Neale, R. B., and Coauthors, 2012: Description of the NCAR Community Atmosphere Model (CAM 5.0). *NCAR Tech. Note,* NCAR/TN-4861STR, 274 pp.
Nguyen, H., A. Evans, C. Lucas, I. Smith, and B. Timbal, 2013: The Hadley circulation in reanalyses: Climatology, variability, and change. *J. Climate*, **26**, 3357–3376, doi:10.1175/JCLI-D-12-00224.1.
Polvani, L. M., D. W. Waugh, G. J. P. Correa, and S.-W. Son, 2011: Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. *J. Climate,* **24**, 795–812, doi:10.1175/ 2010JCLI3772.1.
Rienecker, M. M., and Coauthors, 2011: MERRA: NASA's Modern- Era Retrospective Analysis for Research and Applications*. J. Climate*, **24**, 3624–3648, doi:10.1175/JCLI-D-11-00015.1.
Saha, S., and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.,* **91**, 1015–1057, doi:10.1175/2010BAMS3001.1.
Son, S.-W., N. F. Tandon, L. M. Polvani, and D. W. Waugh, 2009: Ozone hole and Southern Hemisphere climate change. *Geophys. Res. Lett*., **36**, doi:10.1029/2009GL038671.
Tao, L., Y. Hu, and J. Liu, 2016: Anthropogenic forcing on the Hadley circulation in CMIP5 simulations. *Climate Dyn*., **46**, 3337–3350, doi:10.1007/s00382-015-2772-1
Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design*. Bull. Amer. Meteor. Soc*., **93**, 485–498, doi:10.1175/BAMS-D-11-00094.1.
Waugh, D. W., C. I. Garfinkel, and L. M. Polvani, 2015: Drivers of recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion? *J. Climate*, **28**, 6581–6586, doi:10.1175/ JCLI-D-15-0138.1
Wilks, D. S., 1995: Statistical methods in the atmospheric sciences. *Academic Press*, 467 pp., ISBN:9780123850232.

Natural variability in the width of the tropics

Isla Simpson

National Center for Atmospheric Research

Roughly a decade ago, it was realized that in the approximately 30 years since satellite records began the tropics, as measured by various climatological definitions, had been expanding, raising concern as to whether this was an externally forced trend arising from anthropogenic forcings such as increasing greenhouse gas concentrations (e.g., Seidel et al. 2008). While our theoretical expectations and numerical climate model simulations indeed predict that the tropics should expand as the planet warms (Frierson et al. 2007; Lu et al. 2007; Tao et al; 2016), it has now become acknowledged that natural, internal variability has likely played an important role in the expansion that has been observed over recent decades (Quan et al. 2014; Garfinkel et al. 2015; Mantsis et al. 2016; Amaya et al. 2017; Allen and Kovilakam 2017). Over the observational record, the confounding influences of natural variability and external forcings make a quantitative assessment of the magnitude of forced trends extremely challenging, if not impossible. As we wait for our observational record to lengthen and forced trends to emerge (or not), we must maintain an appreciation of the influence of natural variability on what we have seen and what we may see in the future.

There are a number of ways in which to define the width of the tropics (Davis and Rosenlof 2012; Waugh et al. 2018; Davis et al. this issue) and a number of approaches (e.g., seasons, trend lengths) that could be used to characterize variability and change, all of which cannot be covered here. Readers, however, can refer to a number of studies that have used a variety of metrics and approaches to investigate natural variability in tropical width (Kang et al. 2013; Quan et al. 2014; Garfinkel et al. 2015; Allen and Kovilakam 2017; Amaya et al. 2017; Quan et al, 2018). Here, natural variability in tropical width will be illustrated with three examples: the annual mean width (i.e., difference between the Northern Hemisphere and Southern Hemisphere tropical edges); the latitude of the Northern Hemisphere edge during winter (December-January-February average (DJF)); and the latitude of the Southern Hemisphere edge during summer (DJF). The edge of the tropics will be defined here as the latitude of transition of near surface winds from easterly to westerly (e.g., Adam et al. 2018).

