**Process-oriented Evaluation and Study of CMIP5 Climate Models: Biases in the Atlantic Warm Pool Region versus North American Rainfall and Hurricane Activity**

A Proposal from
NOAA/Atlantic Oceanographic and Meteorological Laboratory
To
NOAA/CPO/MAPP FY2015 Competition (ID: 2488569): Process Oriented Evaluation of Climate and Earth System Models and Derived Projections in Focus Area-A and Area-B

By

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**Institution: NOAA/AOML**
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## Abstract

Our current/previous NOAA/CPO-funded research has pointed out the importance of the Atlantic Warm Pool (AWP) for summer climate and extreme events in the Western Hemisphere. AWP variability occurs on seasonal, interannual, multidecadal, and secular (global warming) timescales, with large AWPs being almost three times larger than small ones. The effect of the AWP is to weaken the North Atlantic subtropical high (NASH) and strengthen the summer continental low over the North American monsoon region. A large AWP also weakens the southerly Great Plains low-level jet, which results in reduced northward moisture transport from the AWP to the central U.S. and thus decreases the summer rainfall over the central United States. A large AWP increases the number of Atlantic hurricanes by reducing vertical wind shear and increasing the moist static instability of the troposphere, and influences the hurricane steering flow changes that become unfavorable for hurricanes to make landfall in the southeast United States. Our research also suggests that the AWP serves as a link between the Atlantic Multidecadal Oscillation (AMO) and climate and hurricane activity. Despite its importance, almost of all state-of-the-art coupled models exhibit serious biases in the AWP region, which limit the seasonal prediction of AWP-related climate and extreme events.

We propose to continue our investigation of the AWP by focusing on process-oriented metrics in the AWP region. We will use all available observational data, CMIP5 outputs (past simulations and future projections) and model experiments of both GFDL Climate Model and NCAR Community Earth System Model. The proposed tasks include to (1) develop process-oriented metrics of AWP variability; (2) develop process-oriented metrics of AWP-related climate variability; (3) examine processes related the AWP with the Atlantic Meridional Overturning Circulation (AMOC) and AMO; (4) diagnose the performance of CMIP5 climate models using process-oriented metrics; and (5) explore the sources of errors in CMIP5 climate models. The proposed work directly contributes to the NOAA/CPO MAPP FY15 competition of "*Process-oriented evaluation of climate and Earth system models and derived projections*" in both Area A of "*Metrics for climate and Earth system model development*" and Area B of "*Metrics for the evaluation of model projections in support of the National Climate Assessment*". The proposed analyzed metrics will provide an important role for future model developments in the AWP region. It is hoped that over a longer time frame, this work will result in the regional implementation of data- and model-based outlooks and projections for hurricane activity, climate variability and drought/flood in the United States, when successfully combined with land-based models.

## Results from Prior NOAA Support (Last Three Years)

**(1).** NOAA/CPO MAPP Program: "Diagnostic and modeling studies on impacts, mechanisms and predictability of the Atlantic warm pool", PIs: C. Wang, D. B. Enfield and S.-K. Lee, $318K, 7/1/2009 to 6/30/2012.
**(2).** NOAA/CPO/ESS AMOC Program: "Relationship of the Atlantic warm pool with the Atlantic meridional overturning circulation", PIs: C. Wang and D. B. Enfield, $361.9K, July 1, 2011 to June 30, 2014.
**(3).** NOAA/CPO DYNAMO Program: "Upper ocean processes associated with the Madden-Julian oscillation in the Indian Ocean", PI: C. Wang, $138.0K, July 1, 2011 to June 30, 2014.
**(4).** NOAA/CPO MAPP Program: "Variability and predictability of the Atlantic warm pool and its impacts on extreme events in North America" PIs: C. Wang, S.-K. Lee and D. B. Enfield, $442.2K, August 1, 2012 to July 31, 2015.
**(5).** NOAA/CPO MAPP Program: "Toward developing a seasonal outlook for the occurrence of major U. S. tornado outbreaks" PIs: S.-K. Lee, R. Atlas, C. Wang, D. B. Enfield, and S. Weaver, $430.0K, August 1, 2012 to July 31, 2015.

These NOAA projects cover climate studies in the Atlantic, Pacific and Indian Oceans. Most of our research activities during the past three years are focused on the Atlantic, especially on the Atlantic warm pool (AWP). Through the panoply of papers listed below, these NOAA/CPO-supported projects have established AOML as the primary center for research on the AWP and its climate impacts. These research results have contributed directly to key elements of the NOAA/CPPA Science Plan (A draft is available at http://www.joss.ucar.edu/joss_psg/meetings/Meetings_2008/CPPA/index.html) and the Science and Implementation Plan for IASCLIP (Intra-Americas Study of Climate Processes; available for downloading at ftp://ftp.aoml.noaa.gov/phod/pub/wang/IASCLIP_S&Iplan_spr08_v2.pdf), an endorsed component of CLIVAR/VAMOS (http://www.eol.ucar.edu/projects/iasclip).

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## Statement of Work

### 1. Introduction

Much has been learned about the effects of the Indo-Pacific warm pool on winter climate. These occur primarily in association with the interannual expansion (contraction) and eastward (westward) migrations of the Indo-Pacific warm pool that accompany with El Niño (La Niña) events. The winter effects mainly involve several tropospheric processes: (1) alteration of the subtropical jet streams and associated storm tracks; (2) changes in the intensity and/or location of the nodes of the Walker and Hadley circulations; and (3) excitations of stationary Rossby wave trains such as the Pacific-North American pattern. ENSO's remote effects on global climate and weather events are limited mainly to the winter season; hence, these have been the overriding basis and emphasis for winter climate outlooks. Attempts to link ENSO directly to summer climate impacts have been much less successful and a palpable need exists to find other sources of summer climate predictability.

Recently, the variability and effects of the tropical Western Hemisphere Warm Pool (WHWP) have been emphasized for Western Hemisphere climate (see Section 2 for details). At various stages of development, the WHWP is comprised of the eastern North Pacific west of Central America, the Intra-Americas Sea (IAS) (i.e., the Gulf of Mexico and the Caribbean Sea) and the western tropical North Atlantic (Wang and Enfield 2001, 2003). Unlike the Indo-Pacific warm pool, which straddles the equator, the WHWP is entirely north of the equator. Sandwiched between North and South Americas and between the tropical North Pacific and Atlantic Oceans, the WHWP is the second largest body of very warm water on Earth and hosts the second largest diabatic heating center of the tropics during the boreal summer. The Central America landmass divides the WHWP into two ocean regions: (1) the eastern North Pacific warm pool and (2) the Atlantic Warm Pool (AWP). Wang et al. (2006) show that the eastern North Pacific warm pool is more likely to follow the ENSO events since it is close to the ENSO region of maximum variance and is directly related to ENSO variability. Since we are interested in non-ENSO factors that influence rainfall, climate and hurricane activity during the summer and fall, we will mainly focus on the AWP.

Our previous and current NOAA/CPO-funded projects have investigated AWP's variability and its importance to summer climate and Atlantic hurricanes by using observational data and oceanic/atmospheric GCMs (e.g., Wang et al. 2006, 2007, 2008a and b, 2010, 2011; Lee et al. 2007). These research results and other warm pool related studies have contributed directly to key elements of the Science and Implementation Plan for the Intra-Americas Study of Climate Processes (IASCLIP) (it is available at http://www.eol.ucar.edu/projects/iasclip/ or at ftp://ftp.aoml.noaa.gov/phod/pub/wang/IASCLIP_S&Iplan_spr08_v2.pdf) which was endorsed by the CLIVAR-VAMOS Panel, and of the CPPA (Climate Prediction Program for the Americas) Science Plan (available at http://www.joss.ucar.edu/joss_psg/meetings/Meetings_2008/CPPA/index.html). Despite its importance, almost of all state-of-the-art models exhibit serious biases in the AWP (or IAS) region (e.g., Liu et al. 2012, 2013; Kozar and Misra 2012). When an atmospheric GCM is forced by observed SST, there is an excessive precipitation over the AWP region during the summer (Fig. 1d). However, when the atmosphere and ocean are fully coupled, there is a dry and cold bias in the AWP region (Figs. 1b and c and Figs. 1e and f). Using more CMIP3/CMIP5 models obtains similar results to those in Fig. 1. The cause of the model biases in the AWP region is a challenging problem although it has been suggested that the largest impact on the rainfall bias may come from the negative SST biases since the same CMIP3 models that have the least SST bias also have the most realistic rainfall (Liu et al. 2012). It is thus important and necessary to focus on research in the AWP region. In this proposal, we propose to continue our AWP research. Here we propose to investigate and examine process-oriented metrics and climate model performances in the AWP region with a goal of improving climate model simulations and projections of AWP variability and of its related climate and extreme weather events.

