The Role of Natural Climate Variability in Recent Tropical Expansion

ROBERT J. ALLEN AND MAHESH KOVILAKAM

Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Manuscript received 10 October 2016, in final form 18 February 2017)

ABSTRACT

Observations show the tropical belt has widened over the past few decades, a phenomenon associated with poleward migration of subtropical dry zones and large-scale atmospheric circulation. Coupled climate models also simulate tropical belt widening, but less so than observed. Reasons for this discrepancy, and the mechanisms driving the expansion remain uncertain. Here, the role of unforced, natural climate variability—particularly natural sea surface temperature (SST) variability—in recent tropical widening is shown. Compared to coupled ocean–atmosphere models, atmosphere-only simulations driven by observed SSTs consistently lead to larger rates of tropical widening, especially in the Northern Hemisphere (NH), highlighting the importance of recent SST evolution. Assuming the ensemble mean SSTs from historical simulations accurately represent the externally forced response, the observed SSTs can be decomposed into a forced and an unforced component. Targeted simulations with the Community Atmosphere Model, version 5 (CAM5), show that natural SST variability accounts for nearly all of the widening associated with recent SST evolution. This is consistent with the similarity of the unforced SSTs to the observed SSTs, both of which resemble a cold El Niño–Southern Oscillation/Pacific decadal oscillation (ENSO/PDO)-like SST pattern, which is associated with a wider tropical belt. Moreover, CAM5 coupled simulations with observed central to eastern tropical Pacific SSTs yield more than double the rate of widening compared to analogous simulations without prescribed tropical Pacific SSTs and reproduce the magnitude of tropical widening in atmosphere-only simulations. The results suggest that the bulk of recent tropical widening, particularly in the NH, is due to unforced, natural SST variability, primarily related to recent ENSO/PDO variability.

1. Introduction

Since ~1979, observations and reanalyses show the tropics have widened. This includes a poleward shift of the Hadley cell, jet streams, subtropical dry zones, and extratropical storm tracks (Hu and Fu 2007; Archer and Caldeira 2008; Zhou et al. 2011; Bender et al. 2011; Birner et al. 2014). However, large uncertainty exists on the magnitude of this widening, with estimates ranging from 0.25° to 3.0° decade⁻¹ (Seidel et al. 2008; Lucas et al. 2014). The rapid widening rates derived from some reanalyses have been viewed as unreliable (Quan et al. 2014), and more recent analyses suggest the rate of widening is on the lower end of this range (Fu and Lin 2011; Davis and Rosenlof 2012). Prior to the post-1979 widening, studies have also suggested the existence of a multidecadal period of tropical contraction, particularly in the case of the northern tropical belt (Allen et al. 2014; Bronnimann et al. 2015).

Many causes of tropical widening have been discussed in the literature. In response to increasing greenhouse gas concentrations, climate models yield a wider tropical belt (Lu et al. 2007, 2009; Tao et al. 2016). This is in agreement with scaling relations, where the width of the Hadley cell, assuming 1) angular momentum conserving zonal winds in the upper branch of the Hadley cell and 2) an energetically closed Hadley cell, is proportional to the tropical tropopause height (Held and Hou 1980). A second scaling, based on the poleward extent to which the thermally driven wind becomes baroclinically unstable, implies tropical width is proportional to tropospheric gross static stability and the extratropical tropopause height (Lu et al. 2007). Since tropopause height and tropospheric gross static stability increase in a warmer world, these scaling relations imply a wider tropical belt in response to greenhouse gases.

Besides greenhouse gases, several other anthropogenic climate forcing agents have been implicated in recent tropical widening. This includes polar stratospheric ozone depletion in the Southern Hemisphere (SH), particularly during austral summer (Son et al. 2014).
2009; Polvani et al. 2011; Waugh et al. 2015; Tao et al. 2016). In a recent meta-analysis, Waugh et al. (2015) concludes stratospheric ozone depletion is the dominant driver of tropical summertime expansion from 1979 to the late 1990s (when the ozone hole was formed). In the Northern Hemisphere, anthropogenic aerosols, particularly atmospheric warming black carbon aerosols, have been shown to be important (Allen et al. 2012a,b, 2014; Kovalikam and Mahajan 2015; Allen and Ajoku 2016). Simulation of aerosol-related climate effects, however, possesses significant uncertainty, including factors related to aerosol emissions, radiative properties, transport and removal, and aerosol–cloud interactions (e.g., Bond et al. 2013; Myhre et al. 2013).

Simulations using coupled ocean–atmosphere climate models qualitatively reproduce the observed tropical widening. However, the ensemble mean, which represents the forced signal, is significantly smaller than observed at 0.1°–0.2° decade⁻¹ (Johanson and Fu 2009; Hu et al. 2013; Allen et al. 2014; Quan et al. 2014; Nguyen et al. 2015; Tao et al. 2016). Recent papers suggest that this underestimation is not necessarily due to model shortcomings but may be related to the real-world timing of unforced, natural climate variability (which models will only reproduce by chance). For example, Garfinkeln et al. (2015) use a suite of model simulations to argue a large fraction of recent tropical widening may be due to internal atmospheric variability. Correlations also exist between tropical widening and extratropical modes of climate variability, such as the annular modes. Nguyen et al. (2013) show the Hadley cells contract during the low phase of the annular modes and expand during the high phase. Similarly, Lucas and Nguyen (2015) use radiosonde-based tropical expansion estimates to show the southern annual mode may account for 20%–30% of the SH expansion.

Recent tropical widening may also be related to prominent modes of naturally occurring sea surface temperature (SST) variability, including El Niño–Southern Oscillation (ENSO) and the Pacific decadal oscillation (PDO) (Lu et al. 2008; Grassi et al. 2012; Nguyen et al. 2013; Allen et al. 2014; Adam et al. 2014; Lucas and Nguyen 2015; Mantsis et al. 2017). Tropical extent decreases during the warm phase of ENSO/PDO, and increases during the cold phase (Lu et al. 2008; Grassi et al. 2012; Nguyen et al. 2013; Allen et al. 2014). Lucas and Nguyen (2015) conclude the PDO may account for 50% of the observed tropical widening over Asia, with decadal variations in ENSO accounting for 20%–30% of the global and regional widening. Allen et al. (2014) also argue for the importance of the PDO and show that coupled simulations with a larger −PDO trend post 1979 (similar to observations) yield larger rates of NH tropical widening. Furthermore, atmosphere-only (AMIP) simulations, which are forced with the real-world evolution of SSTs (and hence, the PDO), consistently yield larger rates of tropical widening, particularly in the NH.

Here, we quantify the role of unforced, natural climate variability to recent tropical widening. We devise new climate model simulations that separate the effects of forced versus unforced SST evolution on recent tropical widening. Our major finding is that the unforced components of the SSTs, which resemble the cold phase of ENSO/PDO, are the dominant driver of the widening. This paper is organized as follows: section 2 lists the data and methods we employ, including details on our model simulations; section 3 shows the importance of natural climate variability, particularly recent SST evolution, to recent tropical widening; and section 4 discusses the importance of ENSO/PDO. Finally, a discussion of the results and our conclusions are presented in section 5.