Figure 1 illustrates the challenge that we face in isolating the forced response from natural variability and even in simply characterizing the variability over our observational record. Annual mean tropical width for a variety of reanalysis products is shown in Figure 1a. The two products that cover the entire 20th century show strong disagreement in the earlier part of the record, indicating that we do not have a constrained observational record of tropical width that extends much before the beginning of the satellite era (around 1979). While differences do exist, the agreement is better after 1979 (see also Nguyen et al. 2013), and therefore the following analysis will focus on the variability in the 38-year period between 1980 and 2017.

Since 1980, the annual mean width of the tropics has fluctuated interannually with a standard deviation (σ) of ~0.8°–1° latitude (Figure 1c), with individual years typically varying within an ~4° latitude range (~4σ, Figure 1a). Figure 1b illustrates similar time series but for 40 members of a large ensemble of simulations performed with the Community Earth System Model, version 1 (CESM1, Kay et al. 2015), referred to as LENS hereafter. All 40 simulations are run under an identical forcing scenario (see Figure 1 caption) and differ only in a round-off level perturbation introduced to the surface temperature field in 1920. Thus, the differences between ensemble members arise only from internal ocean-atmosphere variability. From 1980 to 2017, CESM exhibits comparable

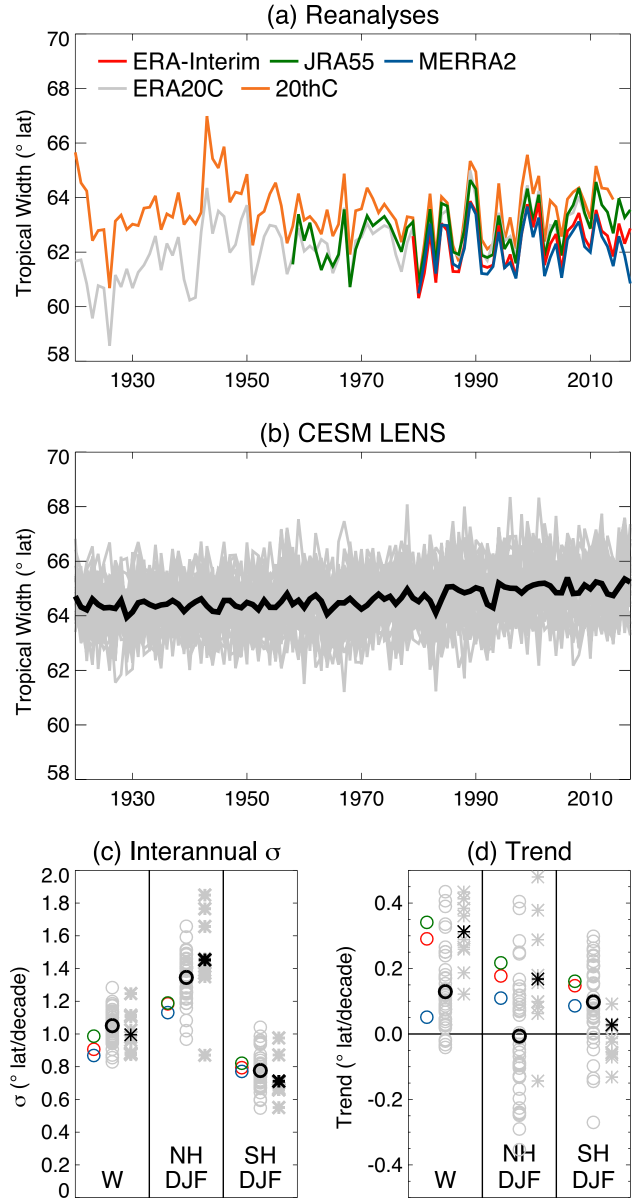

Figure 1. (a) Time series of annual mean tropical width for five different reanalyses: ERA-Interim (Dee et al 2011), JRA55 (Kobayashi et al 2015), MERRA2 (Gelaro et al 2017), ERA20C (Poli et al 2016), 20th century reanalysis (20thC; Compo et al. 2011). (b) Time series of annual mean tropical width from the CESM LENS (grey=individual members, black=ensemble mean). The LENS is run under CMIP5 historical forcings prior to 2006 and under the RCP8.5 scenario thereafter. (c) Interannual standard deviation, σ, of the annual mean width, the NH DJF edge and the SH DJF edge calculated using 1980–2017 for the three more strongly constrained reanalyses (ERA-Interim (red), JRA55 (green), MERRA2 (blue)), the CESM LENS (grey circles) and CESM simulations run with the same forcings as LENS, but with observed SSTs prescribed at the lower boundary (grey asterisks). (d) is as (c) but for the linear trends from 1980-2017. The colors in panels (c) and (d) correspond to those in (a) and (b) and note that zonal wind at 10 m is used for the reanalyses while the zonal wind at the lowest model level is used for CESM.

interannual variability to observations (Figure 1c). But the LENS makes clear that even our assessment of interannual variability over a 38-year record is subject to considerable uncertainty since individual members are characterized by an annual mean tropical width σ of anywhere between 0.8° and 1.3° latitude.

