Final Report for "Interdecadal climate regime transition and its interaction with climate change in CMIP5 simulations" (DOE Grant DE-SC0005344)

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PI information

Principal Investigator:
Huei-Ping Huang
Assistant Professor
School for Engineering of Matter, Transport, and Energy
Arizona State University
Email: hp.huang@asu.edu

Abstract

Large-amplitude interdecadal shifts of atmospheric and ocean states from one climate regime to another have been observed several times in the 20th century. They include the 1976 transition from cool tropical Pacific SST to warm tropical SST and the post-1998 reversal back to a cooler state. The transition events affect both atmospheric circulation and global water cycle. Because on decadal-to-interdecadal time scale the amplitude of the climate shift is comparable to the trend induced by anthropogenic greenhouse gas forcing, understanding the structure, statistics, and predictability of those events is critical for near-term climate projection. This study analyzed the statistics and predictability of the transition events in the CMIP5 climate model simulations by using a set of climate indices, including atmospheric angular momentum (AAM) and regionally integrated hydrological variables. A significant improvement in the simulated 20th century climatology of AAM is found in CMIP5, compared to earlier simulations in CMIP3. Nevertheless, the improvement in the simulated decadal-to-interdecadal variability in AAM is relatively minor. Systematic biases in the regional water cycle that exist in CMIP3 are found to also exist in CMIP5, although with slight improvements in the latter. Climate shift events with an amplitude comparable to the observed 1976 or 1998 event are found to rarely occur in the CMIP5 20th century simulations. In the 21st century simulations with increasing GHG concentration, the upward trend superimposed to natural variability slightly increases the frequency of occurrences of the large-amplitude events. Even so, 1976-like events remain rare in those runs. In an additional analysis of the CMIP5 Decadal Runs for the 20th century, it is found that the decadal predictability in terms of AAM is generally weak, with useful predictability mainly restricted to within ENSO time scale. Overall, this study showed promises in the improved performance of CMIP5 in some aspects but also revealed the relatively limited ability for the models to capture sharp climate shift events.

1. Primary research and development activities and outcome

1a. Interdecadal variability and shifts in observation

To examine the robustness of interdecadal variability and regime shift in the observation, we performed an intercomparison of the global relative angular momentum, M_R, in five reanalysis datasets, including the 20th Century Reanalysis (20CR), for the second half of the 20th Century. The intercomparison forms a stringent test for 20CR because the variability of M_R is known to be strongly influenced by the variability of upper-tropospheric zonal wind while 20CR assimilated only surface observations. The analysis reveals a good agreement on decadal-to-multidecadal variability among all datasets, including 20CR, for the second half of the 20th Century. The discrepancies among different datasets are mainly in the slowest component, the long-term trend, of M_R. Once the data are detrended, the resulting decadal-to-multidecadal variability shows an even better agreement among all datasets. This indicates that 20CR can be reliably used for the analysis of decadal-to-interdecadal variability in the pre-1950 era, provided that the data is properly detrended. As a quick application, it is found that the increase in M_R during the 1976/77 climate shift event remains the sharpest over the entire period from 1871-2008 covered by 20CR. The nontrivial difference in the long-term trend between 20CR and other reanalysis datasets found in this study provides a caution against using 20CR to determine the trend on centennial time scale relevant to climate change. While these conclusions are restricted to the quantities that depend strongly on the upper-tropospheric zonal wind, they provide an impetus for a further intercomparison of the low-frequency variability and trend for other climate indices in the reanalysis datasets. The results of this part of investigation have been published (Paek and Huang 2012a) and a highlight is shown in Fig. 1.