2. Methods and data

a. Tropical edge definition

The tropical edge definitions are the same as employed in several prior studies, including Allen and Ajoku (2016), and the following text is derived from there with minor modifications. We focus on two (dynamical) metrics of tropical width: 1) the latitude of the tropospheric (850–300 hPa) zonal wind maxima (JET) and 2) the latitude where the mean meridional circulation (MMC) at 500 hPa becomes zero on the poleward side of the subtropical maximum. Although a recent analysis concludes the MMC/near-surface jets are decoupled from the subtropical JET (Davis and Birner 2017), we obtain similar JET results using the near-surface jet, based on the 850-hPa zonal winds (not shown). Changes in tropical width (expansion/contraction) are estimated by taking a least squares trend of the annual mean time series of each metric. We focus on annual mean tropical widening because observed seasonal trends are not significantly different from one another (Davis and Rosenlof 2012). Nonetheless, we briefly analyze seasonal rates of tropical widening. Widening of the tropical belt is represented by positive trends in the NH but negative trends in the SH. Trend uncertainty, which accounts for trend robustness across realizations, is estimated as twice the standard error $2 \times \sigma/(n)^{1/2}$, where $\sigma$ is the standard deviation of the trends and $n$ is the number of model realizations. In other cases (e.g., uncertainty in a given realization’s trend), trend significance is based on a standard $t$ test, accounting for the influence of serial correlation by
using the effective sample size \( n(1 - r_1)(1 + r_1)^{-1} \), where \( n \) is the number of years and \( r_1 \) is the lag-1 auto-correlation coefficient (Wilks 1995).

b. Reanalysis data

Observation-based meridional and zonal winds (for MMC and JET calculations) come from seven reanalyses, including NCEP–NCAR (R1) (Kalnay et al. 1996), NCEP–DOE (R2) (Kanamitsu et al. 2002), ERA-Interim (Dee et al. 2011), MERRA (Rienecker et al. 2011), CFSR (Saha et al. 2010), 20CR (Compo et al. 2011), and JRA-55 (Kobayashi et al. 2015). Not all reanalyses extend through 2014: JRA-55 ends in 2013, 20CR ends in 2012, and CFSR ends in 2009. Although these three reanalyses do not extend through 2014, their trends are still used to compare with 1979–2014 tropical widening trends from CAM5. However, all seven reanalyses extend through 2008, the focus of our phase 5 of the Coupled Model Intercomparison Project (CMIP5) analysis.

c. CMIP5 data

CMIP5 (Taylor et al. 2012) monthly mean data were downloaded from the CMIP5 data portal. Table 1 lists the 25 CMIP and AMIP models used. CMIP simulations come from the twentieth-century historical all-forcing experiment, which includes time-varying external forcings (e.g., greenhouse gases, aerosols, ozone, solar variability, and volcanic aerosols). Both CMIP and AMIP simulations use identical external forcing; AMIP simulations also use observed SSTs and sea ice distributions. To extend the CMIP5 historical simulations beyond their nominal ending year of 2005, we use representative concentration pathway 4.5 (RCP4.5). Only those models that archived both CMIP and AMIP simulations are used, and we use the same number of realizations, for each model, for both CMIP and AMIP experiments. This yields 25 nearly identical models, comprising 67 total realizations each. Most AMIP simulations end in 2008, which is why we restrict the CMIP5

<table>
<thead>
<tr>
<th>Institution</th>
<th>Model</th>
<th>CMIP</th>
<th>AMIP</th>
<th>PIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSIRO and Bureau of Meteorology</td>
<td>ACCESS1.0</td>
<td>1</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>ACCESS1.3</td>
<td>1</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>Beijing Climate Center</td>
<td>BCC_CSM1.1</td>
<td>3</td>
<td>3</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>BCC_CSM1.1(m)</td>
<td>3</td>
<td>3</td>
<td>400</td>
</tr>
<tr>
<td>GCESS, Beijing Normal University</td>
<td>BNU-ESM</td>
<td>1</td>
<td>1</td>
<td>559</td>
</tr>
<tr>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>CanESM2</td>
<td>4</td>
<td>0</td>
<td>996</td>
</tr>
<tr>
<td></td>
<td>CanAM4</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>National Center for Atmospheric Research</td>
<td>CSM4</td>
<td>5</td>
<td>5</td>
<td>450</td>
</tr>
<tr>
<td>Centro Euro-Mediterraneo per i Cambiamenti Climatici</td>
<td>CMCC-CM</td>
<td>1</td>
<td>1</td>
<td>330</td>
</tr>
<tr>
<td>Centre National de Recherches Météorologiques (CNRM)/CERFACS</td>
<td>CNRM-CM5</td>
<td>1</td>
<td>1</td>
<td>550</td>
</tr>
<tr>
<td>CSIRO and QCCCE</td>
<td>CSIRO Mk3.6.0</td>
<td>10</td>
<td>10</td>
<td>500</td>
</tr>
<tr>
<td>EC-EARTH consortium</td>
<td>EC-EARTH</td>
<td>1</td>
<td>1</td>
<td>280</td>
</tr>
<tr>
<td>LASG, IAP, Chinese Academy of Sciences, and Center for Earth System Science</td>
<td>FGOALS-g2</td>
<td>1</td>
<td>1</td>
<td>700</td>
</tr>
<tr>
<td>LASG, IAP, Chinese Academy of Sciences</td>
<td>FGOALS-s2</td>
<td>3</td>
<td>3</td>
<td>501</td>
</tr>
<tr>
<td>NOAA/Geophysical Fluid Dynamics Laboratory</td>
<td>GFDL CM3</td>
<td>1</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>GFDL HIRAM-C180</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>NASA Goddard Institute for Space Studies</td>
<td>GISS-E2-R</td>
<td>6</td>
<td>6</td>
<td>831</td>
</tr>
<tr>
<td>Met Office Hadley Centre</td>
<td>HadGEM2-ES</td>
<td>4</td>
<td>0</td>
<td>336</td>
</tr>
<tr>
<td></td>
<td>HadGEM2-A</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Institute for Numerical Mathematics</td>
<td>INM-CM4.0</td>
<td>1</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>L’Institut Pierre-Simon Laplace</td>
<td>IPSL-CM5A-LR</td>
<td>4</td>
<td>4</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>IPSL-CM5A-MR</td>
<td>1</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>IPSL-CM5B-LR</td>
<td>1</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and JAMSTEC</td>
<td>MIROC5</td>
<td>2</td>
<td>2</td>
<td>670</td>
</tr>
<tr>
<td>Max Planck Institute for Meteorology</td>
<td>MPI-ESM-LR</td>
<td>3</td>
<td>3</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>MPI-ESM-MR</td>
<td>3</td>
<td>3</td>
<td>1000</td>
</tr>
<tr>
<td>Meteorological Research Institute</td>
<td>MRI-CGCM3</td>
<td>3</td>
<td>3</td>
<td>500</td>
</tr>
<tr>
<td>Norwegian Climate Centre</td>
<td>NorESM1-M</td>
<td>3</td>
<td>3</td>
<td>501</td>
</tr>
</tbody>
</table>
analyses to the 1979–2008 time period (other analyses, to be described below, are based on a longer, 1979–2014 time period).

We also use 35 analogous coupled ocean–atmosphere realizations from the Community Earth System Model (CESM) Large Ensemble (LENS) Community Project (Kay et al. 2015). CESM LENS simulations were downloaded from the Earth System Grid at the National Center for Atmospheric Research (NCAR). These simulations are run at 0.9° × 1.25° resolution and extended from 2005 to 2014 using RCP8.5 (the only future pathway available for these experiments). Each of these realizations is identically forced; the only difference is the initial condition, which allows the assessment of natural climate variability. Note that the ensemble mean averages out natural climate variability and thus represents the forced response.

Thirty-year tropical widening trends from unforced, preindustrial control (PIC) simulations (Table 1) are also quantified. PIC experiments are used to generate 30-yr overlapping segments for the distribution of unforced tropical widening trends. A total of the number of PIC minus 30 yr plus one 30-yr overlapping segments is used for each model, resulting in 13770 realizations in total. The 90% confidence interval is calculated as the range in which 90% of the samples fall. An analogous method is used to generate 36-yr tropical widening trends from unforced, preindustrial control simulations from the CESM LENS dataset.

d. CAM5 experiments

CAM5 (Neale et al. 2012) AMIP simulations are conducted at 1.9° × 2.5° resolution over the 1970–2014 time period. Time-varying forcing follows the CMIP5 dataset, using RCP4.5 after 2005, including solar variability, estimated concentrations of greenhouse gases, ozone, and volcanic aerosols, and primary emissions of sulfur dioxide and black and organic carbon. All CAM5 results are based on 10 ensemble members, and we analyze the 1979–2014 time period. Each member is integrated from an independent initial condition, which is obtained by applying a random surface temperature perturbation in the year 1970. Initiating simulations in 1970 allows a decade for each simulation to diverge from the initial state of the atmosphere as a result of internal atmospheric variability.