Between 1980 and the present, ERA-Interim (Dee et al. 2011) and JRA-55 (Kobayashi et al. 2015) reanalyses have exhibited an annual mean widening trend of around 0.3° per decade (Figure 1d, see also Lucas et al. 2014 and references therein). MERRA2 (Gelaro et al. 2017) exhibits a considerably weaker trend, but there may be reasons to be concerned about the ability of MERRA2 to constrain the divergent tropical circulation (DeWeaver and Nigam 1997). The ensemble mean trend of the CESM LENS, which can be considered to be the externally forced trend in CESM, is only around 0.13° per decade. The wide range of trends exhibited by individual members, however, indicates the dominant role that natural variability can play over a 38-year record. Individual members are characterized by trends of anywhere between 0.04° per decade and 0.43° per decade, which illustrates the importance of comparing the observations with a large number of model simulations that span the range of possible outcomes that could arise as a result of the combined influences of external forcing and natural variability (Garfinkel et al. 2015). The presence of external forcings has clearly weighted the CESM simulations toward exhibiting a widening trend in the annual mean, but the wide range of behaviors seen in individual members demonstrates the challenges in quantifying the forced trend in our one observed record.

Even if the presence of internal variability renders our estimation of the forced trend in the real world highly uncertain, can we at least conclude that the trends that have been observed are outside of the expectations from natural variability alone? To provide an indication of this, we can compare with the trends that are present in unforced preindustrial control (piControl) simulations. This comparison is made in Figure 2 using 22 piControl simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5), along with an 1800 year long piControl simulation that accompanies the CESM LENS. For annual mean tropical width and the Northern Hemisphere DJF tropical edge, the majority of the CMIP5 models exhibit interannual variability that is comparable with observations (Figure 2a,c). The discrepancy between models and reanalyses is slightly greater in the Southern Hemisphere DJF, which may relate to common biases in the Southern Hemisphere jet stream (which is often biased equatorward) and Southern Annular Mode behavior (which is often overly persistent) (Kidston and Gerber 2010; Simpson and Polvani 2016). Nevertheless, roughly half of the CMIP5 models and CESM exhibit interannual variability in the Southern Hemisphere DJF tropical edge that is comparable with reanalyses. Figures 2b,d,f illustrate the range of possible trends that could be obtained from 38-year segments of these piControl simulations (black bars). For annual mean tropical width, the ERA-Interim and JRA55 trends lie outside of the distribution of trends found in the piControl simulations of almost all the models, indicating that, to the extent we can trust the representation of long term natural variability in the models, the observed trends in annual mean tropical width are extremely unlikely to have arisen from natural variability alone (consistent with the tendency of the forced LENS simulations to produce a tropical widening (Figure 1d)). The same cannot be said for the DJF Northern and Southern Hemisphere trends. While the reanalyses indicate a poleward migration of the Northern and Southern Hemisphere tropical edges during DJF, these trends are not outside of the realms of what natural variability can produce. While there is good reason to believe that stratospheric ozone depletion has contributed to an expansion of the tropics in the Southern Hemisphere during DJF (Polvani et al 2011; McLandress et al 2011; Garfinkel et al. 2015; Waugh et al 2015; Solomon and Polvani 2016), consistent with the fact that the forced CESM LENS does show a poleward expansion in the ensemble mean (Figure 1d), this has not been sufficient to give rise to an observed trend that is larger than could arise from natural variability alone. In the Northern Hemisphere DJF, the fact that the reanalysis trends lie within the expectations from natural variability