## 2. Background

### *2.1. Seasonal, interannual and multidecadal variability of the AWP*

In addition to a large seasonal cycle (Wang and Enfield 2001, 2003), the AWP also shows a large anomalous variation (Wang et al. 2006, 2008b; Figs. 2 & 3). The size of large summer AWPs is much larger than that of small ones (Fig. 2). For the case of large AWPs, warm water is warmer than 29.5°C in a large area surrounding the Greater Antilles (Cuba, Haiti, Dominican Republic, and Puerto Rico) and the isotherm of 28.5°C extends from the northwestern TNA southeastward to the eastern TNA. Figure 3a shows the June-November (JJASON; the hurricane season) AWP area anomaly index which is calculated as the anomalies of the area of SST warmer than 28.5°C divided by the climatological JJASON AWP area. The index displays multiscale variability that includes interannual, multidecadal, and linear trend variations. The detrended AWP index (removing the linear trend) is shown in Fig. 3b. To separate longer (mainly multidecadal) from interannual timescale variability, we apply a seven-year running mean to the detrended AWP index (Fig. 3c). Interannual variability is calculated by subtracting the multidecadal variability from the detrended AWP index, as shown in Fig. 3d. We recognize that the linear detrended method may not be the optimal approach for removing global warming mode since global warming signal may not be linear. In the future, we may choose other ways for removing global warming mode, such as that of using the signal to noise maximizing empirical orthogonal function (EOF) analysis by Ting et al. (2009).

The correlation between the DJF (December-February) Nino3 SST anomalies and the following summer/fall AWP interannual index of Fig. 3d is 0.47, suggesting a delayed ENSO effect on the AWP. The delayed impact of ENSO on the AWP has been analyzed by Enfield et al. (2006). However, the contemporaneous correlation of the summer/fall Nino3 SST anomalies and summer/fall AWP index is only 0.1 (not significant). This reflects the facts that (1) large/small AWPs in the summer and fall have no clear relation to contemporaneous El Niño/La Niña development, and (2) by the summer and fall of the following year the Pacific El Niño/La Niña anomaly has almost always disappeared. These facts suggest that local processes in the Atlantic sector play a direct role in the AWP interannual variability (Enfield et al. 2006; Lee et al. 2008), in addition to the remote delayed influence of Pacific ENSO (also the influence of the North Atlantic Oscillation as shown by Enfield et al. 2006 and Liu et al. 2012).

The AWP multidecadal variability (Fig. 3c) shows that the multidecadal AWPs are large before 1888, during 1934-1962, and after 1995 and small during 1889-1933 and 1963-1994. The periods for large and small AWPs coincide with the warm and cool phases of the AMO (e.g., Enfield et al. 2001; McCabe et al. 2004; Bell and Chelliah 2006) with 80% of large (small) warm pools occurring during the warm (cool) phases of the AMO (Wang et al. 2008b). That is, AWP variability is tied to simultaneous alterations of SST in the high latitudes of the North Atlantic in a mode that operates primarily on multidecadal timescale. Enfield et al. (2001) show that the AMO is inversely correlated with rainfall and river flows over most regions of the U.S., and McCabe et al. (2004) show that the AMO was associated with past megadroughts. Since the climate response to the AMO SST anomalies is primarily forced by the TNA SST anomalies (Sutton and Hodson 2007; Hoerling et al. 2001), the relationships of the AMO with North American rainfall and Atlantic hurricanes may operate through the mechanism of the AWP-induced atmospheric changes. In other words, the AWP acts as a link of the AMO with North American rainfall, climate response and hurricane activity (Wang et al. 2008b).

### *2.2. Impact of the AWP on summer rainfall in North America*

Observational and modeling studies have shown that the AWP (or the IAS) serves as a moisture source for rainfall in North, Central, and South Americas dependent on the season (e.g., Higgins et al. 1997; Bosilovich and Schubert 2002; Mo and Berbery 2004; Ruiz-Barradas and Nigam 2005; Mestas-Nuñez et al. 2007; Wang et al. 2007). Located on the AWP's northeastern side is the North Atlantic subtropical high (NASH) that energizes the tropical easterly trade winds. Figure 4 shows the summer (JJA) vertically integrated moisture flux calculated from the NCEP-NCAR reanalysis and the CTRL ensemble run (the CTRL run is the NCAR CAM3 model forced globally by the monthly HadISST climatological SST). During the summer, the easterly trade winds carry moisture from the TNA into the Caribbean Sea where the flow intensifies forming the easterly Caribbean low-level jet (CLLJ), due to a strong meridional pressure gradient set up by the NASH (Wang 2007). As the CLLJ transits the Caribbean Sea, it then splits into two branches: One turning northward and connecting with the Great Plains low-level jet (GPLLJ), and the other one continuing westward across Central America into the eastern North Pacific. These two branches of moisture transport act to provide a linkage between the AWP and climate variability over the central U.S. and the eastern North Pacific moisture source for the North American monsoon.

The model runs of CAM3 show that a large (small) AWP weakens (strengthens) the summertime NASH and strengthens (weakens) the summertime continental low over the North American monsoon region (Wang et al. 2008a). In response to the pressure changes, the easterly CLLJ is weakened (strengthened), as are its westward and northward moisture transports. The model runs also show that a large (small) AWP weakens (strengthens) the southerly GPLLJ, which results in reduced (enhanced) northward moisture transport from the Gulf of Mexico to the

U.S. east of the Rocky Mountains (Fig. 5) and thus decreases (increases) the moisture available for summer rainfall over the central United States (Wang et al. 2008a; Fig. 6). These results are consistent with previous observations of Wang et al. (2006) who found a negative correlation between the AWP index and rainfall anomalies in the central United States. These are also consistent with Mestas-Nuñez et al. (2007) who show that a positive northward moisture flux anomaly across the Gulf of Mexico is associated with a cool IAS and greater summer rainfall east of the Rockies. In summary, the AWP is an important moisture source for rainfall over North America and AWP variability can contribute to drought and flood over North America.

Is the AWP-influenced rainfall in North America dependent on timescales? To answer this question, we separate the AWP index into the interannual (2-7 years) and decadal to multidecadal (longer than 7 years) variations. We then regress rainfall onto the interannual and multidecadal AWP indices by using different rainfall datasets (Liu et al. 2014). On interannual timescale, the warming of the AWP is associated with more precipitation in the central and eastern U.S. and less precipitation in the western United States. However, on multidecadal timescale the warming of the AWP is corresponded to less precipitation in the central and eastern United States. These different influences on U.S. rainfall may be due to that the AWP is associated with different SST anomaly patterns which induce different atmospheric circulations and thus have different rainfall impacts. This issue can be addressed by using an atmospheric GCM, a simple atmospheric model, and a coupled ocean-atmosphere GCM.