We also use 10 archived CAM5 AMIP realizations, similar to the above, but with the real-world evolution of tropical SSTs only (so-called Tropical Ocean and Global Atmosphere experiments). These simulations span 1880–2014 and use RCP8.5 after 2005. In addition to using RCP8.5, as opposed to RCP4.5, they are also run at a higher spatial resolution of 0.9° × 1.25°. SSTs are based on observations in the tropics, from 28°S to 28°N, and are linearly interpolated from 28° to 35°N and from 28° to 35°S to avoid sharp transitions at 28°N and 28°S. Poleward of 35°, SSTs and sea ice are set to the 1880–2014 climatology. As with the CESM LENS data, these CAM5 AMIP Tropical Ocean and Global Atmosphere (TOGA) simulations were downloaded from the Earth System Grid at NCAR.

Ten additional archived CESM coupled pacemaker simulations are used (CAM5 CMIP pacemaker). These simulations are run at 0.9° × 1.25° resolution and span 1920–2013, using RCP8.5 after 2005 (i.e., radiative forcing is identical to that in CESM LENS). SST anomalies in the central and eastern tropical Pacific (8°N–8°S, 180°–80°W) follow the observed evolution by restoring the SST to the model climatology plus historical anomaly by a Newtonian cooling over the deep tropical eastern Pacific. The restoring time scale is 10 days for a 50-m-deep mixed layer. Outside the tropical central and eastern Pacific, the atmosphere and ocean are fully coupled and free to evolve (Kosaka and Xie 2013). These simulations were downloaded from the NCAR’s High Performance Storage System (HPSS).

In addition to the standard AMIP simulations conducted with CAM5, we also conduct 10 analogous experiments, but without external forcing (CAM5 AMIP NOFORC). This is accomplished by setting greenhouse gas concentrations, volcanic aerosols, solar forcing, ozone, and aerosol emissions to a repeating monthly cycle based on the first year of simulation. Thus, evolution of tropical width in CAM5 AMIP NOFORC is only due to internal atmospheric variability and the real-world evolution of SSTs and sea ice. Comparing CAM5 AMIP with CAM5 AMIP NOFORC approximates the anthropogenic contribution to tropical widening. Note, however, that the real-world SST evolution has an anthropogenic fingerprint, which would affect CAM5 AMIP NOFORC. We address this caveat with additional experiments, as described in the next paragraph. Similarly, we also conduct a series of CAM5 AMIP simulations, but without time-varying ozone forcing (CAM5 AMIP NOOZONE). By comparing CAM5 AMIP with CAM5 AMIP NOOZONE, one is able to assess the role of time-varying ozone on tropical width.

We assume the observed SST evolution can be decomposed into a forced (FSST) and an unforced (UFSST) component. The forced component is obtained from the ensemble mean SSTs from the CMIP5 coupled ocean–atmosphere models. Implicitly, we are assuming the models accurately simulate the true forced signal. As will be shown below, the forced SST component from 1979–2014 is neither El Niño–nor La
Niño–like. Uncertainty exists in whether or not the tropical Pacific will become more El Niño–like with continued warming (which includes enhanced warming of the tropical eastern Pacific and a slowdown of the tropical Pacific Walker circulation). All but one (FGOALS-g2) CMIP5 RCP8.5 model realization and all 40 CESM LENS realizations shows warming of Niño-3.4 SSTs through the twenty-first century. And 70% of the CMIP5 RCP8.5 model realizations and all 40 CESM LENS RCP8.5 realizations show enhanced warming of the tropical eastern Pacific relative to the western Pacific (Allen and Luptowitz 2017). These results suggest a possible shift of the tropical Pacific to a more El Niño–like background state (Cai et al. 2015). Although model biases may influence this projection—including possible overestimation of tropical convection (Sohn et al. 2016)—there are relatively fundamental arguments that support these model projections (Cai et al. 2015; Allen and Luptowitz 2017).

If the true forced signal from 1979 to present is more El Niño–like than what the models simulate, then that would imply a larger tropical contraction signal from the forced SST component. Therefore, natural SST variability would lead to a larger tropical expansion contribution than what we show. If, however, the true forced signal from 1979 to present is more La Niña–like than what the models simulate, then this would imply a stronger tropical expansion signal from the forced SSTs. Thus, natural SST variability would lead to weaker widening than what we show.

The unforced component is estimated by removing the forced SST trend from the observed SST at each grid point. This is done by estimating the 1979–2014 FSST least squares monthly trend at each grid point. This monthly regression coefficient is then multiplied by the deviation of the NH and SH JET trends over all CMIP model realizations. The reanalysis mean JET widening is 0.22° ± 0.06° and −0.18° ± 0.14° decade⁻¹ in the NH and from −0.70° to 0.03° decade⁻¹ in the SH (note that negative SH trends represent tropical widening). This highlights the large uncertainty in observational/reanalysis-based estimates of recent tropical widening (e.g., Davis and Rosenlof 2012; Garfinkel et al. 2015). Nonetheless, the reanalysis mean shows significant poleward displacement of the NH and SH tropical edge for both metrics, particularly the MMC (Table 2). Ensemble mean JET widening is 0.22° ± 0.06° and −0.18° ± 0.14° decade⁻¹ in the NH and SH, respectively; for the MMC, the corresponding trends are about twice as large at 0.55° ± 0.11° and −0.32° ± 0.18° decade⁻¹.

CMIP and AMP simulations driven by observed SSTs yield a large range in tropical widening trends, with many realizations capturing the magnitude of widening from reanalyses. Although this large range could be due to model differences, the CSIRO Mk3.6.0 and CNRM-CM5 models, which archived 10 realizations each, also yield a large range in trends. For example, the standard deviation of the NH and SH JET trends over all CMIP models is 0.24° and 0.34° decade⁻¹. The corresponding standard deviation for the 10 CSIRO Mk3.6.0 simulations is 0.22° and 0.20° decade⁻¹. Similarly, the 10 CNRM-CM5 realizations yield a standard deviation of 0.26° and 0.35° decade⁻¹, respectively. This implies natural climate variability, including both internal atmospheric variability and natural SST variability, significantly contributes to the large range of simulated trends. Note that AMIP simulations are forced with identical, real-world SST evolution, implying that the large range of AMIP trends is due to internal atmospheric variability, as opposed to SST variability.

The role of natural climate variability is further supported by estimating tropical widening trends from

### 3. Results

#### a. CMIP5 results

Figure 1 shows 1979–2008 NH and SH annual mean tropical widening histograms based on climate models from CMIP5 (Table 1), as well as estimates from seven different reanalyses (section 2). Two dynamic measures of tropical widening are shown: one based on the tropospheric jet stream (JET) and the other based on the Hadley circulation, as represented by the MMC. Reanalyses show a considerable spread in both metrics, with MMC trends ranging from 0.35° to 0.74° decade⁻¹ in the NH and from −0.70° to 0.03° decade⁻¹ in the SH (note that negative SH trends represent tropical widening). This highlights the large uncertainty in observational/reanalysis-based estimates of recent tropical widening (e.g., Davis and Rosenlof 2012; Garfinkel et al. 2015). Nonetheless, the reanalysis mean shows significant poleward displacement of the NH and SH tropical edge for both metrics, particularly the MMC (Table 2). Ensemble mean JET widening is 0.22° ± 0.06° and −0.18° ± 0.14° decade⁻¹ in the NH and SH, respectively; for the MMC, the corresponding trends are about twice as large at 0.55° ± 0.11° and −0.32° ± 0.18° decade⁻¹.
unforced PIC simulations. Similar to the forced experiments, a large range in unforced tropical widening trends exists, especially based on the JET metric, solely as a result of natural climate variability. Figure 1 shows that most of the JET trends from reanalysis, as well as the CMIP and AMIP ensemble means, fall within the 5th and 95th percentile of the unforced distribution (red horizontal lines), implying they are not statistically different from natural climate variability. This implies the rate of tropical widening based on the JET metric is not uncommon in the context of natural climate variability. In contrast, tropical widening based on the MMC metric possesses a narrower range of unforced trends, and most reanalyses fall outside the 90% PIC confidence interval, as do the AMIP ensemble means.