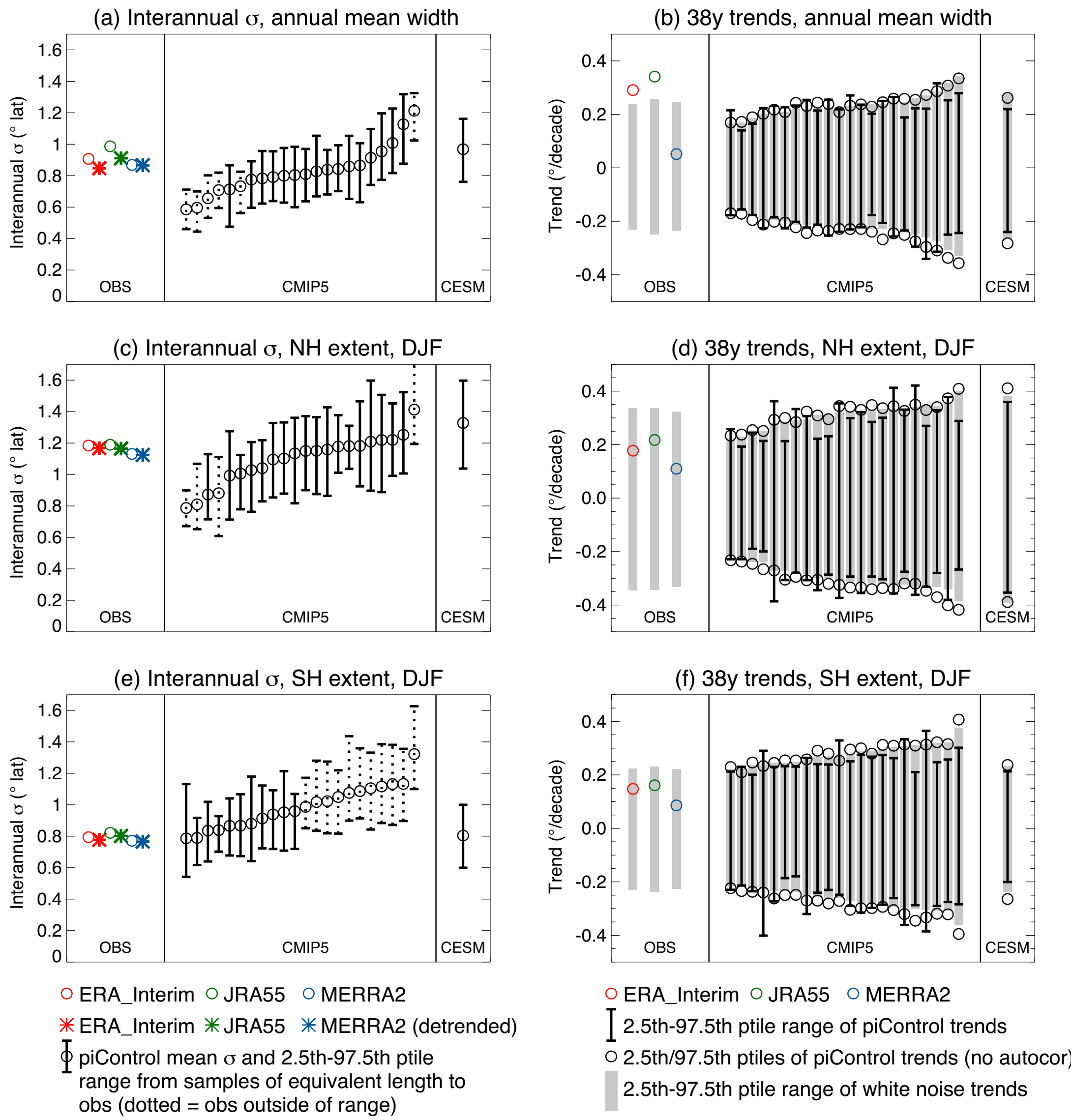

Figure 2. (top) Annual mean tropical width, (middle) Northern Hemisphere DJF tropical edge, (bottom) Southern Hemisphere DJF tropical edge. (left) Interannual standard deviation (σ) for the reanalyses (1980–2017) both before and after detrending, for CMIP5 piControl simulations from 22 models, and for a piControl simulation with CESM. Black circles depict the mean σ calculated from all years of simulation and the error bars depict the 2.5 to 97.5 percentile range of σ's estimated from overlapping segments of length 38 years from the piControl simulations. 2.5 to 97.5 percentile ranges that do not encompass the observed value are shown by dotted lines. (right) Trends from 1980-2017 for the reanalyses along with the 2.5 to 97.5 percentile range of trends obtained from overlapping 38-year segments of the piControl simulations (black error bars). Black circles depict the 2.5 and 97.5 percentiles of trends obtained from 1000, 38-year time series obtained by picking individual years at random from the piControl simulation i.e., removing any autocorrelation from the time series due to slow processes. Grey bars depict the 2.5 to 97.5 percentile range of trends obtained from 1000, 38-year samples of synthetic time series generated using Gaussian white noise with an interannual σ equal to that of the respective reanalysis (detrended) or simulation. Note that for DJF, a record length of 38 years means 37 DJF seasons are used to calculate σ and the trend. The CMIP5 piControl simulation lengths range from 255 to 1000 years, and the CESM piControl simulation is 1800 years long.

is consistent with the results from the forced LENS simulations, which show no forced trend over this time period (Figure 1d).

What then is the nature of this natural variability? Many studies have discussed the important role of the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) in contributing to observed trends, particularly for the Northern Hemisphere (Grassi et al. 2012; Garfinkel et al. 2015; Mantsis et al. 2016; Allen and Kovilakam 2017; Amaya et al; 2017) with cold ENSO/PDO phases being characterized by a wider tropical belt (see also Allen et al. this issue). Indeed, it can be seen in Figure 1d that the ensemble mean of 10 CESM simulations with prescribed historical SSTs as opposed to a coupled ocean (gray asterisks) exhibits a greater expansion of the Northern Hemisphere tropics during DJF. However, ambiguity remains over whether decadal modes of variability in the ocean are actually required to explain the trends or whether the apparent decadal influence of the ocean simply arises from the chance sampling of individual years characterized by different ENSO states. An appropriate null hypothesis to consider is that the trends that arise due to internal variability do so simply as a result of the chance sampling of individual years with no underlying correlation from one year to the next. Can we distinguish the variability from this possibility? The answer is no. In Figure 2b, this is tested in two different ways for the piControl