*2.3. Impact of the AWP on Atlantic hurricane genesis, intensification and tracks*

The model runs also show that AWP variability can affect Atlantic hurricane activity through the changes of the dynamical parameter of the vertical wind shear and the thermodynamical parameter of the moist static instability in the hurricane main development region (MDR) (Wang and Lee 2007; Wang et al. 2007, 2008a). Dynamically, the AWP-induced atmospheric circulation pattern is baroclinic (Gill 1980), with a large warm pool producing a cyclone in the lower troposphere and an anticyclone in the upper troposphere, both situated on the northern flank of the AWP. This anomalous circulation structure reduces the lower tropospheric easterly flow and the upper tropospheric westerly flow over the AWP, thus reducing the vertical wind shear in a way that favors atmospheric convection. Thermodynamically, the AWP increases convective available potential energy that provides the fuel for moist convection and thus facilitates the formation and development of tropical cyclones (TCs). We use observations and numerical model experiments to show that the AWP plays an important role in steering TCs in the Atlantic (Wang et al. 2011). An eastward expansion of the AWP shifts the cyclogenesis location eastward, decreasing the possibility for a hurricane to make landfall (Fig. 2 in Wang et al. 2011). A large AWP also induces barotropic stationary wave patterns that weaken the NASH and produce the eastward and northeastward TC steering flow anomalies along the eastern seaboard of the United States (Fig. 7). Due to these two mechanisms, hurricanes tend to be recurved toward the northeast without making landfall in the southeastern United States. As an example, although both the La Niña event and large AWP in 2010 were associated with the increased number of Atlantic hurricanes, landfalling activity in 2010 was determined by the AWP: effect of the large AWP overwhelmed that of the La Niña. As a result, the 2010 Atlantic hurricane season was extremely active, but no hurricanes made landfall in the United States. The 2011 season has also been active with a warm TNA and almost all storms have followed a similar pattern. Hurricane Sandy in 2012 is another example for the large AWP to steer Sandy northward with severe damage in New Jersey and New York.

*2.4. Links of the AWP with the AMOC and the tropical southeastern Pacific*

Both observational and modeling studies show that the AWP has an inter-hemispheric influence on the tropical southeast Pacific (Wang et al. 2006, 2010, 2014). The AWP alternates with the Amazon basin in South America as the seasonal heating source for circulations of the Hadley and Walker type in the Western Hemisphere. During the boreal summer/fall, a strong Hadley-type circulation is established, with ascending motion over the AWP and subsidence over the southeastern tropical Pacific. This is accompanied by equatorward flow in the lower troposphere over the southeastern tropical Pacific, as dynamically required by the Sverdrup vorticity balance. A large (small) AWP during the boreal summer/fall results in a strengthening (weakening) of the Hadley-type circulation with enhanced descent (ascent) over the southeastern tropical Pacific. Given that the southeastern tropical Pacific can be remotely influenced by AWP variability, it is suggested and shown that if models cannot succeed in simulating AWP variability, they will also fail at least partially over the southeastern Pacific (Wang et al. 2014) where almost of all state-of-the-art coupled models exhibit serious errors in the form of a severe warm bias in simulated SSTs (e.g., Mechoso et al. 2003). Hence, the improved simulation and understanding of the AWP are important topics in global climate modeling research.

In a recent paper (Wang et al. 2014), we find in CMIP5 climate models that global SST biases are commonly linked with the Atlantic meridional overturning circulation (AMOC), which is characterized by the northward flow in the upper ocean and returning southward flow in the deep ocean. A simulated weak AMOC is associated with cold biases in the entire Northern Hemisphere with an atmospheric pattern that resembles the Northern Hemisphere annular mode. The AMOC weakening is also associated with a strengthening of Antarctic bottom water formation and warm SST biases in the Southern Ocean. It is also shown that cold biases in the AWP and West African/Indian monsoon regions during the warm season in the Northern Hemisphere have interhemispheric links with warm SST biases in the tropical southeastern Pacific and Atlantic, respectively. The results suggest that improving the simulation of regional processes may not suffice for overall better model performance, as the effects of remote biases may override them.

*2.5. Relationship of the AWP with AMOC and AMO variability*

The observational and modeling studies (Wang et al. 2013; Zhang et al. 2014) suggest that variability of freshwater and ocean salinity associated with the AWP may have the potential to affect the AMOC. On one hand, as the AMOC weakens, its northward heat transport reduces and thus the North Atlantic cools and the AWP becomes small. On the other hand, a small AWP decreases rainfall in the tropical North Atlantic and increases the cross-Central American moisture export to the eastern North Pacific. Both of these factors tend to increase salinity in the tropical North Atlantic Ocean. Advected northward by the wind-driven ocean circulation, the positive salinity anomalies may increase the upper-ocean density in the deep-water formation regions and thus strengthens the AMOC. Therefore, the AWP plays a negative feedback role that acts to restore the AMOC after it is weakened or shut down. This hypothesis is tested and confirmed by ocean model experiments (Zhang et al. 2014). The roles of the AWP in the AMOC and climate needs to be further studied.

The multidecadal tropical North Atlantic (TNA; or AWP) subsurface ocean temperature variation could be taken as a proxy or fingerprint for AMOC variability (Zhang 2007; Wang and Zhang 2013). Similar to the coupled GFDL CM2.1 analyses (Zhang et al. 2007), we have used the SODA and Ishii et al. (2006) data sets to calculate the AMO indices and the regression of the Atlantic zonal mean ocean temperatures onto the AMO indices (Fig. 8). The Atlantic Ocean shows an anticorrelated variation between the surface and subsurface temperatures on multidecadal timescales. It can be seen that the surface temperature is characterized by a basin-wide and uniform warming (cooling) in the entire North Atlantic with a maximum magnitude occurring in the subpolar region during the warm (cold) phase of the AMO, in agreement with the definition of the AMO index. The penetrated depth of the surface warming is latitude-dependent, i.e., the higher the latitude the deeper the heat penetration, which is a result of the mixed layer depth difference. In the subsurface, there is an opposite relationship, where the temperature tends to become cool (warm) during the warm (cold) phase of the AMO. In the TNA Ocean, the anomalous cooling appears below 100 m and penetrates down to 1500 m, with a maximum cooling around 200 m between 8°N and 20°N. The anticorrelated surface and subsurface temperature variation or vertical dipole temperature structure in the TNA occurs only on multidecadal timescales (lower panels of Fig. 8). On interannual timescales, the temperature profile exhibits a uniform positive regression between the surface and subsurface oceans.

## 3. Datasets and numerical models

Many observational datasets will be analyzed and compared with model simulations and projections. The atmospheric data mainly include the NCEP-NCAR reanalysis, the ERA40 reanalysis, the North American Regional Reanalysis (NARR), the NOAA/ESRL 20$^{th}$ Century Reanalysis (20CR) and the CPC Merged Analysis of Precipitation (CMAP). Other rainfall data include the Observed Land Surface Precipitation (OLSP) dataset from 1850 to 1995 based on gauge records (Dai et al. 1997) and the Merged Statistical Analyses of Historical Monthly Precipitation Anomalies (MSAHMPA) dataset from 1900 to 2000 (Smith et al. 2010). The oceanic data include the NOAA extended reconstructed SST, the Hadley Centre Sea Ice and SST data, the Global Ocean Data Assimilation System (GODAS) data, the Simple Ocean Data Assimilation (SODA) (Carton and Giese 2008), the objectively analyzed temperature and salinity version 6.7 (Ishii et al. 2006), the Argo data, and the PIRATA observations.

The model outputs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) will be analyzed. These include the simulations of the past and projections of future climate change on two timescales of near-term (out to about 2035) and long-term (out to 2100 and beyond). The analyses of the past simulations will conduct a systematic assessment and inventory of model performance in simulating variables. One of the principal aims for the future model projections is to understand how the normal functioning of climate mechanisms is altered by future global warming.

Two climate models will also be used for performing some model experiments. The first one is the NCAR Community Climate System Model version 4 (CCSM4), which also called the Community Earth System Model version 1 (CESM1). It consists of four dynamical geophysical models (i.e., atmosphere, ocean, land and ice) linked by a central coupler. The second climate model is the GFDL coupled model (CM). More technical details about CESM1 and CM can be found in Vertenstein et al. (2010) and Donner et al. (2011), respectively. We have already installed CESM1 at NOAA high performance computing system and performed a long-term spinup simulation (1,500 years) as well as a surface-forced real-time ocean-sea-ice simulation for the period of 1871-2010.

## 4. Proposed work

Section 2 provides the detailed AWP variability and its influences on climate and extreme events. Figure 9 briefly summarizes these results. Given the importance of the AWP, we propose the following research tasks.