Figure 1 also shows that, in most cases, the ensemble mean AMIP signal is significantly larger than the ensemble mean CMIP signal and in better agreement to the observations. For example, the NH and SH CMIP ensemble mean JET widening is $0.07^\circ \pm 0.06^\circ$ and $-0.21^\circ \pm 0.08^\circ$ decade$^{-1}$. The corresponding AMIP widening is $0.22^\circ \pm 0.06^\circ$ and $-0.35^\circ \pm 0.07^\circ$ decade$^{-1}$. Similar results are obtained in the NH for MMC, where the CMIP5 ensemble mean widening is $0.03^\circ \pm 0.03^\circ$ compared to the AMIP mean of $0.20^\circ \pm 0.04^\circ$ decade$^{-1}$ (Table 2). However, in the SH, comparable ensemble mean CMIP and AMIP MMC trends are obtained. Because the ensemble mean averages out natural climate variability, it represents the forced response. Since identical models and number of realizations are used for the CMIP and AMIP ensemble mean, the different rates of widening between coupled ocean–atmosphere models and atmosphere-only models is not likely due to model (dynamical cores, parameterizations, etc.) or forcing differences. The larger rate of ensemble mean tropical widening in AMIP, particularly in the NH, is likely related to the real-world evolution of SSTs.

Despite producing larger ensemble mean trends that better resemble reanalyses, the AMIP ensemble mean MMC trend is smaller than most estimates from reanalyses. This is partially consistent with the role of internal atmospheric variability, since some AMIP realizations do yield MMC trends as large as most reanalyses. However, some MMC trends from reanalyses are not matched in
Table 2. The 1979–2008 and 1979–2014 ensemble mean tropical widening trends (° lat decade\(^{-1}\)) for models and reanalyses. NH and SH trends are shown for the MMC and JET metrics. CMIP5 trends are based on 1979–2008 only. CAM5 CMIP pacemaker results for the 1979–2014 time period are based on 1979–2013. Reanalyses trends are calculated over both time periods using all seven reanalyses (even though three reanalyses end before 2014), and using the four reanalyses that span the entire 1979–2014 time period. The larger rate of NH (SH) tropical widening for 1979–2008 (1979–2014) from reanalyses is due to the different ending years (as opposed to reanalysis used), but these differences are not statistically significant. CAM5 experiments also yield nonsignificant differences between the two time periods, and they do not consistently yield larger NH (SH) trends for 1979–2008 (1979–2014). Tropical expansion is represented by positive (negative) trends in the NH (SH). Trends are significant at the 95% confidence level, unless in bold.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NH</td>
<td>SH</td>
<td>NH</td>
<td>SH</td>
</tr>
<tr>
<td>CMIP5 CMIP</td>
<td>0.07</td>
<td>−0.21</td>
<td>0.03</td>
<td>−0.11</td>
</tr>
<tr>
<td>CMIP5 AMIP</td>
<td>0.22</td>
<td>−0.35</td>
<td>0.20</td>
<td>−0.12</td>
</tr>
<tr>
<td>CAM5 CMIP</td>
<td>0.13</td>
<td>−0.22</td>
<td>0.04</td>
<td>−0.21</td>
</tr>
<tr>
<td>CAM5 AMIP</td>
<td>0.18</td>
<td>−0.24</td>
<td>0.17</td>
<td>−0.12</td>
</tr>
<tr>
<td>CAM5 AMIP TOGA</td>
<td>0.11</td>
<td>−0.24</td>
<td>0.08</td>
<td>−0.13</td>
</tr>
<tr>
<td>CAM5 CMIP pacemaker</td>
<td>0.26</td>
<td>−0.36</td>
<td>0.16</td>
<td>−0.11</td>
</tr>
<tr>
<td>CAM5 AMIP NOFORC</td>
<td>0.12</td>
<td>−0.28</td>
<td>0.12</td>
<td>−0.08</td>
</tr>
<tr>
<td>CAM5 AMIP NOOZONE</td>
<td>0.19</td>
<td>−0.42</td>
<td>0.20</td>
<td>−0.14</td>
</tr>
<tr>
<td>CAM5 FSST</td>
<td>0.01</td>
<td>−0.08</td>
<td>0.03</td>
<td>−0.04</td>
</tr>
<tr>
<td>CAM5 UFSST</td>
<td>0.17</td>
<td>−0.23</td>
<td>0.20</td>
<td>−0.01</td>
</tr>
<tr>
<td>7 Reanalyses</td>
<td>0.22</td>
<td>−0.18</td>
<td>0.55</td>
<td>−0.32</td>
</tr>
<tr>
<td>4 Reanalyses</td>
<td>0.22</td>
<td>−0.22</td>
<td>0.58</td>
<td>−0.37</td>
</tr>
</tbody>
</table>

any AMIP realization. Moreover, these large MMC trends from reanalyses exceed all 13 770 realizations from preindustrial control simulations. Even after expanding our PIC analysis of unforced tropical widening trends with an additional 12 models (resulting in a total of nearly 20000 realizations), these large MMC trends from reanalyses remain unprecedented. The largest rate of 30-yr tropical widening based on the MMC metric in PIC is 0.63° and −0.43° decade\(^{-1}\) in the NH and SH, respectively. Three of the seven reanalyses exceed this NH rate of maximum PIC widening, including R2, 20CR, and R1 at 0.65°, 0.67°, and 0.74° decade\(^{-1}\), respectively. Two of the seven reanalyses exceed the SH rate, including 20CR and R2 at −0.44° and −0.70° decade\(^{-1}\), respectively. All of this suggests that such large MMC trends are either extremely rare or that models possess deficiencies in simulating such variability, underestimate the forcing, or underestimate the response to the forcing. Alternatively, this suggests the large MMC trends in reanalysis may be an artifact, due, for example, to changes in observational input through time or biases in the observations and/or model, which can introduce spurious variability and trends into reanalysis products. We note that the first-generation reanalyses (e.g., R1 and R2), which may be less reliable than more recent reanalyses (e.g., because of the use of an older data assimilation system and atmospheric model), tend to yield the largest rates of MMC tropical widening, which are unprecedented in PIC. Furthermore, 20CR, which also yields rates of MMC tropical widening that are unprecedented in PIC, only assimilates three observations: surface pressure, SSTs, and sea ice distributions. Similar to others (Quan et al. 2014), we suggest that it is likely the very large rates of MMC tropical widening in some realizations—particularly R1, R2, and 20CR—are unreliable.

b. CESM LENS results

Figure 2 presents a similar result, but based on one model, over a longer time period (1979–2014). The coupled simulations come from the Large Ensemble Community Project (Kay et al. 2015), of which there are 35 realizations (CAM5 CMIP). The AMIP simulations, for which there are 10 realizations, were conducted by the authors (CAM5 AMIP; section 2). As in the previous multimodel CMIP and AMIP comparison, a large range of trends exist for CAM5 CMIP and AMIP, supporting the conclusion that the large range is not due to model differences, but due to natural climate variability. For example, the standard deviations of the NH and SH multimodel AMIP JET trends are 0.21° and 0.27° decade\(^{-1}\); the corresponding values for CAM5 AMIP (also over 1979–2008) are 0.16° and 0.20° decade\(^{-1}\). Similarly, the standard deviation of the NH and SH multimodel CMIP JET trends are 0.24° and 0.34° decade\(^{-1}\); the CAM5 CMIP (over 1979–2008) values are 0.18° and 0.35° decade\(^{-1}\). Similar results exist using the MMC metric.