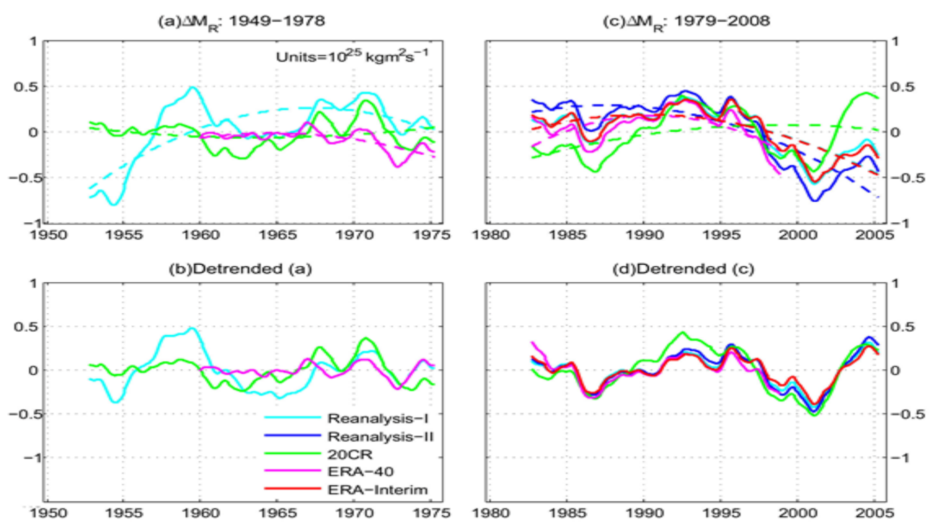

Fig. 1 Panels (a) and (c) show the time series of the relative atmospheric angular momentum for five reanalysis datasets (solid lines) and the quadratic fits to those curves (dashed lines), for 1952-2005. Panels (b) and (d) are the same but for the detrended time series.

1b. A further confirmation of the quality of data in reanalysis

To further consolidate the conclusion drawn from the analysis in Section 1a, we cross validated the global atmospheric angular momentum from eight reanalysis datasets with the length-of-day (LOD) data from geodetic observations. This validation is meaningful only for shorter-term variability (so the variation LOD is not affected by core-mentle coupling of the Earth). Therefore, we filter the time series to retain only the interannual and shorter-term variability for both AAM and LOD. We found a very satisfactory agreement between LOD and AAM at those timescales. This generally affirms the quality of the reanalysis datasets, including 20CR. A key comparison between AAM and LOD is highlighted in Fig. 2. The results are published in Paek and Huang (2012b).