### *4.1. Developing process-oriented metrics of AWP variability*

All available modern atmosphere and ocean reanalysis products, as stated in the last section, will be used to perform various analyses (e.g., upper ocean heat budget analysis, composite analysis and regression analysis) to describe and quantify (with statistical confidence limit) atmosphere-ocean processes linked to the onset, peak and decay of the AWP at seasonal, interannual and multidecadal time scales. Particularly, our focused areas are (1) processes involving the seasonal onset and decay of the AWP (Enfield and Lee 2005; Lee et al. 2007; Wang et al. 2007); (2) variability of the AWP; and (3) the influences of external and local processes on AWP variability (Wang and Enfield 2003; Enfield et al. 2006; Lee et al. 2008b). Using these analyses, guided by our earlier AWP studies, we will develop a list of process-oriented metrics for AWP variability.

Additionally, our previous studies define the AWP index by the area of SST warmer than 28.5°C. These are temperatures that have a significant impact on organized tropical convection (e.g., Graham and Barnett 1987). The AWP usually disappears at the winter minimum and tends a large but closed region during the summer maximum. Not only is the choice of 28.5°C based on limiting the AWP to a closed region, it is also based on the fact that the depth of the 28.5°C isotherm is the closest to the average mixed layer depth in the AWP region. However, this definition of the AWP does not tell us the vertical structure of the AWP. In particular, the upper ocean thermal structure is very important to hurricane intensification. In this proposal, we would like to further develop the AWP index by considering the vertical structure of the AWP. A simple way is to use the volume of the 28.5°C isotherm or other isotherms for measuring the AWP. We will re-examine all climate and hurricane variability based on the volume of the AWP and compare with our previous results used the area of SST for the AWP index. Particularly, we will focus on how the vertical structure of the AWP affects hurricane intensification. It is expected that a new index or metric can be served as a better indicator of the effects of the AWP on climate and hurricane variability.

*4.2. Developing process-oriented metrics of AWP-related climate variability*

We will use all available atmosphere and ocean reanalysis products to perform various statistical analyses to describe and quantify (with statistical confidence limit) processes of AWP-related climate variability. The analyses of AWP-related climate variability will include (1) processes of the AWP-related variability of the North Atlantic subtropical high, Caribbean low-level jet, Great Plains low-level jet and associated moisture transports to and rainfall in the United States; (2) local and remote processes that provide seasonal AWP predictability; and (3) the AWP-related environmental factors contributing to Atlantic hurricane activity (Wang and Lee 2007; Wang et al. 2007; 2008a and b). The local processes may include the feedback between surface wind, evaporation and SST (e.g., Xie and Philander 1994; Chang et al. 1997), ocean dynamical processes (Lee et al. 2007) and the feedback involving longwave radiation and cloudiness (Wang and Enfield 2003). The remote influences include ENSO, the NAO, the AMO and AMOC. Various statistical analysis methods will be used to carry out the tasks described above. Based on these analyses, a list of process-oriented metrics for the AWP's impacts on hurricanes and summer rainfall in North America will be developed.

*4.3. Examining processes related the AWP with the AMOC and AMO*

As stated in Section 2.5, the AWP is strongly linked to AMOC variability. The anticorrelated variation between the TNA (or AWP) surface and subsurface ocean temperatures is a distinctive signature of the AMOC and can be taken as the AMOC fingerprint (Zhang 2007; Wang and Zhang 2013). We will analyze this signature and its associated heat budget terms in CMIP5 simulations and compare with those from the ocean reanalysis products. We will attempt to explore a process-oriented metric based on the anticorrelated temperature variation between the surface and subsurface TNA Oceans in relation to the AMOC.

Additionally, our recent study (Wang et al. 2014) showed that the CMIP5 models with stronger than observed AMOC strength still contributes to cold SST bias in the North Atlantic. This suggests that the AMOC strength may not be the only factor that causes the cold SST bias. Particularly, it is important to realize that although the AMOC strength is correctly simulated, if the AMOC cell is too shallow, the associated northward heat transport could be too weak. This argument is readily supported by a well-known deficiency in level coordinate models that North Atlantic Deep Water is too shallow (Yeager and Danabasoglu 2012). Therefore, we will explore various process-oriented metrics to properly measure the performance of AMOC strength, vertical structure and associated meridional heat transport in CMIP5 models.

*4.4. Diagnosing the performance of CMIP5 climate models using process-oriented metrics*

A set of process-oriented metrics developed from Tasks 4.1-4.2 will be used to diagnose the performance of CMIP5 climate models (under pre-industrial and historical scenarios and future projections) in simulating AWP variability and AWP-related variability contributing to hurricane activity and summer rainfall in North America. Following the observational process-oriented metric analyses in Tasks 4.1-4.2, the analyses of CMIP5 climate models should be straightforward. Using CMIP5 model outputs, we will repeat all metric analyses proposed in Tasks 4.1-4.2. By comparing the observed and modeled process-oriented metrics, we can assess and evaluate the performance of CMIP5 climate models in the AWP region. One metric that we can use is the Taylor diagrams of statistics as used in our previous studies (Liu et al. 2012, 2013). These analyses will play an important role in future model developments because almost all CMIP5 climate models show a large cold SST and dry bias in the AWP region.

*4.5. Exploring the sources of errors in CMIP5 climate models*

The major purpose of this proposal is to analyze the process-oriented metrics in the AWP region and to provide information and guidline for future model developments. However, the above proposed metric analyses will give us some clues what processes possibly cause model biases in the AWP region. Thus, based on these previous analyses, we also would like to perform some diagnostic and modeling experiment studies for exmining processes or factors that may be responsible for causing the model biases. The model experiments will be designed based on the proposed process-oriented metric analyses in Tasks 4.-1-4.4. We will use both GFDL Climate Model (CM) and NCAR Community Earth System Model (CESM) to explore and identify the potential sources of errors in CMIP5 models.

Additionally, we also will test various configurations of these two models. For instance, we will perform three CESM experiments by changing the atmosphere-land model resolutions only (i.e., $1.9° \times 1.25°$; $0.47° \times 0.65°$ and $0.23° \times 0.31°$) to explore if the AWP-related process metrics could be better simulated by increasing the horizontal resolution of the atmosphere-land model. Similarly, we will perform two CM experiments by changing the ocean-sea ice model resolutions only from a non-eddy permitting resolution to an eddy-permitting resolution. We will also perform other CESM experiments by strongly relaxing the model SSTs in the remote oceans toward the observed SSTs to understand whether the AWP-related model errors are remotely forced.

## 5. Work plan

All of the proposed research in this proposal will be performed in a coordinated manner. However, a year-by-year work plan may be listed as follows:

**Year 1:**

(a). Analyze processes involving the seasonal onset and decay of the AWP.

(b). Analyze variability of the AWP.

(c). Analyze the influences of external and local processes on AWP variability.

(d). Work on the AWP index by considering the vertical structure of the AWP (use the volume of the 28.5°C isotherm or other isotherms for measuring the AWP) and re-examine all climate and hurricane variability based on the volume of the AWP and compare with our previous results used the area of SST for the AWP index.

**Year 2:**

(a). Analyze processes of the AWP-related variability of the North Atlantic subtropical high, Caribbean low-level jet, Great Plains low-level jet and associated moisture transports to and rainfall in the United States.

(b). Examine local and remote processes that provide seasonal AWP predictability.

(c). Analyze the AWP-related environmental factors contributing to Atlantic hurricane activity.

(d). Analyze processes that can relate AWP variability with AMOC variability.

**Year 3:**

(a). Analyze the anticorrelated variation between the TNA (or AWP) surface and subsurface ocean temperatures and related processes that can be taken as the AMOC fingerprint.

(b). Examine and analyze the relationship of the vertical AMOC structures with global SST biases

(c). Diagnose the performance of CMIP5 climate models using process-oriented metrics.

(d). Perform model experiments for studying the sources of errors in climate models.