Figure 2 also shows that some realizations capture the magnitude of observed tropical widening, especially in...
Furthermore, in most cases, the ensemble mean CAM5 AMIP signal is significantly larger than the corresponding CAM5 CMIP signal, and in better agreement with reanalyses. The NH and SH CAM5 CMIP ensemble mean JET widening is $0.07^{+0.05}_{-0.07}$ and $0.08^{+0.17}_{-0.07}$ decade$^{-1}$. The corresponding CAM5 AMIP widening is $0.25^{+0.08}_{-0.07}$ and $0.31^{+0.17}_{-0.07}$ decade$^{-1}$. Similar results are obtained for MMC, where the CAM5 CMIP ensemble mean NH and SH widening are $0.03^{+0.04}_{-0.07}$ and $0.04^{+0.02}_{-0.07}$ decade$^{-1}$, respectively, compared to the CAM5 AMIP mean of $0.18^{+0.04}_{-0.13}$ and $0.13^{+0.03}_{-0.07}$ decade$^{-1}$ (Table 2). We note that these CAM5 CMIP and AMIP ensemble mean tropical widening estimates are nearly identical to those from CMIP5. Because the ensemble mean CMIP trend provides an estimate of the forced response, we thus find similar forced responses in CMIP5 models and CESM LENS. Furthermore, since the CAM5 CMIP/AMIP analysis is restricted to the same model, driven with nearly identical external forcing (recall CAM5 CMIP uses RCP8.5 after 2005; CAM5 AMIP uses RCP4.5), the larger rates of tropical widening in CAM5 AMIP, especially in the NH, are due to observed SSTs. This again suggests the importance of the real-world evolution of SSTs.

Additional analyses using 10 archived realizations of CAM5 AMIP, but with the real-world evolution of tropical (as opposed to global) SSTs only, shows the importance of low-latitude SSTs. Depending on the hemisphere and the metric, these CAM5 AMIP TOGA simulations reproduce much of the widening in CAM5 AMIP. For example, the NH and SH ensemble mean JET widenings in CAM5 AMIP TOGA is $0.22^{+0.08}_{-0.07}$ and $0.18^{+0.15}_{-0.07}$ decade$^{-1}$ (Fig. 3), which are 88% and 55% as large as the corresponding values in CAM5 AMIP. The corresponding CAM5 AMIP TOGA rates based on the MMC metric are $0.09^{+0.05}_{-0.07}$ and $0.12^{+0.03}_{-0.07}$ decade$^{-1}$, which are 50% and 92% as large as the corresponding values in CAM5 AMIP (Table 2). We reiterate that these experiments have fixed SSTs outside the tropics, which could mute any tropical–extratropical connections.

We also analyzed 10 archived CAM5 CMIP pacemaker simulations (Fig. 3). These coupled simulations, in addition to historical and RCP8.5 radiative forcing, feature observed SST anomalies in the central and eastern tropical Pacific ($8^\circ N$–$8^\circ S$, $180^\circ$–$80^\circ W$). Outside this region, the atmosphere and ocean are fully coupled and free to evolve (Kosaka and Xie 2013) (thus, tropical–extratropical connections are not muted). Similar to the
CAM5 AMIP TOGA results, CAM5 CMIP pacemaker simulations show the important role of low-latitude SSTs in recent tropical widening, particularly those in the tropical central/eastern Pacific region associated with ENSO. CAM5 CMIP pacemaker simulations reproduce the magnitude of tropical widening in CMIP5 AMIP and yield more than double the rate of widening relative to CAM5 CMIP. Since the only difference between CAM5 CMIP pacemaker and CAM5 CMIP is observed SSTs in the central/eastern tropical Pacific, the enhanced rate of widening in CAM5 CMIP pacemaker is due to the observed evolution of central/eastern Pacific SSTs. The NH and SH ensemble mean JET widenings in CAM5 CMIP pacemaker are $0.29^\circ \pm 0.07^\circ$ and $-0.38^\circ \pm 0.14^\circ$ decade$^{-1}$ (Table 2). The corresponding rates of tropical widening based on the MMC metric are $0.14^\circ \pm 0.07^\circ$ and $-0.12^\circ \pm 0.02^\circ$ decade$^{-1}$.

c. CAM5 results

1) NO EXTERNAL FORCING EXPERIMENTS

To further show the importance of the real-world SST evolution, we conduct another 10-member ensemble of CAM5 AMIP simulations, but with no external forcing. Figure 4a shows NH and SH JET trends from reanalyses, CAM5 AMIP, and CAM5 AMIP NOFORC. CAM5 AMIP NOFORC yields similar rates of widening as CAM5 AMIP. For example, the CAM5 AMIP ensemble mean is $0.25^\circ \pm 0.08^\circ$ decade$^{-1}$ in the NH, relative to the CAM5 AMIP NOFORC ensemble mean of $0.20^\circ \pm 0.08^\circ$ decade$^{-1}$. Similar results exist for the SH, where the CAM5 AMIP ensemble mean is $-0.31^\circ \pm 0.10^\circ$ decade$^{-1}$ relative to $-0.28^\circ \pm 0.10^\circ$ decade$^{-1}$ for CAM5 AMIP NOFORC (Table 2). Thus, CAM5 AMIP NOFORC reproduces 80%–90% of the JET-based tropical widening from CAM5 AMIP. Similar conclusions are obtained with the MMC metric, where CAM5 AMIP NOFORC yields similar ensemble mean tropical widening as CAM5 AMIP ($\sim$80% as large; Fig. 4b).

These two experiments further support the importance of observed SSTs to recent tropical widening.

2) NO OZONE EXPERIMENTS

Several studies have shown the importance of ozone depletion to SH tropical widening, particularly during austral summer (Son et al. 2009; Polvani et al. 2011; Waugh et al. 2015; Garfinkel et al. 2015). However, several other studies have disputed this, suggesting that observed SSTs are the dominant driver of tropical widening (Staten et al. 2012; Quan et al. 2014; Adam et al. 2014). Our results are consistent with the latter: we find negligible differences in annual mean tropical widening between CAM5 AMIP and corresponding simulations without time-varying ozone (Fig. 5). For example, the CAM5 AMIP ensemble mean JET trend in the NH is $0.25^\circ \pm 0.08^\circ$ decade$^{-1}$, relative to the CAM5 AMIP NOOZONE ensemble mean of $0.30^\circ \pm 0.06^\circ$ decade$^{-1}$ (Table 2). More importantly, similar results exist for the SH, where the CAM5 AMIP ensemble mean JET is $-0.31^\circ \pm 0.10^\circ$ decade$^{-1}$ relative to $-0.40^\circ \pm 0.12^\circ$ decade$^{-1}$ for CAM5 AMIP NOOZONE. Similar conclusions are obtained with the MMC metric (Fig. 5c; Table 2). Although an ozone-induced tropical widening fingerprint could exist in the observed SSTs (FSST experiments described below suggest this is likely not a factor, especially for MMC), this result implies ozone is not the dominant driver of recent (annual mean) SH tropical widening, based on CAM5. Furthermore, even
over the time period when the ozone hole was formed (1979–99), the difference between CAM5 AMIP and CAM5 AMIP NOOZONE SH trends is not statistically different (Figs. 5b,d). For example, based on JET, the 1979–99 CAM5 AMIP (CAM5 AMIP NOOZONE) ensemble mean SH tropical widening trend is 0.30 ± 0.25° decade⁻¹ (0.22° ± 0.20° decade⁻¹). Based on MMC, the corresponding CAM5 AMIP (CAM5 AMIP NOOZONE) trend is 0.12° ± 0.04° decade⁻¹ (0.10° ± 0.07° decade⁻¹). We note that internal atmospheric variability is very large over this shorter time period: a larger number of realizations may be required to truly isolate the ozone signal.

We mention again that the CAM5 CMIP ensemble mean SH (and NH) tropical widening estimates are nearly identical to those from CMIP5 (Table 2). Since this shows that the forced response is similar between CMIP5 models and CAM5, we do not think CAM5 model biases contribute to a lack of an ozone hole impact on SH tropical widening. However, we acknowledge that the CMIP5 ozone dataset may underrepresent the observed Antarctic ozone depletion (Waugh et al. 2015; Garfinkel et al. 2015), which could contribute to an underestimate of SH tropical widening in our experiments (and in CMIP5). Nonetheless, even when an interactive ozone hole is simulated (and in better agreement to the observations), the role of observed SSTs on annual mean 1980–2009 SH tropical widening appears to dominate the response [Fig. 2b in Garfinkel et al. (2015)].