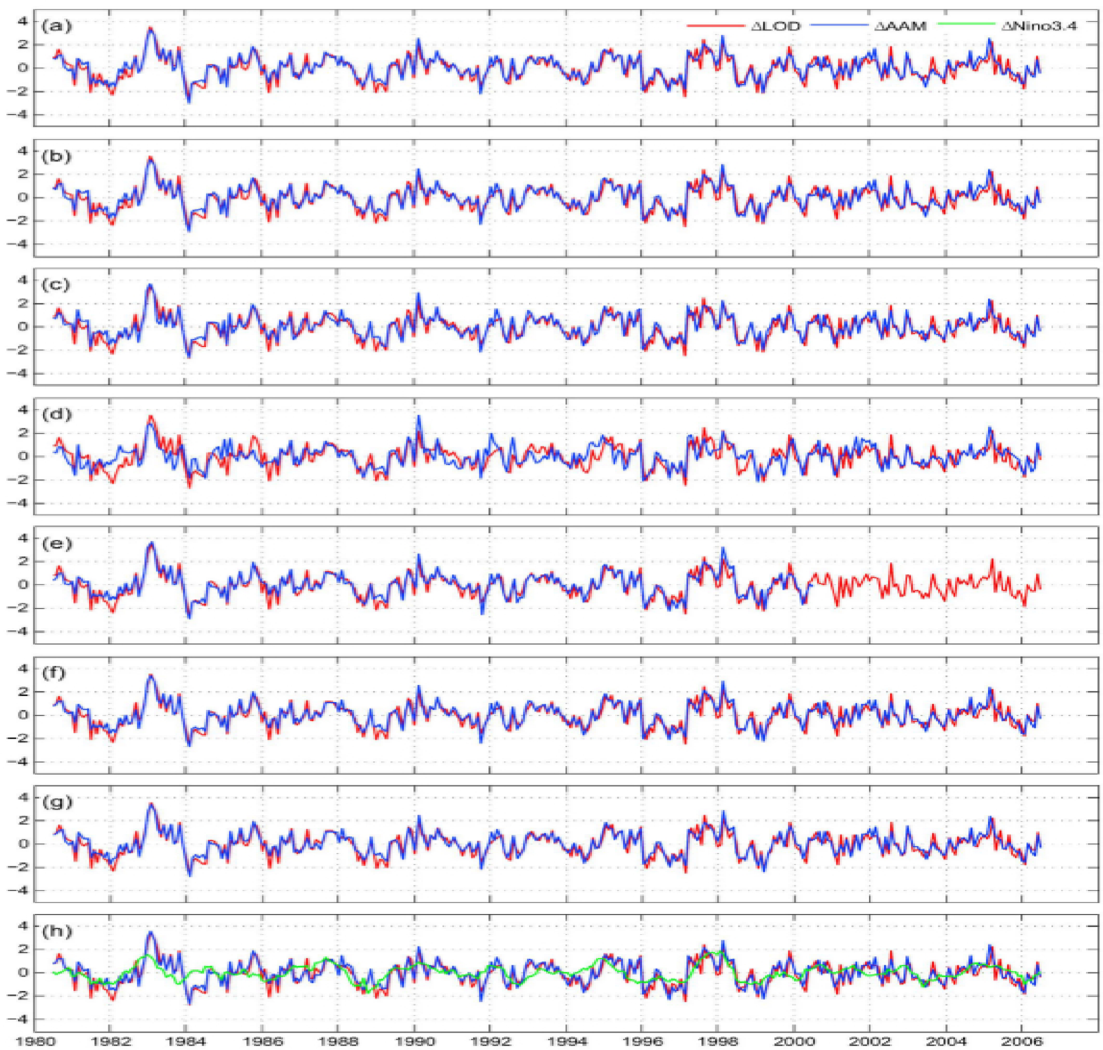

Fig. 2 Cross validation of interannual AAM (blue), LOD (red), and NINO3.4 SST (green) anomalies for 1980-2006. AAM is derived from reanalysis: (a) NCEP R-1 (b) NCEP R-2 (c) CFSR (d) 20CR (e) ERA-40 (f) ERA-Interim (g) JRA-25 (h) MERRA. Units are 10^{25} kg m^2s^{-1} for AAM and LOD (equivalent) and degC for SST.

1c. Interdecadal climate shifts in CMIP3/5 simulations

Using globally angular momentum as a climate index (e.g., as surveyed by Huang et al. 2003), the decadal-to-interdecadal variability in CMIP5 and CMIP3 simulations are analyzed and compared to the observation of the 20th century. We also aim to detect interdecadal shifts similar to the observed 1976/77 transition from a cooler to a warmer Tropics that affected global climate. For this purpose, a set of criteria are developed to detect large-amplitude shifts in low-pass filtered time series of global atmospheric angular momentum (AAM) based on the magnitude of the tendency of AAM and statistical significance of the difference in the mean of AAM between the pre- and post-shift epochs. Confirming the validity of the criteria, the 1976/77 event is found to stand out when they are applied to the 20th Century Reanalysis dataset. These criteria are then tested on the (i) pre-industrial runs, (ii) historical runs with only natural forcing, and (iii) historical runs with GHG forcing, in CMIP3 and CMIP5. It is found that an interdecadal shift in AAM with a magnitude comparable to the 1976/77 very rarely happens in the pre-industrial runs and the historical runs with only natural forcing, implying that the climate models underestimate the interdecadal variability. In the historical runs with GHG forcing, the mild but non-negligible upward trend in AAM due to GHG forcing combined with natural variability produced a few events in different models that satisfy our criteria for a regime shift. This hints at the possibility that anthropogenic global warming might lead to an increase in the likelihood for the occurrence of an upward shift of AAM similar to the 1976/77 event. In the simulations for the future with strong GHG forcing, the GHG-induced increase in AAM becomes dominant towards the end of the 21st Century and eventually overwhelms the interdecadal climate shift events. A highlight of the result is in Fig. 3 which shows selected time series of AAM from CMIP5 historical runs.