## 6. Relevance to the Goal of the NOAA/CPO MAPP Program Priorities

The overall goal of the NOAA Climate Program is to understand climate variability and change to enhance society's ability to plan and respond. The program aims to advance scientific understanding of the earth's past and present climate variability and change to improve climate forecast skill, increase the credibility of climate change projections, and provide climate information for policy and decision makers and resource managers. One of NOAA's long-term goals is "*Climate Adaptation and Mitigation – An informed society anticipating and responding to climate and its impacts*". The proposed work directly contributes to the NOAA/CPO MAPP FY15 competition of "*Process-oriented evaluation of climate and Earth system models and derived projections*" in both Area A of "*Metrics for climate and Earth system model development*" and Area B of "*Metrics for the evaluation of model projections in support of the National Climate Assessment*".

The proposed analyzed metrics will provide an important role for future model developments in the AWP region. In addition, the proposed research along with our current projects will also make a contribution to the IASCLIP (Intra-Americas Study of Climate Processes) program, an endorsed component of CLIVAR-VAMOS (http://www.eol.ucar.edu/projects/iasclip). It is hoped that over a longer time frame, this work will result in the regional implementation of data- and model-based outlooks and projections for hurricane activity, climate variability and drought/flood in the United States, when successfully combined with land-based models.

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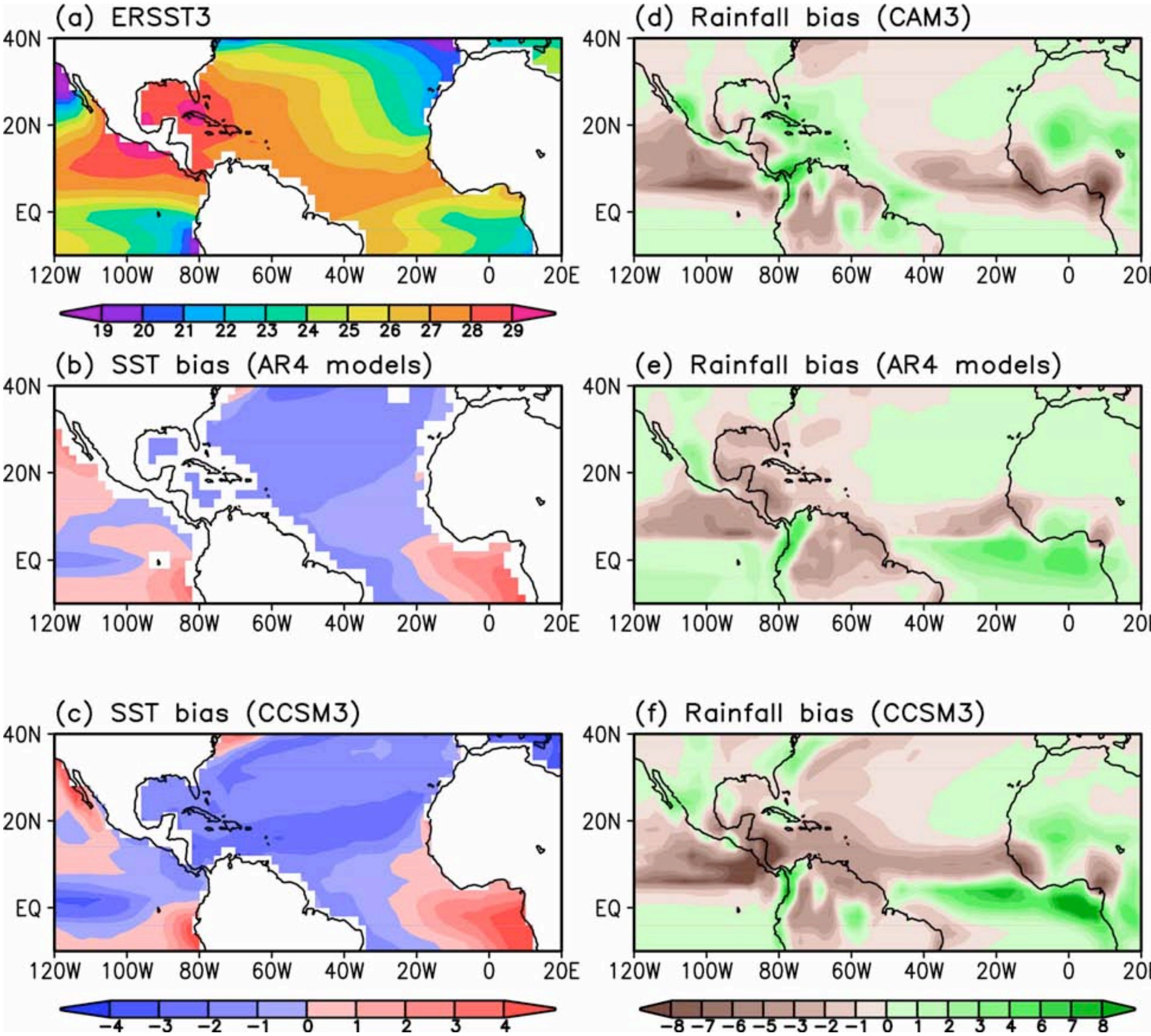


**Figure 1.** The observed SST and long-term averaged model biases in the summer months of June-August (JJA). Shown are (a) the ERSST, (b) the model SST bias of the 22 IPCC-AR4 coupled model ensemble, (c) the model SST bias of CCSM3, (d) the model rainfall bias of the atmospheric GCM (CAM3), (e) the model rainfall bias of the 22 IPCC-AR4 coupled model ensemble, and (f) the model rainfall bias of CCSM3.