3) FORCED AND UNFORCED SST EXPERIMENTS

The similarity of tropical widening trends between CAM5 AMIP and CAM5 AMIP NOFORC implies direct atmospheric forcing from greenhouse gases (GHGs), aerosols, ozone, solar variability, and volcanic eruptions are not the dominant driver of the CAM5 AMIP signal. Note, however, that direct atmospheric forcing is not negligible, since the ensemble mean in coupled simulations yields relatively small, but significant, tropical widening trends, particularly in the SH. This apparent contradiction can be reconciled by noting that direct atmospheric forcing affects SSTs, and this effect will be accounted for in atmosphere-only simulations driven by observed SSTs, such as CAM5 AMIP NOFORC.

The real-world evolution of SSTs has both a forced component due to anthropogenic emissions, volcanic eruptions, and solar variability, and an unforced component due to natural SST variability. We assume the observed SST evolution can be decomposed into a forced and an unforced component (Fig. 6). The forced component is obtained from the ensemble mean SSTs from the CMIP5 coupled ocean–atmosphere models (Table 1). The unforced component is estimated by removing the forced SST trend from the observed SST at each grid point. We note that the UFSST trend pattern resembles the observations throughout the Pacific, including cooling of the tropical eastern and central Pacific, and an off-equatorial boomerang-like shaped warming in the western and central Pacific (i.e., a cold ENSO/PDO-like pattern). This is particularly prominent for the time period 1991–2011, when the cold ENSO/PDO-like SST pattern is exceptionally strong. In contrast, the FSST trend pattern, which shows large-scale, relatively uniform warming bears little resemblance to the observed SST trends. We also note that UFSST bears several similarities to the SST pattern associated with tropical widening, which also resembles a cold ENSO/PDO-like SST pattern (Fig. 7). These results alone imply that the importance of observed SSTs to recent tropical widening is unlikely related to the forced component. Figure 6 also shows the corresponding ensemble mean SST trends from CAM5 CMIP.
pacemaker. Despite being constrained by the observed SST anomalies in the central and eastern tropical Pacific (8°N–8°S, 180°–80°W), CAM5 CMIP pacemaker SST trends are similar to the observed trends throughout many ocean basins, particularly the extratropical Pacific. Thus, similar to observations, CAM5 CMIP pacemaker SST trends resemble a cold ENSO/PDO pattern.

We perform an additional 10-member ensemble of CAM5 AMIP NOFORC experiments but replace the observed SST dataset with either the forced or unforced contribution. To isolate the effects of SSTs only, we also fix the sea ice in these simulations (to a repeating monthly climatology based on the first year of simulation). Figure 8a shows NH and SH rates of tropical widening based on JET in reanalyses, CAM5 FSST, and CAM5 UFSST. Consistent with prior results, a large range of trends exists for both CAM FSST and CAM5 UFSST, as a result of internal atmospheric variability. However, Fig. 8a shows that CAM5 FSST yields weaker ensemble mean rates of tropical widening. The ensemble mean CAM5 FSST JET trends are not significant, at 0.01° ± 0.07° in the NH and −0.11° ± 0.13° decade⁻¹ in the SH. Despite the lack of significance, we note the ensemble mean SH JET trend is relatively large, implying the possibility of an ozone-induced SH tropical widening fingerprint in the observed SSTs (this, however, is not the case for the MMC metric). The corresponding trends from CAM5 UFSST are much larger and significant at 0.23° ± 0.08° and −0.30° ± 0.10° decade⁻¹,
Fig. 6. The 1979–2014 and 1991–2011 SST trends (K decade$^{-1}$). (a),(e) Hadley Centre observed SST trends; (b),(f) the forced component, estimated from the ensemble mean of the CMIP5 twentieth-century all-forcing experiments, combined with RCP4.5; (c),(g) the unforced component, which is estimated by removing the forced SST trend from the observed SST at each grid point; and (d),(h) CAM5 CMIP pacemaker SST trends. The trend (left) from 1979 to 2014 and (right) from 1991 to 2011 when the rate of tropical widening is largest. This shorter, 21-yr time period also corresponds to the maximum trend (toward the cold ENSO phase) in the SOI and PDO. Trend symbols represent significance at the 90% (diamond symbols); 95% (× symbols); and 99% (dots) confidence level, accounting for autocorrelation.
respectively. These CAM5 UFSST rates of widening are also nearly the same as those from CAM5 AMIP NOFORC. Similar CAM5 UFSST conclusions are obtained with the MMC metric (Fig. 8b; Table 2). These results show the importance of the unforced component of the real-world evolution of SSTs to recent tropical widening.

In terms of the linearity of the response, the NH JET response is relatively linear, with the sum of CAM5 FSST and UFSST tropical widening (0.01° and 0.23° decade⁻¹, respectively) similar to that from CAM5 AMIP NOFORC (0.20° decade⁻¹); in the SH, however, there is less linearity as the sum of CAM5 FSST and UFSST tropical widening (−0.11° and −0.30° decade⁻¹, respectively) exceeds that in CAM5 AMIP NOFORC (−0.28° decade⁻¹). The MMC response exhibits more linearity, as the sum of NH CAM5 FSST and UFSST MMC tropical widening (0.02° and 0.18° decade⁻¹, respectively) is similar to, but larger than, that from CAM5 AMIP NOFORC (0.15° decade⁻¹). In the SH, the sum of CAM5 FSST and UFSST MMC tropical widening (−0.03° and −0.05° decade⁻¹, respectively) is also similar to that in CAM5 AMIP NOFORC (−0.10° decade⁻¹).

Finally, comparing the ensemble mean CAM5 UFSST tropical widening trends (which provide an estimate of the unforced component of the real-world evolution of SSTs to recent tropical widening.

Fig. 7. The 1979–2014 correlation map between annual mean tropical width and observed SSTs. Correlations maps are shown based for the (a),(b) JET and (c),(d) MMC metric for (top) CAM5 AMIP and (bottom) reanalyses. Results are shown for total (NH and SH) tropical widening.
Thus, we conclude that natural SST variability accounts for the bulk of the widening, particularly in the NH.

d. Seasonal rates of tropical widening

Several studies have suggested tropical widening possesses seasonality (Hu and Fu 2007; Polvani et al. 2011; Allen et al. 2012b), with maximum widening trends—primarily based on the MMC metric—in each hemisphere’s summer/fall season. Furthermore, JET widening in the SH seems to primarily occur during austral summer (Polvani et al. 2011). A more recent analysis of observed tropical widening, however, found nonsignificant seasonality in all metrics analyzed, including MMC- and JET-based metrics, as well as additional diagnostics based on the tropopause height, outgoing longwave radiation, and precipitation minus evaporation (Davis and Rosenlof 2012). As shown in Fig. 6 from Davis and Rosenlof (2012, p. 1074), “in no cases were the seasonal trends different from one another at the 5% level, although the qualitative observations regarding the MMC and JET metrics are borne out at the 15% level.” Although observations do not support strong tropical widening seasonality, we briefly analyze seasonal trends.

Our analysis supports the previous results, as the reanalysis mean MMC NH widening is largest during JJA at $0.76 \pm 0.19^\circ$ decade$^{-1}$, followed by SON at $0.59 \pm 0.12^\circ$ decade$^{-1}$ (Fig. 9b). For the SH, the mean reanalysis MMC widening is largest during DJF at $-0.64 \pm 0.28^\circ$ decade$^{-1}$, followed by MAM at $-0.46 \pm 0.22^\circ$ decade$^{-1}$. Based on JET, however, the NH tropical edge during JJA contracts at $-0.32 \pm 0.10^\circ$ decade$^{-1}$ (similar results are obtained for the near-surface JET). Maximum NH JET widening occurs during SON, at $0.36 \pm 0.09^\circ$ decade$^{-1}$ (Fig. 9a). In the SH, consistent with the MMC metric, maximum widening based on JET also occurs during DJF at $-0.57 \pm 0.07^\circ$ decade$^{-1}$, followed by MAM. We note that averaging over the reanalyses and showing the uncertainty in the trend across reanalyses leads to somewhat clearer seasonality, as compared to looking at each reanalysis separately (as in Davis and Rosenlof 2012). For example, Fig. 9b clearly shows a significant difference between NH MMC widening in JJA/SON relative to DJF/MAM. However, the NH seasonality is not consistent across our two metrics. The only consistent seasonal signal appears to be in the SH (which is not our main focus), where both JET and MMC show maximum widening during DJF, followed by MAM.