simulations. The first is just by using a bootstrapping methodology where individual years from the piControl simulation are randomly sampled and then strung together so that, by construction, there is no correlation from one year to the next. An assessment of the range of 38-year trends that can be obtained from such samples is shown by the black circles that accompany the piControl trend ranges in Figure 2b,d,f. These indicate that the actual trends simulated by the models are consistent with the chance sampling of individual years with no correlation from one year to the next. The second test takes this a step further and assumes that the variability in tropical width is given by a Gaussian white noise distribution characterized by the interannual σ. The gray bars in Figure 2b,d,f indicate that the trends simulated by the models are consistent with this representation of the variability. We, therefore, have no indication from the models that their internal variability is anything more than the chance sampling of year-to-year fluctuations with one year being unrelated to the next. While multidecadal modes of variability in the ocean could play a role, this it not necessary to explain the long-term trends that arise due to natural variability in the models. Building on this model analysis, if we then assume that the observed atmosphere displays internal variability that is simply represented by Gaussian white noise with σ equal to the observed interannual σ, then it can be seen that random sampling of this noise can give rise to 38-year trends as large as 0.25° per decade in the annual mean width, 0.33° per decade in Northern Hemisphere DJF extent and 0.23° per decade in Southern Hemisphere DJF extent (gray bars in Figure 2b,d,f). The actual observed annual mean width trend lies outside of this range, but the Northern and Southern Hemisphere DJF trends do not.

The asterisks in Figure 1d make clear that even without differences in SST variability, the sampling of atmospheric noise can give rise to a wide range of trends. The relative roles of atmosphere-only variability and coupled ocean-atmosphere variability can be assessed more quantitatively within CESM by comparison of the coupled piControl simulation with a control simulation with prescribed climatological SSTs derived from the coupled simulation (Figure 3). Certainly, ocean variability is required to explain the full range of interannual variability that is seen in the coupled simulation, but variability that is internal to the atmosphere is actually a dominant contribution. The interannual σ found in the climatological SST simulation is around 72% of that in the coupled simulation for annual mean tropical width, 78% for the Northern Hemisphere DJF edge, and 84% for the Southern Hemisphere DJF edge. Furthermore, upon regressing out the contribution to interannual variability that is linearly related to ENSO in the coupled simulation (via the Nino3.4 index), the σ of tropical width/extent is reduced to similar values to those of the climatological SST simulation (compare filled circles and asterisks in