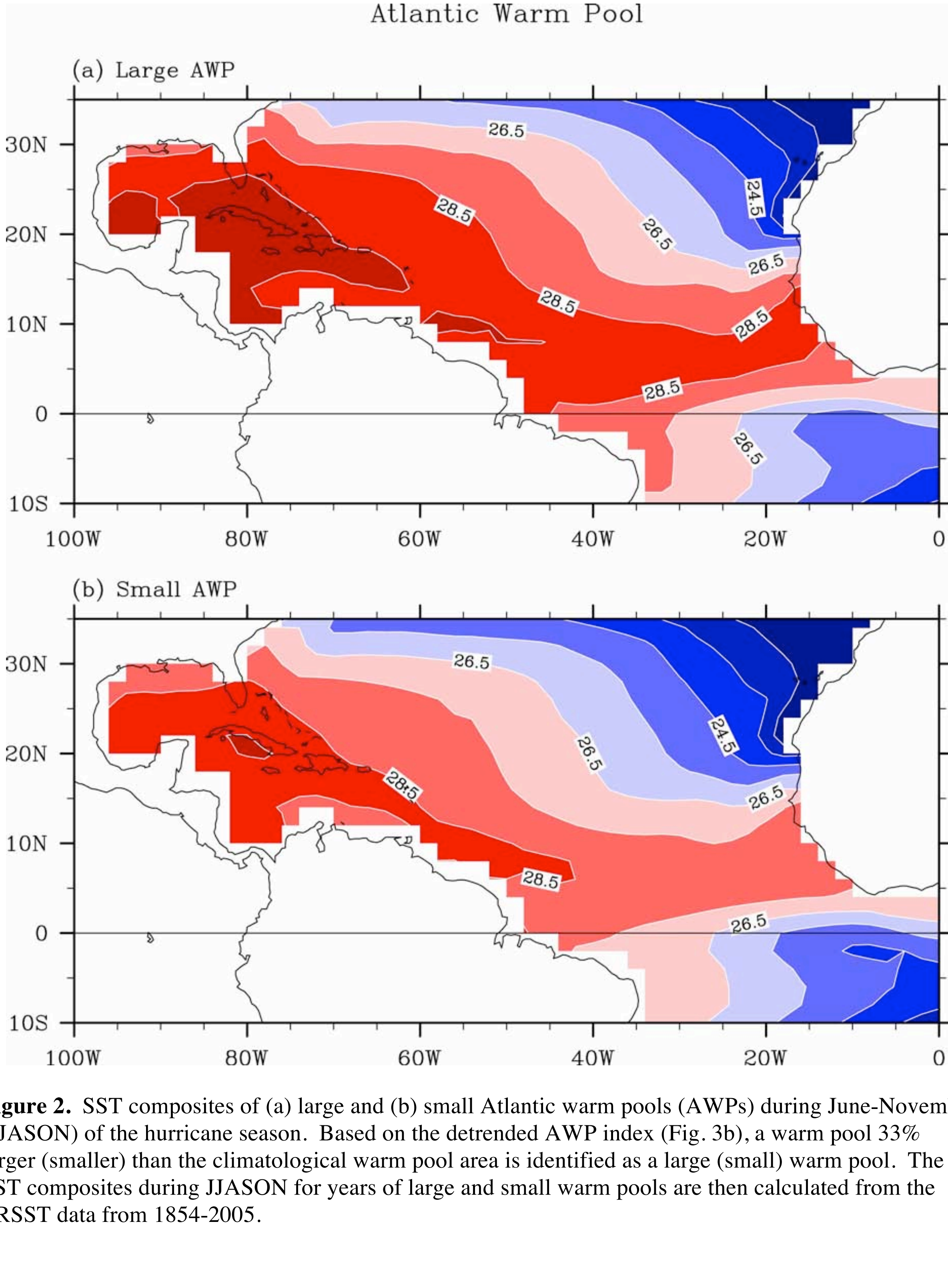


**Figure 2.** SST composites of (a) large and (b) small Atlantic warm pools (AWPs) during June-November (JJASON) of the hurricane season. Based on the detrended AWP index (Fig. 3b), a warm pool 33% larger (smaller) than the climatological warm pool area is identified as a large (small) warm pool. The SST composites during JJASON for years of large and small warm pools are then calculated from the ERSST data from 1854-2005.

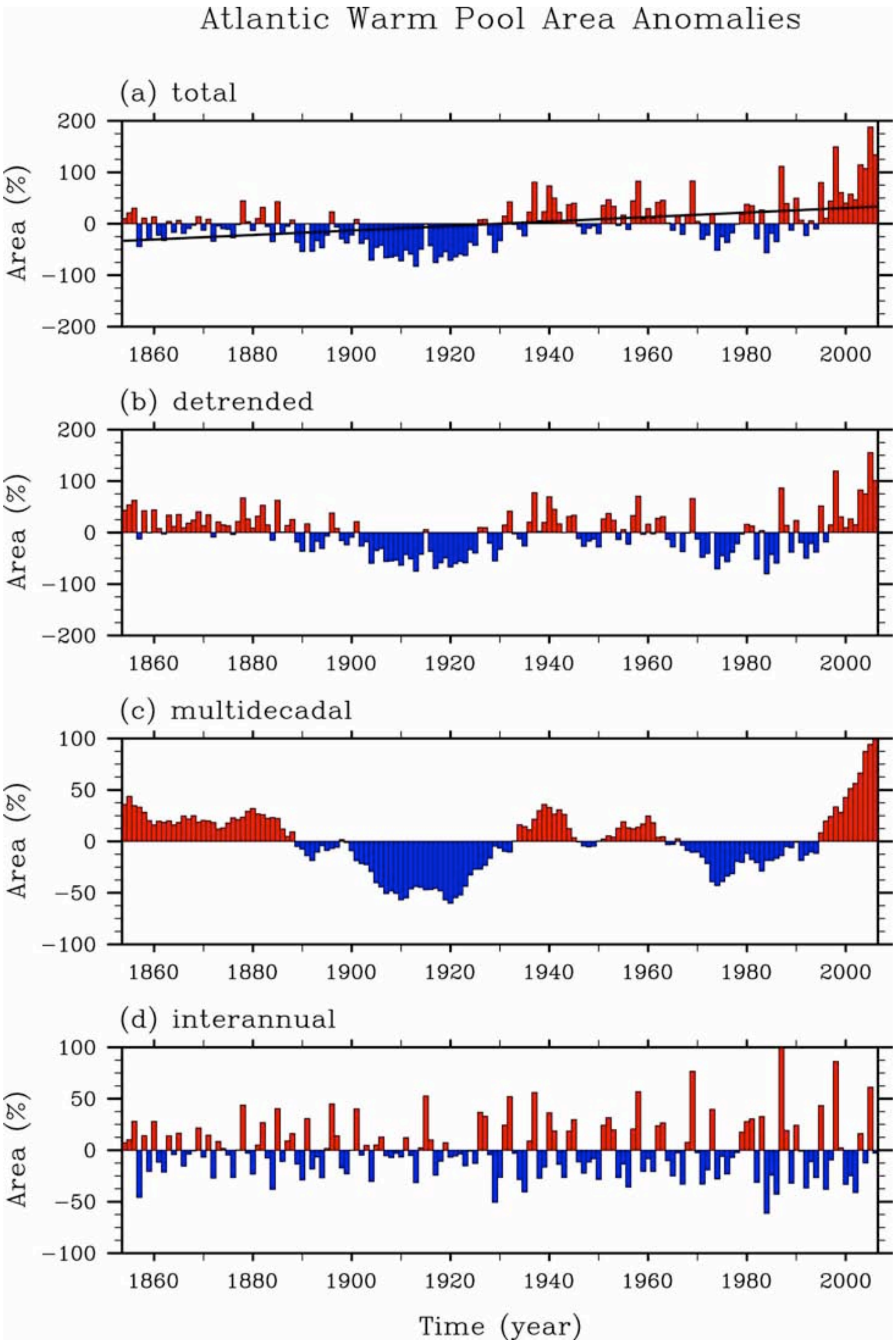


**Figure 3**. AWP area anomaly indices (%) during June-November (JJASON). The area index is calculated as the anomalies of the area of SST warmer than 28.5°C divided by the climatological JJASON AWP area. Shown are the (a) total, (b) detrended (removing the linear trend), (c) multidecadal, and (d) interannual area anomalies. The multidecadal variability is obtained by performing a seven-year running mean to the detrended AWP index. The interannual variability is calculated by subtracting the multidecadal variability from the detrended AWP index. The multidecadal (interannual) variability accounts for 54% (46%) of the total variance of the detrended AWP index. The black straight line in (a) is the linear trend that is fitted to the total area anomaly.