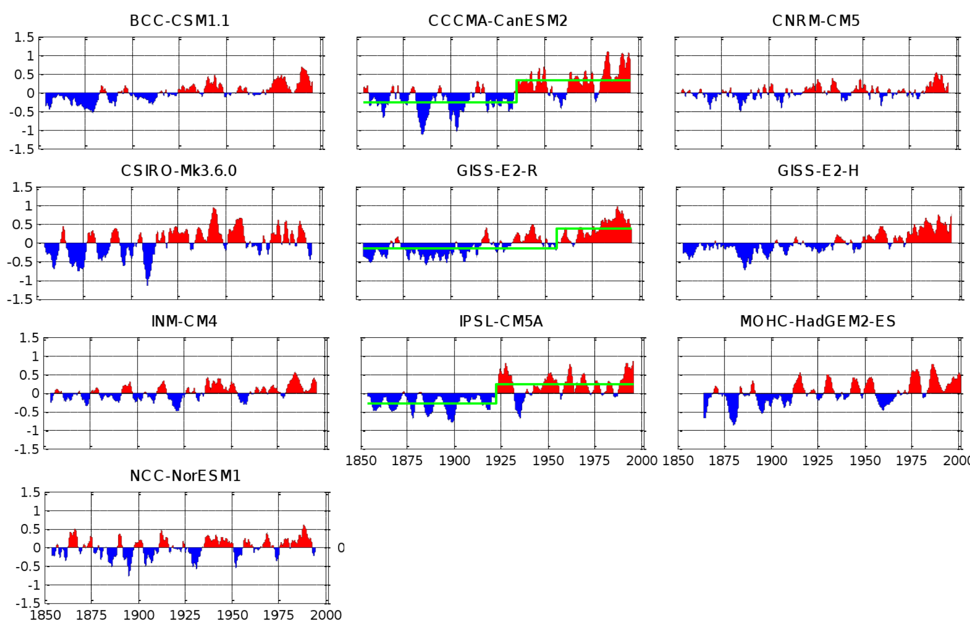

Fig. 3 The evolution of atmospheric angular momentum from selected CMIP5 simulations. Shown are the historical runs and the green lines indicate a potential climate shift event.

1d. Cross validation between reanalysis and CMIP3/5

After establishing our confidence in the reanalysis datasets, they are first used as observation to cross validate the 20th century climatology and trend of relative AAM in CMIP3/5 simulations. Figure 4(a) (climatology vs. trend) shows the comparison for CMIP3. Also superimposed in Fig. 4(a) are the 21st century runs from CMIP3 under the A1B scenario. Figure 4(b) is the CMIP5 counterpart of Fig. 4(a). We found significant reduction in the bias, and a reduction in the intra-ensemble spread, in the AAM in CMIP5.