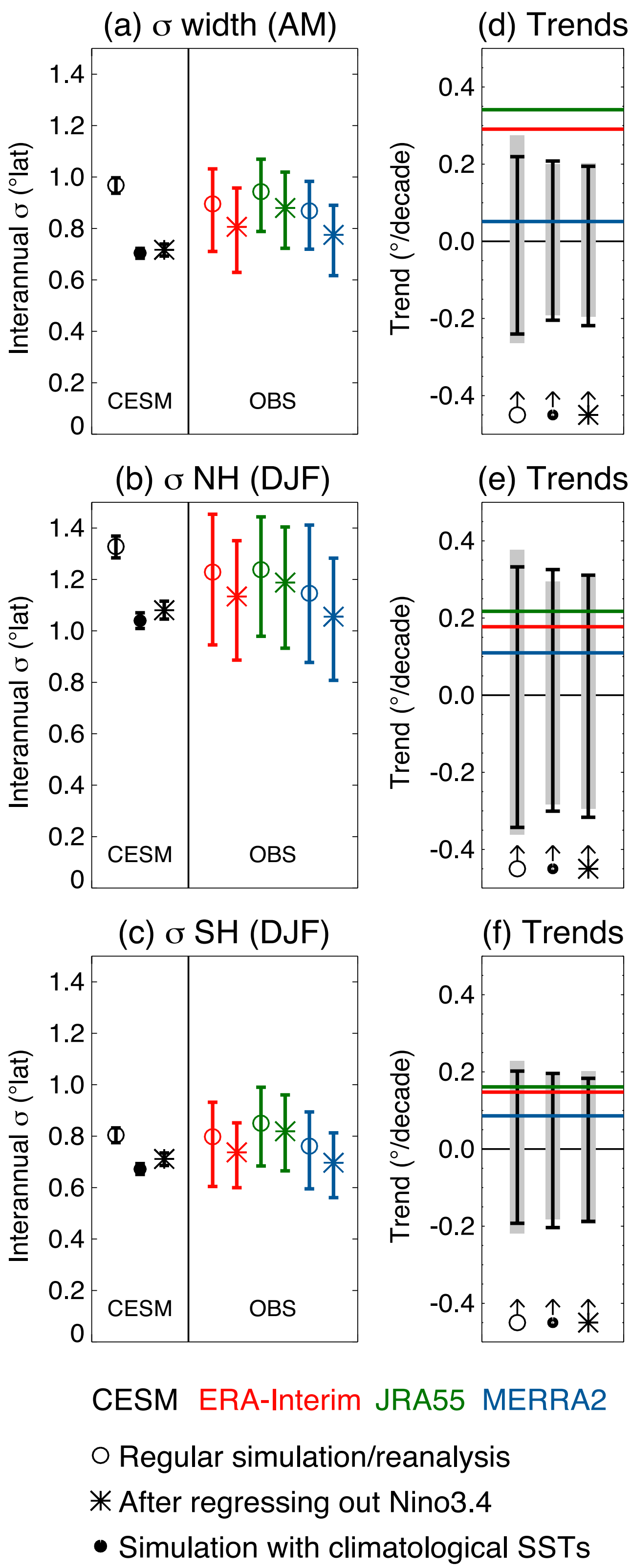

Figure 3. (a), (b) and (c) show interannual standard deviation of the annual mean tropical width, the DJF Northern Hemisphere tropical edge and the DJF Southern Hemisphere tropical edge respectively. CESM simulations and three reanalyses are shown. Open circles show the regular simulation/reanalysis; closed circle for CESM shows a simulation where the climatological SSTs of the coupled run are prescribed and asterisk shows the standard deviation after regressing out the contribution related to the Nino3.4 index (SST anomalies area averaged over 5°S–5°N, 190°E–240°E). The error bars depict the 2.5 to 97.5 percentile range of uncertainty on the value estimated using bootstrapping with replacement. (d), (e) and (f) show 38-year trends in annual mean tropical width, DJF Northern Hemisphere tropical edge and DJF Southern Hemisphere tropical edge, respectively. The grey bar shows the 2.5 to 97.5 percentile range of trends obtained from a synthetic white noise time series with the interannual standard deviation while the black bars show the actual 2.5 to 97.5 percentile range of 38-year trends from the simulations. The horizontal lines for reference show observed trends. The coupled piControl "regular" simulation with CESM is 1800 years long, and the simulation with climatological SSTs is 2600 years long.