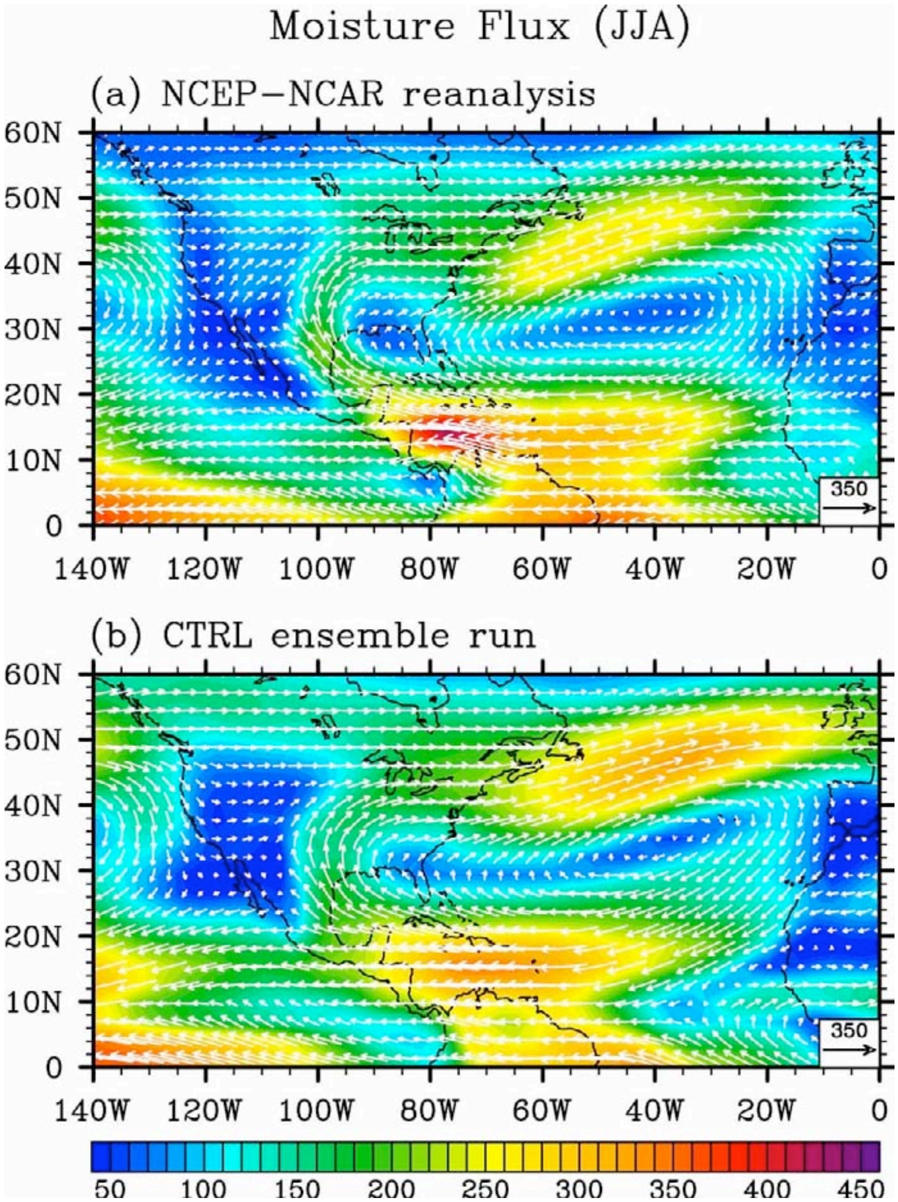


**Figure 4.** Summer (JJA) vertically integrated moisture flux ($\vec{Q} = \int_{300mb}^{sfc} (q\vec{u} / g)dp$ , where $q$ is specific humidity, $\vec{u}$ is vector wind, $p$ is pressure, and $g$ is gravity; in unit of kg $m^{-1}$ $s^{-1}$) calculated from (a) the NCEP-NCAR reanalysis and (b) the control (CTRL) ensemble model run. Arrows indicate the moisture flux vector and colors represent the amplitude of the moisture flux. The CTRL run is the CAM3 simulation forcing by the monthly global HadISST climatological SST.

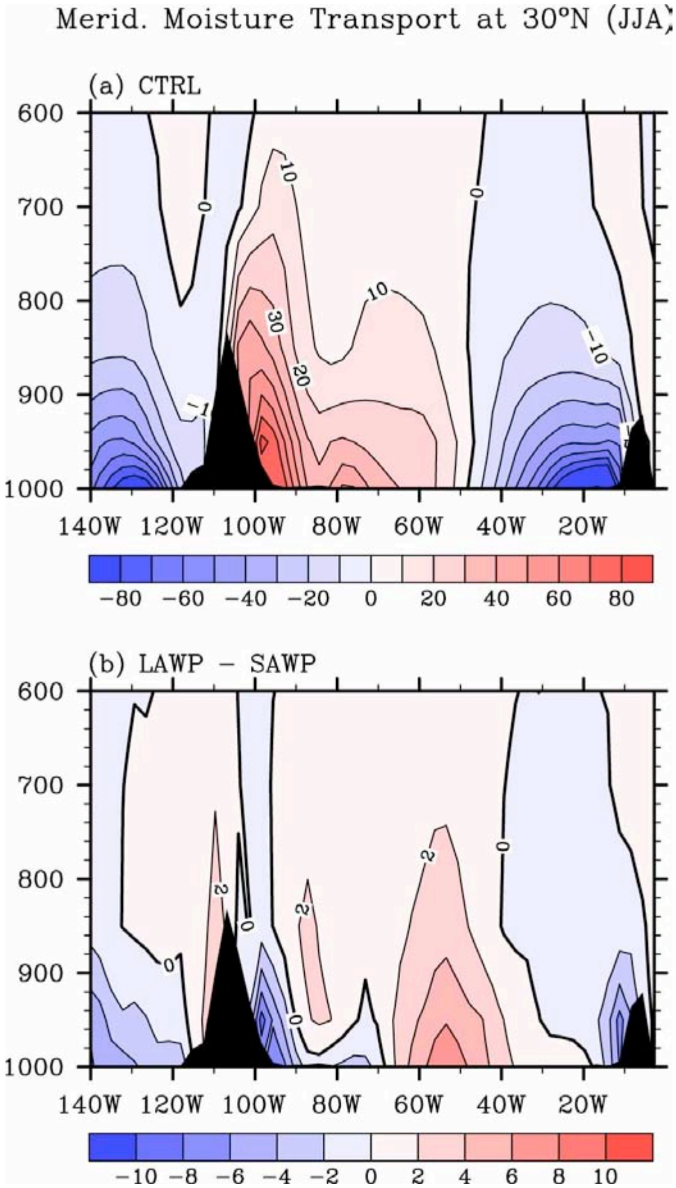


**Figure 5.** Zonal-vertical sections of the meridional moisture transport of $qv$ (g $kg^{-1}$ m $s^{-1}$) at 30°N during the summer (JJA) from (a) the control (CTRL) ensemble CAM3 run and (b) the difference between the large and small AWP runs (LAWP – SAWP). The unit on the vertical axis is mb.

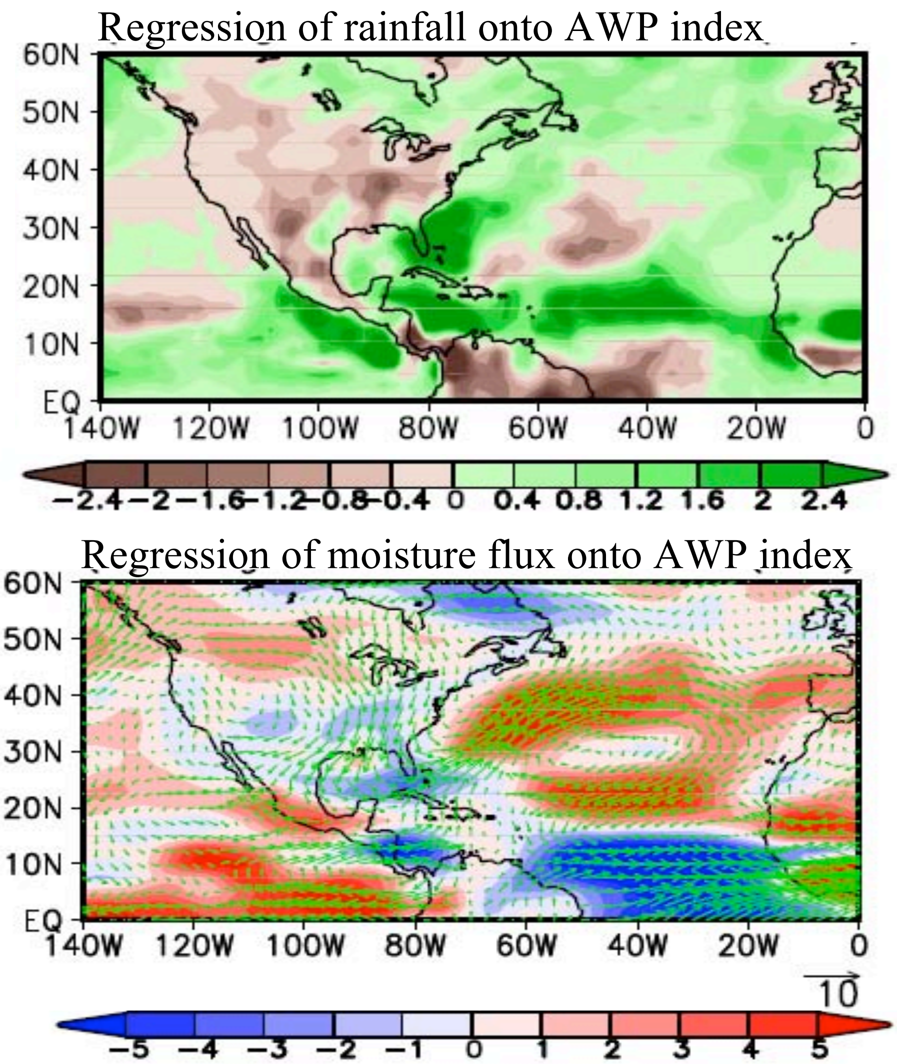


**Figure 6.** The AWP and rainfall. Shown are the regression of rainfall onto the AWP index (top) and the regressions of moisture transport (vector) and moisture convergence (shading) onto the AWP index (bottom). Moisture transport (g kg$^{-1}$ m s$^{-1}$) is calculated at each vertical level and integrated from the sea surface to 300 mb.