Similar to observations, simulated tropical widening from anthropogenic forcings display qualitative seasonality, with minimal significant seasonal differences. For example, in the NH, GHGs yield maximum widening (based on MMC) during SON and minimum widening during JJA (Tao et al. 2016). Ozone yields maximum NH widening during MAM (although other seasons are similar), and aerosols yield maximum widening during JJA and minimum widening during SON (Allen et al. 2012b; Tao et al. 2016). If the observed seasonality from reanalyses is real, there is no clear anthropogenic forcing agent that accounts for the observed maximum NH widening during JJA and SON (unless aerosols are underestimated). Seasonality of external forcing in the SH is more clear, as ozone leads to maximum widening during DJF and minimum widening during JJA (Tao et al. 2016). GHGs yield uniform SH widening, with no significant seasonal cycle. Thus, in the SH, the seasonal effects of ozone on tropical widening closely match the observed seasonality.

Based on CAM5 AMIP–type simulations for MMC in the NH, we find CAM5 UFSST and CAM5 CMIP

![Fig. 8. The 1979–2014 annual mean tropical expansion for individual realizations. As in Fig. 4, but based on 10 CAM5 AMIP NOFORC simulations driven by the CAM5 FSST (cyan) and the CAM5 UFSST (blue) evolution of SSTs; the reanalysis results are in black.](image-url)
pacemaker yield maximum MMC widening during JJA at 0.31° ± 0.22° and 0.37° ± 0.24° decade⁻¹, respectively. CAM5 AMIP and CAM5 AMIP NOFORC yield maximum MMC widening in MAM, followed by JJA. This seasonality, however, is not significant. CAM5 FSST also yields maximum NH JET widening during SON; CAM5 FSST yields maximum widening during MAM; CAM5 UFSST yields maximum widening during JJA; and CAM5 CMIP pacemaker yields maximum widening during JJA (followed by DJF). Again, however, the seasonality is generally not significant.

In the SH, reanalyses yield maximum JET widening during DJF, followed by MAM, in agreement to the maximum SH widening based on MMC. CAM5 AMIP also yields maximum SH JET widening during DJF. Other CAM5 experiments yield a range of seasons with maximum SH JET widening. CAM5 AMIP NOFORC yields maximum SH JET widening during MAM, including CAM5 AMIP, CAM5 AMIP NOFORC, and CAM5 UFSST. CAM5 CMIP pacemaker yields maximum NH JET widening during JJA.

In the SH, reanalyses yield maximum JET widening during DJF, followed by MAM, in agreement to the maximum SH widening based on MMC. CAM5 AMIP also yields maximum SH JET widening during DJF. Other CAM5 experiments yield a range of seasons with maximum SH JET widening. CAM5 AMIP NOFORC yields maximum SH JET widening during MAM, including CAM5 AMIP, CAM5 AMIP NOFORC, and CAM5 UFSST. CAM5 CMIP pacemaker yields maximum widening during JJA (followed by DJF). Again, however, the seasonality is generally not significant.

To conclude, observations yield weak seasonality of tropical widening trends that is not consistent across metrics. Reanalyses show maximum MMC widening during JJA for the NH and during DJF for the SH. Although ozone yields a similar seasonal cycle as observed in the SH, the role of anthropogenic forcings on the seasonality of tropical widening in the NH is less clear. CAM5 AMIP–type simulations can reproduce the observed summertime maxima, including CAM5 UFSST, implying natural SST variability may be able to explain the weak seasonal cycle of tropical widening based on the MMC metric. Corresponding results based on the JET metric are more mixed.

4. Relationship to ENSO/PDO

Although the exact mechanism by which the unforced component of recent SST trends, as well as the observed SST trends themselves (Fu et al. 2006; Lau et al. 2008; Johanson and Fu 2009), lead to a wider tropical belt is unclear, both trend patterns resemble a cold ENSO/PDO-like pattern (Fig. 6), which has been associated with a wider tropical belt (Lu et al. 2008; Grassi et al. 2012; Allen et al. 2014; Lucas and Nguyen 2015). This is further explored by quantifying the SST pattern associated with tropical widening/contracting over 30-yr time periods in preindustrial control simulations. Since these simulations lack time-varying external forcing, changes in tropical belt width arise solely as a result of
natural climate variability, including internal atmospheric variability and natural SST variability. Similar to the pattern of recent observed SST trends, as well as UFSST, we find that unforced tropical widening in both JET and MMC trends is associated with a cold ENSO/PDO-like pattern; tropical contraction is associated with the opposite pattern (Figs. 10 and 11). Moreover, the magnitude of this pattern, as quantified by the Niño-3.4 (5°S–5°N, 170°–120°W) SST trend, significantly (anti) correlates with the magnitude of tropical widening/contraction (i.e., colder Niño-3.4 SSTs are associated with larger tropical widening, and vice versa). Binning tropical widening/contraction into 0.1° decade⁻¹ bins for JET and 0.05° decade⁻¹ bins for MMC and averaging over all such PIC realizations yields correlations with the corresponding Niño-3.4 SST trends that range from −0.88 for NH MMC to −0.99 for SH JET. Based on total (NH + SH) tropical widening, the corresponding correlations are −0.98 for MMC and −0.99 for JET. Binning the trends, in effect, cancels out much of the scatter, due, for example, to internal atmospheric variability. The corresponding correlations for total tropical widening, without binning, are still significant, but smaller, at −0.36 for MMC and −0.45 for JET.

Idealized CAM5 simulations also exhibit significant tropical widening, particularly in the NH, when forced with the cold ENSO tropical Pacific SST pattern. These CAM5 ENSO experiments yield tropical widening based on the JET metric of 2.1° in the NH and 0.70° in the SH; the corresponding values based on the MMC metric are about half as large at 1.2° and 0.30°. Based on a standard t test using the pooled variance, the NH responses are significant at the 99% confidence level; SH responses are significant at the 95% confidence level. Thus, a cold ENSO-like SST pattern is associated with a wider tropical belt. Because recent SST evolution has resembled this pattern, this helps to explain why the observed SST evolution is critical for producing larger tropical widening, in better agreement to observations.

Over decadal time intervals, tropical widening exhibits considerable variability, which is also significantly correlated with the magnitude of ENSO/PDO trends. Figure 12 shows 21-yr moving window tropical widening trends for several AMIP experiments, CAM5 CMIP pacemaker, and reanalyses, as well as the corresponding PDO and SOI trends. Tropical widening exhibits two maxima, near 2002 and 2011, which in turn correspond to peaks in the PDO/SOI trend. The second maxima near 2011 is particularly pronounced, which corresponds to amplification of the cold ENSO/PDO-like SST pattern (Fig. 6).

Based on sixteen 21-yr moving window trends (1979–99, . . . , 1994–2014), a correlation larger than 0.5 is significant at the 95% confidence level. For JET, all AMIP and reanalyses ensemble mean trends yield significant decadal correlations with the PDO/ SOI trend. For example, the corresponding correlations based on CMIP5 AMIP NOFORC are 0.81 (0.94) in the NH and 0.64 (0.96) in the SH for the PDO (SOI). Similar results apply for the total (NH + SH) rate of tropical widening (Fig. 12b), where the CMIP5 AMIP NOFORC JET–PDO (JET–SOI) 21-yr moving window trend correlation is 0.74 (0.97). The lone exception is CAM5 FSST, where the correlations are much weaker (if not negative), especially in the NH. This, however, is expected since natural modes of climate variability, like the PDO/ SOI, have been removed from FSST. CAM5 CMIP pacemaker also yields significant correlations, particularly between 21-yr moving window tropical widening trends and the corresponding SOI trends. For example, the correlation based on NH (SH) JET widening and the SOI trend is 0.78 (0.79). Based on total (NH + SH) JET widening, the corresponding correlation with the SOI trend is 0.86. Similar, but somewhat weaker, results apply for the MMC metric (Figs. 12c,d), as well as trends based on a static beginning year, but an ever increasing ending year (1979–99, 1979–2000, . . . , 1979–2014) (not shown). In nearly all cases, correlations with the SOI are larger than those with the PDO, further supporting the important role of low-latitude (Pacific) SSTs.