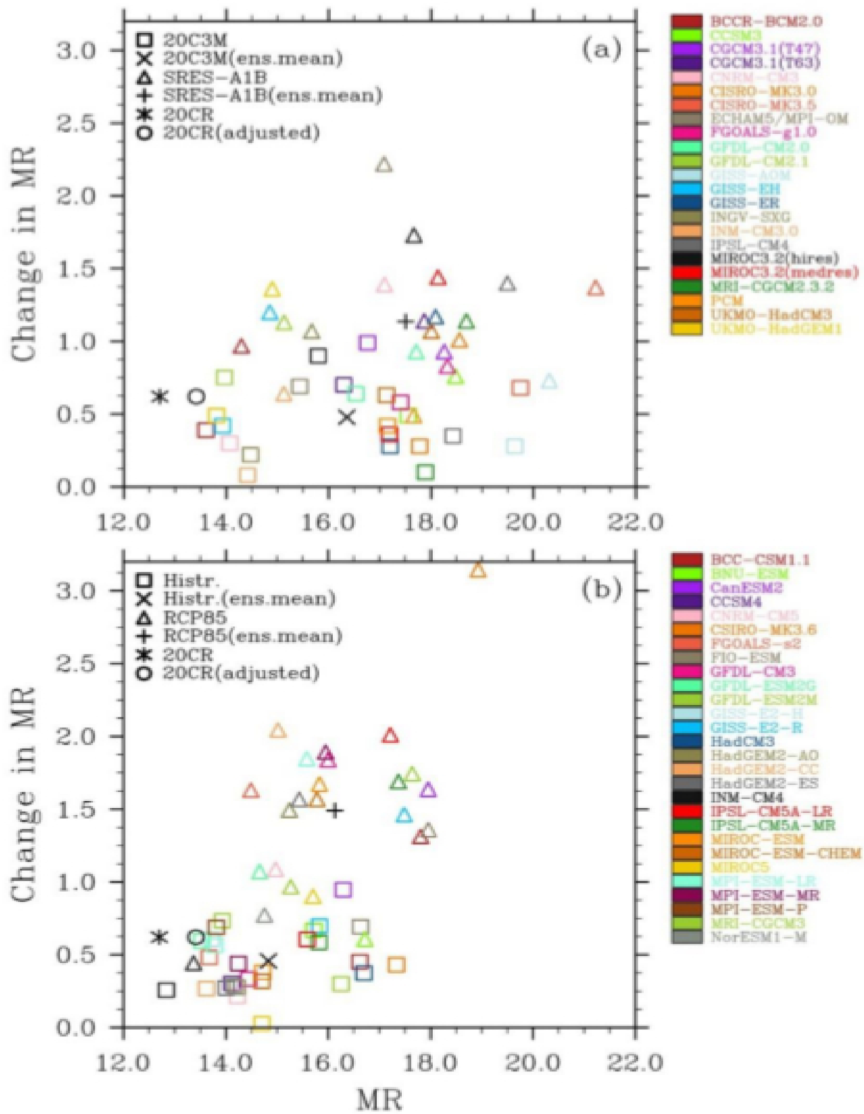

Fig. 4 Centennial climatology vs. trend of the relative AAM. Top: CMIP3 (20C3M and A1B), bottom CMIP5 (Historical and RCP8.5). The 20CR reanalysis is also indicated in the figure.

After detrending the data by removing the linear centennial trend, we compare the decadal and interdecadal variability of relative AAM, as shown in Fig. 5. Shown is the standard deviation of decadal (7-12 yr) vs. interdecadal (15-30 yr) variability. Among the 23 models in CMIP3, it is found that three quarters of them simulated a decadal variance that is indistinguishable from observation at 95% significance level. On the other hand, almost all CMIP3 models underestimate the interdecadal variance. The counterparts of those quantities in CMIP5 have a smaller spread in the multi-model ensemble but overall behaviors of CMIP5 and CMIP3 are similar. The results of the intercomparison are published in Paek and Huang (2013).