Figure 3), indicating that the ocean's influence on tropical width occurs primarily through ENSO. Interannual variability is also reduced in the reanalyses upon regressing out the component related to ENSO, but the magnitude of this reduction is uncertain given the length of the records.

The 38-year trends that can arise as a result of internal atmospheric variability in CESM are almost as large as those found in the fully coupled simulation (Figure 3d,e). Based on CESM, internal atmospheric variability, which is inherently unpredictable, is capable of giving rise to trends over the length of the satellite record that are of the order 0.2° per decade for annual mean tropical width, 0.3° per decade for the Northern Hemisphere DJF edge, and 0.2° per decade for the Southern Hemisphere DJF edge. Given that CESM compares favorably with the reanalyses in terms of its interannual variability and no model gives any indication of long-term variability being more than the result of the random sampling of individual years, there is good reason to believe that this is also true of the real world; although this is difficult to conclude with certainty.

In summary, natural variability has likely played an important role in the trends that have been observed in tropical width in recent decades and will continue to influence the trends we observe in the future. A substantial fraction of this natural variability likely arises from internal atmospheric processes, with the remainder being accounted for primarily by ENSO variability. While we can make use of state-of-the-art global climate models to determine the magnitude of forced trends, we must continue to bear in mind the power of internal variability when it comes to isolating the influence of external forcings on our single observed record.

References

Adam, O., K. M. Grise, P. Staten, I. R. Simpson, S. M. Davis, N. A. Davis, D. W. Waugh, and T. Birner, 2018: The TropD software package: Standardized methods for calculating tropical width diagnostics. *Geosci. Mod. Dev*., submitted.

Allen, R. J., and M. Kovilakam, 2017: The role of natural climate variability in recent tropical expansion. *J. Climate*, **30**, 6329–6350, doi:10.1175/JCLI-D-16-0735.1.

Amaya, D. J., N. Siler, S.-P. Xie, and A. J. Miller, 2017: The interplay of internal and forced modes of Hadley Cell expansion: lessons from the global warming hiatus. *Climate Dyn*., doi:10.1007/s00382-017-3921-5.

Compo, G. P., and Coauthors, 2011: The Twentieth Century Reanalysis Project. *Quart. J. Roy. Met. Soc*., **137**, 1–28, doi:10.1002/qj.776.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. Roy. Met. Soc*., **137**, 553-597, doi:10.1002/qj.828.

DeWeaver, E., and S. Nigam, 1997: Dynamics of zonal-mean flow assimilation and implications for winter circulation anomalies. *J. Atmos. Sci*., **54**, 1758–1775, doi:10.1175/1520-0469(1997)054<1758:DOZMFA>2.0.CO;.

Davis, S. M., and K. H. Rosenlof, 2012: A multidiagnostic intercomparison of tropical-width time series using reanalyses and satellite observations. *J. Climate*, **25**, 1061–1078, doi:10.1175/JCLI-D-11-00127.1.

Frierson, D. M. W., J. Lu, and G. Chen, 2007: Width of the Hadley cell in simple and comprehensive general circulation models, *Geophys. Res. Lett.,* **34**, doi:10.1029/2007GL031115.

Garfinkel, C. I., D. W. Waugh, and L. M. Polvani, 2015: Recent Hadley cell expansion: The role of internal atmospheric variability in reconciling modeled and observed trends. *Geophys. Res. Lett*., **42**, 10824–10831, doi:10.1002/2015GL066942.

Gelaro, R. and Coauthors, 2017: The modern-era retrospective analysis for research and applications, version 2 (MERRA-2), *J. Climate*, **30**, 5419–5454, doi:10.1175/JCLI-D-16-0758.1.

Grassi, B., G. Redaelli, P. O. Canziani, and G. Visconti, 2012: Effects of the PDO phase on the tropical belt width. *J. Climate,* **25**, 3282–3290, doi:10.1175/JCLI-D-11-00244.1.

