. That is, they do not demonstrate the trends in any of these variables. To address this, I compute the trends in each of the three subtropical high metrics, for each of the highs (NPSH and NASH) in each of the 40 members of the CESM large ensemble. I then multiply the regression pattern of, for example, SLP onto NPSH longitude, by the ensemble-mean trend in the NPSH longitude itself. This gives an estimate of the anticipated trend in SLP attributable to the trend in the NPSH longitude. The resulting patterns (not shown) suggest that the latitudes of the subtropical highs are in fact the least important of the three metrics for determining long-term trends.

Conclusion

In order to estimate changes in North American precipitation and drought frequency over the 21st century, it will be crucial to understand the local effects of large-scale circulation changes. The expansion of the Hadley cells is likely to impact precipitation in some regions. However, these impacts are zonally asymmetric, and we can learn more by studying the regional manifestations of the Hadley cells—the subtropical highs. These highs can shift meridionally with the zonal-mean Hadley cells, but they can also move zonally, and the latter shifts—together with changes in strength—appear to be more important than Hadley cell expansion itself for determining local climate in North America.

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