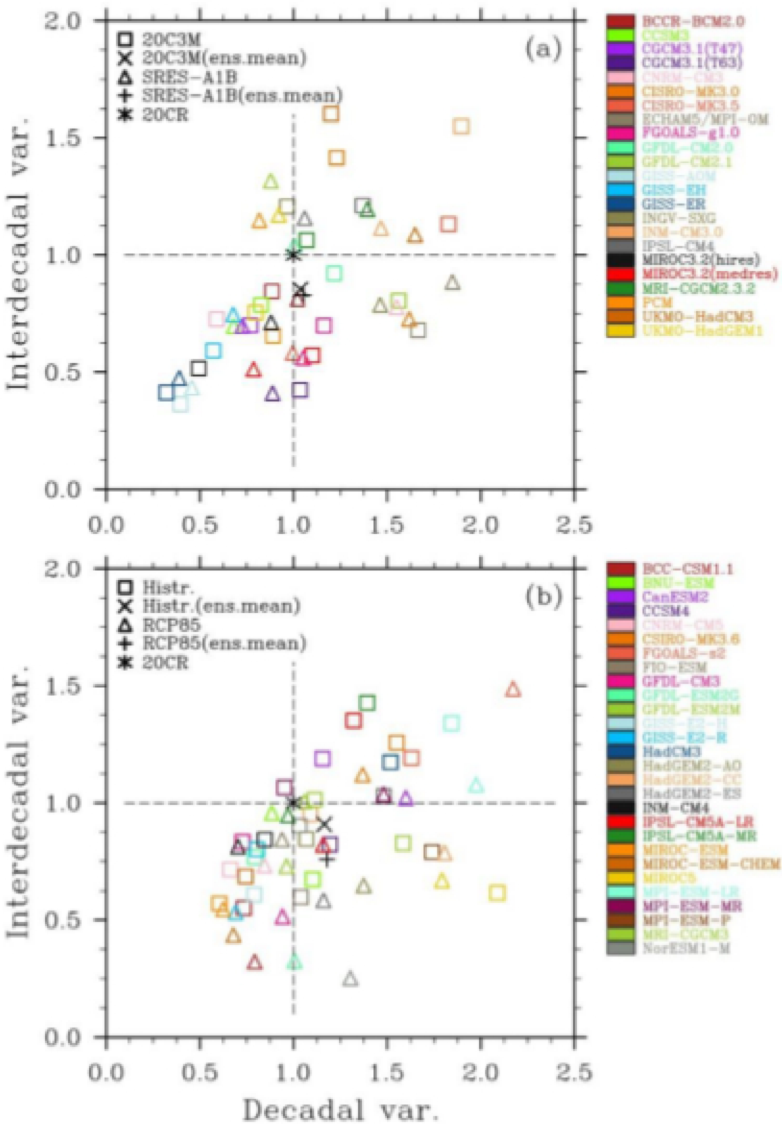

Fig. 5 Decadal vs. interdecadal standard deviation of relative AAM for (a) CMIP3, and (b) CMIP5. All quantities are normalized by the observed values derived from 20CR reanalysis.

1e. Analysis of the Decadal Runs in CMIP5

The Decadal Runs (for selected initial time in the 20th century) in CMIP5 are analyzed to determine whether the coupled climate models have the ability to capture the decadal variability of AAM (and NINO3.4 SST, for additional comparisons), including for the case when the model is initialized before the 1976 transition event. We use the root-mean-squre error and anomaly correlation as two measures of the predictability. Figure 6 shows the outcome from selected models. We found very weak decadal predictability. In fact, most of the predictability in the decadal simulation is limited to within the ENSO predictability time scale of about 1 year. This result indicates that, in the context of an initial value problem, it is difficult to predict the decadal evolution of AAM (an index of the large-scale zonal flow). An examination of the case initialized before the 1976 event did not reveal an enhanced predictability.