Kang, S. M., C., Deser, and L. M. Polvani, 2013: Uncertainty in climate change projections of the Hadley circulation: The role of internal variability. *J. Climate*, **26**, 7541–7554, doi:10.1175/JCLI-D-12-00788.1.

Kay, J. E., and Coauthors, 2015: The Community Earth System Model (CESM) Large Ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.,* **96**, 1333–1349, doi:10.1175/BAMS-D-13-00255.1.

Kidston, J., and E. P. Gerber, 2010: Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th Century climatology. *Geophys. Res. Lett*., **37**, doi:10.1029/2010GL042873.

Kobayash, S., and Coauthors, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan*., **93**, 5-48, doi:10.2151/jmsj.2015-001.

Lucas, C., B. Timbal, and H. Nguyen, 2014: The expanding tropics: a critical assessment of the observational and modeling studies. *WIREs Climate Change*, **5**, 89-112, doi:10.1002/wcc.251.

Lu, J., G. A. Vecchi, and T. Reichler, 2007: Expansion of the Hadley cell under global warming. *Geophys. Res. Lett.,* **34**, doi:10.1029/2006GL028443.

McLandress, C., T. G. Shepherd, J. F. Scinocca, D. A. Plummer, M. Sigmond, A. I. Jonsson, M. C. Reader, 2011: Separating the dynamical effects of climate change and ozone depletion. Part 2: Southern Hemisphere troposphere. *J. Climate,* **24**, 1850–1868, doi:10.1175/2010JCLI3958.1.

Mantsis, D. F., S, Sherwood, R. Allen, and L. Shi, 2016: Natural variations of tropical width and recent trends. *Geophys. Res. Lett*., **44**, 3825–3832, doi:10.1002/2016GL072097.

Nguyen, H., A. Evans, C. Lucas, I. Smith, and B. Timbal, 2013: The Hadley Circulation in reanalyses: Climatology, variability, and change. *J. Climate,* **26**, 3357–3376, doi:10.1175/JCLI-D-12-00224.1.

Polvani, L. M., D. W. Waugh, G. J. P. Correa, S.-W. Son, 2011: Stratospheric ozone depletion; the main driver of 20th Century atmospheric circulation changes in the Southern Hemisphere, *J. Climate*, **24**, 795–812, doi:10.1175/2010JCLI3772.1.

Poli, P., and Coauthors, 2016: ERA-20C: An atmospheric reanalysis of the Twentieth Century. *J. Climate*, **29**, 4083–4097, doi:10.1175/JCLI-D-15-0556.1.

Quan, X.-W., M. P. Hoerling, J. Perlwitz, H. F. Diaz, and T. Xi, 2014: How fast are the tropics expanding? *J. Climate*, **27**, 1999–2013, doi:10.1175/JCLI-D-13-00287.1.

Quan, X.-W., M. P. Hoerling, J. Perlwitz, and H. F. Diaz, 2018: On the time of emergence of tropical width change. *J. Climate,* submitted.

Seidel, D. J, Q. Fu, W. J., Randel, and T. J. Richler, 2008: Widening of the tropical belt in a changing climate. *Nat. Geosci,* **1**, 21–24, doi:10.1038/ngeo.2007.38.

Simpson, I. R., and L. M. Polvani, 2016: Revisiting the relationship between jet position, forced respons, and annular mode variability in the southern midlatitudes. *Geophys. Res. Lett.,* **42**, 2896–2903, doi:10.1002/2016GL067989.

Solomon, A., and L. M. Polvani, 2016: Highly significant responses of anthropogenic forcings of the midlatitude jet in the Southern Hemisphere. *J. Climate,* **29**, 3462–3470, doi:10.1175/JCLI-D-16-0034.1.

Tao, L, Y. Hu, and J. Liu, 2016: Anthropogenic forcing of the Hadley circulation in CMIP5 simulations. *Climate Dyn*., **46**, 3337–3350, doi:10.1007/s00382-015-2772-1.

Waugh, D. W., C. I. Garfinkel, and L. M. Polvani, 2015: Drivers of the recent tropical expansion in the Southern Hemisphere: Changing SSTs or ozone depletion? *J. Climate,* **28**, 6581–6586, doi:10.1175/JCLI-D-15-0138.1.

Waugh, D. W., and Coauthors, 2018: Revisiting the relationship among metrics of tropical expansion. *J. Climate*, submitted.