5. Discussion and conclusions

Using a variety of simulations, we have shown the importance of the internal atmospheric variability and, in particular, the real-world SST evolution to recent tropical widening. Coupled ocean–atmosphere (CMIP) and atmosphere-only simulations driven by observed SSTs (AMIP) yield a large range in tropical widening trends (Figs. 1 and 2), consistent with the importance of natural climate variability. In the case of AMIP simulations, this large range of trends is due to internal atmospheric variability. Many CMIP and, in particular, AMIP realizations capture the magnitude of widening from reanalyses. However, some MMC tropical widening estimates from reanalyses are not matched in any AMIP/CMIP realization, including nearly 20 000 PIC experiments. Although models may underestimate internal variability, we suggest that it is likely the very large rates of MMC tropical widening in some reanalyses are unreliable (Quan et al. 2014).

AMIP simulations yield larger rates of tropical widening relative to CMIP simulations, in better agreement to reanalyses. This is particularly the case in the Northern Hemisphere, where the AMIP ensemble mean is 3 (6) times the rate of JET (MMC) widening relative
to the CMIP ensemble mean, in both CMIP5 and CAM5 simulations (Table 2). In the Southern Hemisphere, AMIP simulations yield about double the rate of JET widening relative to CMIP. Similarly, CAM5 AMIP yields about double the rate of SH MMC widening relative to CAM5 CMIP; however, similar SH MMC rates are obtained for CMIP5 coupled ocean–atmosphere and atmosphere-only models. Since identical CMIP5 models and number of realizations are used for the CMIP and AMIP ensemble mean (and the same model is used for CAM5 CMIP/AMIP), the different rates of widening between couple ocean–atmosphere models,
FIG. 11. SST trend pattern (K decade$^{-1}$) associated with (a),(b),(e),(f) NH and (c),(d),(g),(h) SH relatively large (top 5%) tropical widening/contraction in unforced PIC experiments. Results are shown for tropical widening based on (left) JET and (right) MMC metrics, using 30-yr time chunks.
Idealized experiments with CAM5 were conducted to isolate the role of real-world SSTs and external forcing. CAM5 AMIP NOFORC, which is identical to CAM5 AMIP but with fixed external forcing, yields 80% of the CAM5 AMIP JET and MMC tropical widening (Fig. 4). Similarly, CAM5 experiments with fixed ozone forcing (CAM5 AMIP NOOZONE) yield similar rates of tropical widening as CAM5 AMIP. Furthermore, similar ensemble mean tropical widening trends are obtained for both CAM5 CMIP and CMIP5 CMIP (Table 2), implying the forced component of tropical widening in CAM5 is similar to other models. Thus, the CAM5 AMIP NOFORC experiments imply that direct atmospheric forcing from GHGs, aerosols, solar variability, and volcanic eruptions, as well as ozone depletion, are not the dominant driver of tropical widening. Although we cannot rule out the possibility a forcing...
mechanism is underestimated (e.g., ozone or aerosols) in all models, our point is that it is not necessary to invoke this possibility to explain the coupled model underestimation of recent tropical widening: underestimation in the coupled runs, especially in the NH, is due to natural SST variability.

To isolate the role of external forcing versus natural climate variability on recent SST evolution, we decompose the observed SSTs into a forced (FSST) and an unforced (UFSST) component. This assumes that the ensemble mean SSTs from historical (all forcing) simulations accurately represent the externally forced response. The spatial pattern of FSST bears little resemblance to the observed SSTs, as well as to the SST pattern associated with a wider tropical belt. Thus, FSST is unlikely to be the cause of the enhanced rate of tropical widening in AMIP simulations. The unforced component of recent SST evolution, however, bears several similarities to the observed SSTs, including a cold ENSO/PDO-like pattern (Figs. 6, 7). UFSST also resembles the SST pattern associated with a wider tropical belt, which is also cold ENSO/PDO-like.

If the true forced signal from 1979 to present is more El Niño–like than what the models simulate, then that would imply a larger tropical contraction/weaker tropical widening signal from the forced SST component. Therefore, natural SST variability would lead to a larger tropical widening contribution than what we show. If, however, the true forced signal from 1979 to present is more La Niña–like than what the models simulate, then this would imply a stronger tropical expansion signal from the forced SSTs. Thus, natural SST variability would lead to weaker widening than what we show.

The importance of the unforced component of recent SST evolution was further confirmed by CAM5 UFSST simulations (Fig. 8). CAM5 UFSST showed significant tropical widening in both hemispheres for both metrics, nearly as large as those from CAM5 AMIP NOFORC. In contrast, CAM5 FSST simulations yielded significantly less tropical widening, which was also not significant. Moreover, CAM5 UFSST yields more than double the rate of total (NH + SH) tropical widening relative to the forced contribution. The importance of natural SST variability in driving NH tropical widening is particularly robust, where the CAM5 UFSST JET and MMC trends are more than 3 times as large as those based on the forced signal.

Tropical widening also exhibits considerable variability on decadal time scales, and much of this variability in both AMIP simulations and reanalyses, is correlated with ENSO/PDO evolution (Fig. 12). Although it is difficult to draw conclusions on which of these two modes of climate variability is most important, we do find significant tropical widening in idealized CAM5 simulations when forced with the cold ENSO tropical Pacific SST pattern. CAM5 AMIP TOGA experiments also reproduce 50%–90% of the tropical widening in CAM5 AMIP experiments. We note that these experiments have fixed SSTs outside the tropics, which could mute any tropical–extratropical connections. More realistic experiments (CAM5 CMIP pacemaker) reproduce the magnitude of CMIP5 AMIP and CAM5 AMIP tropical widening, as well as 2 to 4 times the widening relative to CAM5 CMIP. Finally, analysis of PIC experiments shows that the magnitude of the SST pattern associated with tropical widening/contraction, as quantified by the Niño-3.4 SST trend, significantly correlates with the magnitude of tropical widening/contraction. Thus, low-latitude SSTs, particularly those in the central/eastern tropical Pacific, which are the dominant location for ENSO variability, are of central importance.

Although we have not investigated the role of natural climate variability (e.g., ENSO/PDO) on the pre-1979 period, our results here are consistent with Allen et al. (2014) and Bronnimann et al. (2015). In agreement with the reversal of the PDO trend from ~1950–1979 (i.e., warm phase), these studies found contraction of the NH tropical belt, in both observations and models (e.g., CMIP5 AMIP).

We conclude by noting that anthropogenic forcing will likely become more important through the twenty-first century. Several studies have noted the importance of future, projected GHG increases in driving a wider tropical belt (Lu et al. 2007; Johanson and Fu 2009; Hu et al. 2013), as well as future decreases in aerosol emissions (Allen et al. 2012a; Allen and Ajoku 2016). However, our results imply that any future, anthropogenically forced tropical widening signal will be significantly modulated by natural climate variability associated with ENSO/PDO evolution. We also note that in the near future, tropical widening is likely to slow down, as the ENSO/PDO cycle transitions to the opposite phase.

Acknowledgments. This study was funded by NASA NEWS grant NNX13AC06G and NSF award AGS-1455682. We acknowledge the CESM Large Ensemble Community Project and supercomputing resources provided by NSF/CISL/Yellowstone, as well as the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP. For CMIP the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization.
for Earth System Portals. CAM5 simulations, and all code are available from RJA (tjallen@ucr.edu).

REFERENCES