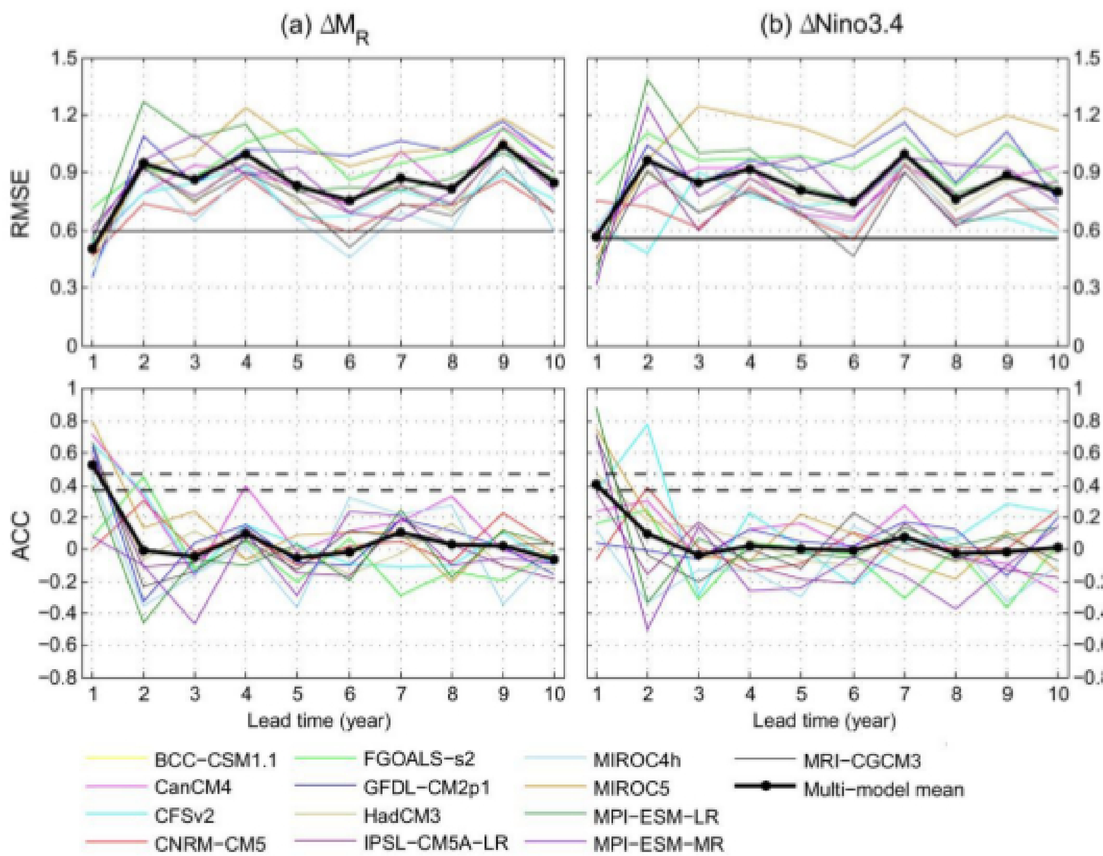

Fig. 6 The RMS error (top panels) and anomaly correlation (bottom panels) of the predicted AAM (left) and NINO3.4 SST (right) from the CMIP5 Decadal Runs. The individual models are labeled at bottom and teh multi-model ensemble mean is shown as the bold black curve.

1f. Exploring the efficient uses of multi-model ensemble for climate projection

When two or more subsets of the multi-model ensemble exhibit different regime behavior, the classical multi-model ensemble average might not be the best way to extract a useful projection from all models. To investigate this issue, this part of the study compares two methods of multi-model averaging for the future projection of precipitation based on the "absolute" and "relative" climate changes. In the relative change scheme, the multi-model average of the percentage changes in precipitation is multiplied by the observed present climate to form the future projection; this method is equivalent to applying unequal weighting to the absolute change scheme. The new scheme and the classical equal weight scheme for the absolute change do not produce radically different large-scale patterns of the trend in precipitation. Nevertheless, notable differences emerge in regional scales. Our analysis showed that, for precipitation at least, the simple multi-model averaging of the relative change is a viable alternative to the classical equal weight scheme for the absolute change. Moreover, the alternative scheme can potentially provide a bias correction. The detailed results are published in a paper (Baker and Huang 2012)

1g. Atmospheric GCM simulations with CMIP5-derived SSTs

We completed a set of in-house atmospheric GCM simulations forced with the SST taken from CMIP5 simulations. The specially designed numerical experiment helped to extract the influence of the changing SST (as a manifestation of the greenhouse gas effect, e.g., DiNezio et al. 2009) on the trend in tropospheric circulation. Using NCAR CAM3 model, total of ten 30-year simulations were completed. They consist of five pairs, each pair forced with repeated seasonal cycles of the late-20th and late-21st century SST from a CMIP5 simulation (using the framework in Huang et al. 2005). The analysis of the outputs revealed that SST-forced atmospheric model simulations capture many key features in the fully coupled CMIP5 simulations in terms of atmospheric zonal wind and angular momentum. This shows the strong influence of the SST on the atmospheric state. Thus, the lack of sharp interdecadal shifts in atmospheric angular mmentum in the models could be attributed in part to the lack of sharp transitions in the SSTs.

2. Project participants

1) Huei-Ping Huang is the Principal Investigator who oversees the scientific analysis and the design of the computer simulations for this project. He also supervises two graduate students who participate in this project as part of their PhD research.

2) Noel Baker was a PhD student who studied the properties of multi-model ensembles of CMIP3 and CMIP5 and explored the strategy of multi-model ensemble averaging for climate projection. She also helped processing the CMIP data and performing statistical analyses relevant to this project. She graduated in Summer, 2013.

3) Houk Paek was a PhD student who worked on the analysis of decadal-to-interdecadal variability and climate shifts in CMIP simulations and observations as part of his thesis research. He was also responsible for executing the in-house atmospheric GCM simulations for this

project. He graduated in Spring, 2013.

4) Michael Makiyama was an undergraduate student who participated in this project, mainly in assisting the analysis of the regime behavior of tropospheric zonal wind.

3. Publications resulted from the project

Paek, H., and H.-P. Huang, 2012: A comparison of decadal-to-interdecadal variability and trend in reanalysis datasets using atmospheric angular momentum, *Journal of Climate*, **25**, 4750-4758

Baker, N. C., and H.-P. Huang, 2012: A comparison of absolute and relative changes in precipitation in multi-model climate projection, *Atmospheric Science Letters*, **13**, 174-179

Paek, H., and H.-P. Huang, 2012: A comparison of the interannual variability in atmospheric angular momentum and length-of-day using multiple reanalysis datasets, *Journal of Geophysical Research*, **117**, doi:10.1029/2012JD018105

Paek, H., and H.-P. Huang, 2013: Centennial trend and decadal-to-interdecadal variability of atmospheric angular momentum in CMIP3 and CMIP5 simulations, *Journal of Climate*, **26**, 3846-3864

Baker, N. C., and H.-P. Huang, 2013: A comparative study of precipitation and evaporationin semi-arid regions between the CMIP3 and CMIP5 climate model ensembles, *Journal of Climate*, submitted (accepted with major revision)

4. Conference presentations

Baker, N. C., and H.-P. Huang, 2011: An alternative method for model weighting applied to climate projection, *World Climate Research Program Open Science Conference*, Denver, Colorado, October 2011.

Baker, N. C., and H.-P. Huang, 2011: An alternative method for model weighting applied to climate projection, *American Geophysical Union Fall Meeting*, San Francisco, December 2011

Makiyama, M., and H.-P. Huang, 2011: The structure of Southern Hemisphere tropospheric zonal flow in climate model simulations, *18th Conference on Atmospheric and Oceanic Fluid Dynamics*, American Meteorological Society, Spokane, Washington, June 2011

Paek, H., and H.-P. Huang, 2011: Comparing interdecadal variability and climate shift in CMIP simulations using atmospheric angular momentum, *DOE PI Meeting*, Washington, D.C., September 2011

Paek, H., and H.-P. Huang, 2011: Comparing interdecadal variability and climate shift in CMIP simulations using atmospheric angular momentum, *American Geophysical Union Fall Meeting*, San Francisco, December 2011

Paek, H., and H.-P. Huang, 2012: An intercomparison of interdecadal variability and climate shifts in reanalysis datasets and climate model simulations, *4th WCRP Conference on Reanalysis*, May 2012, Silver Spring, Maryland

Paek, H., and H.-P. Huang, 2012: Detecting 1976-like climate shift events in climate model simulations using atmospheric angular momentum, *AGU Fall Meeting*, San Francisco, December 2012

Baker, N. C., and H.-P. Huang, 2012: A comparative study of seasonal moisture transport for semiarid regions between CMIP3 and CMIP5 climate model ensembles, *AGU Fall Meeting*, San Francisco, December 2012

5. Dissertations completed under the suport of the project

Paek, H., 2013: Climate variability and trend on interannual-to-centennial time scales from global observations and atmosphere-ocean model simulations, PhD dissertation, Arizona State University, 143 pp.

Baker, N. C., 2013: Improving climate projections through the assessment of model uncertainty and bias in the global water cycle, PhD dissertation, Arizona State University, 147 pp.

6. Travel

The PI and students who worked on this project have attended several conferences and workshops during the reporting period, as detailed in *Conference presentations*. The participation of N. Baker and H. Paek in the AGU 2011 and 2012 Fall Meetings, and the participation of H. Paek in the 4th WCRP Conference on Reanalysis, were supported in part by the fund from this project.

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