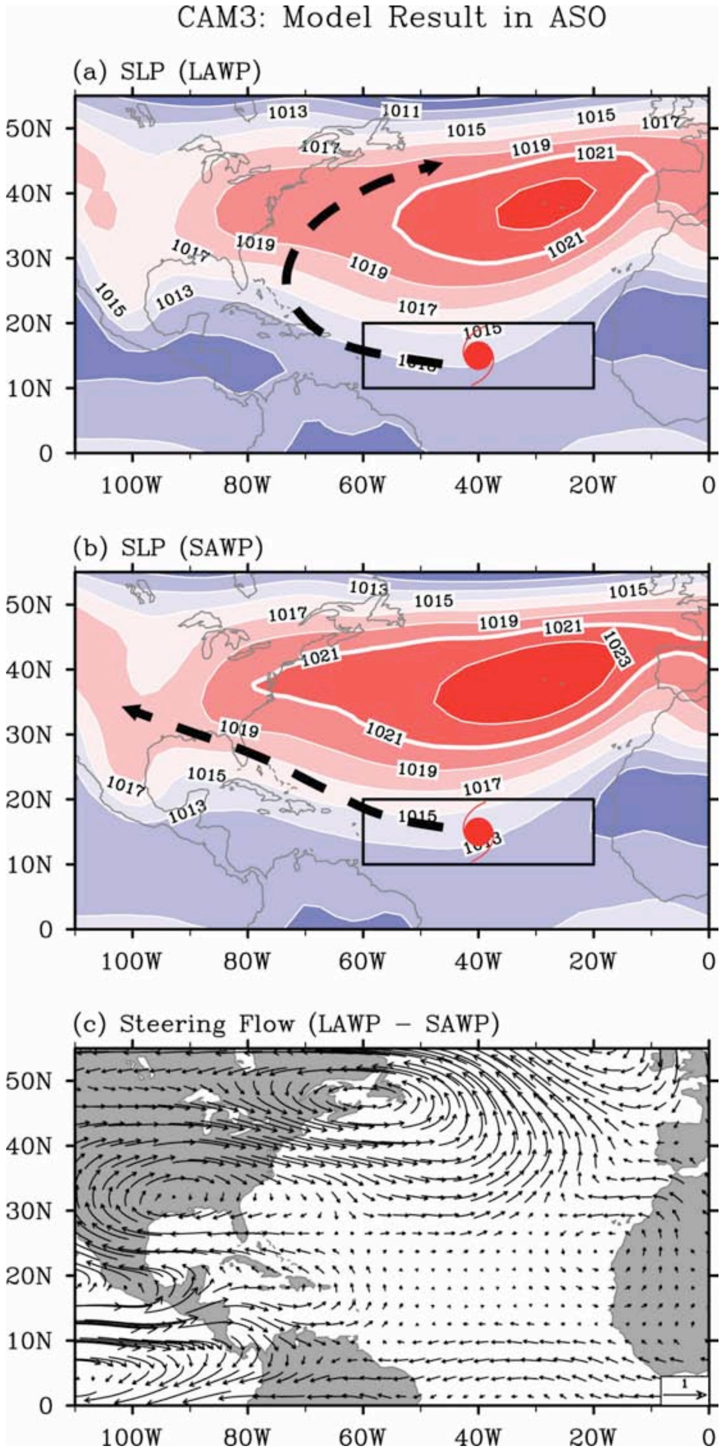


**Figure 7.** The simulated effect of the AWP on the NASH from the CAM3 runs during August-October (ASO). Shown are the sea level pressures (SLPs) for the (a) large AWP (LAWP) run, (b) small AWP (SAWP) run and (c) hurricane steering flow difference between LAWP and SAWP runs. The steering flow ($\times 10^3$ hPa m/s) is calculated as the vertically-averaged wind from 850 hPa to 200 hPa. The dashed arrows are schematically drawn, illustrating the hurricane track if a hurricane forms in the MDR (box).

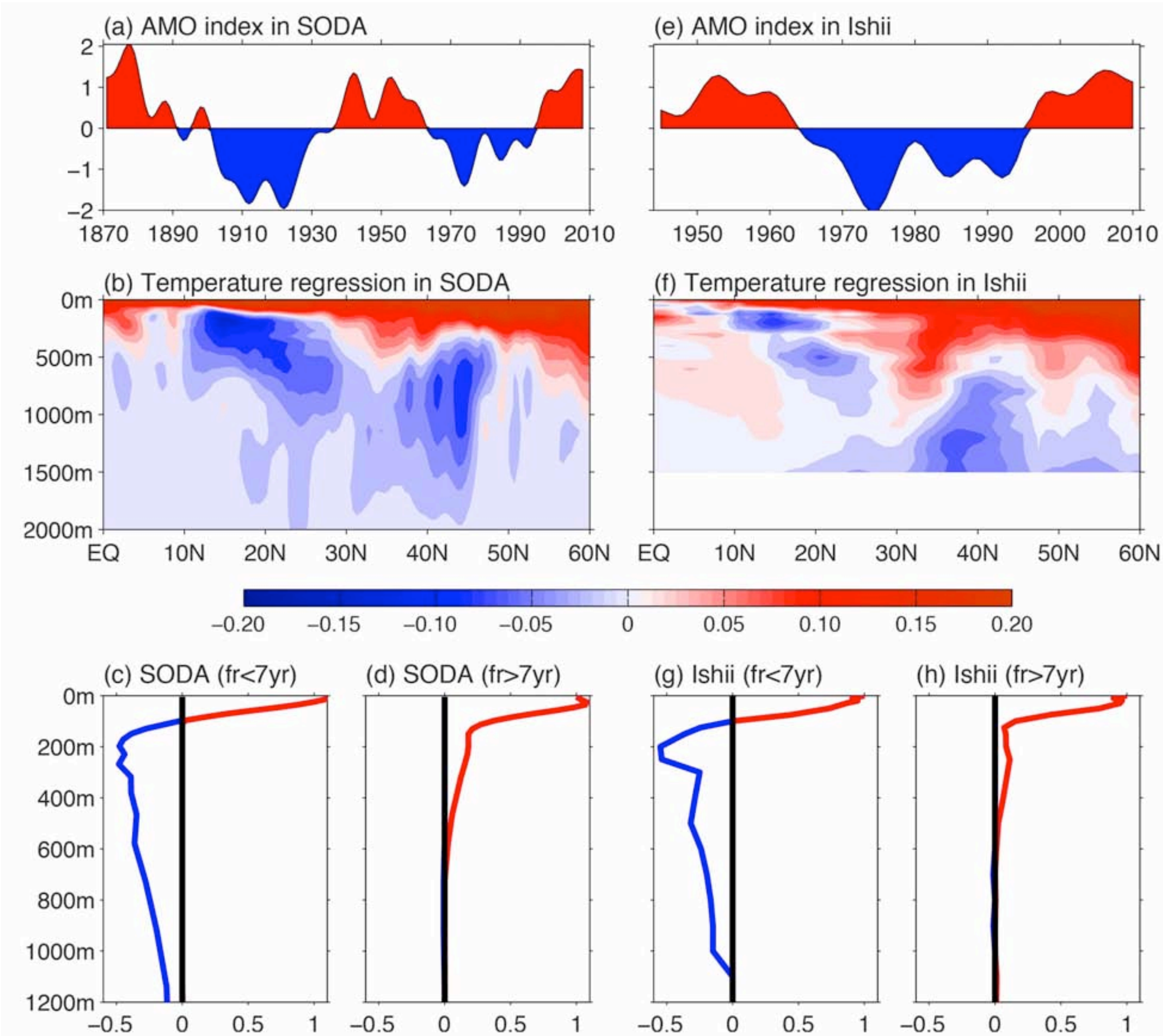


**Figure 8.** Variations of ocean temperature in the North Atlantic. Shown are the normalized (by standard deviation) AMO index from the (a) SODA and (e) Ishii data, the regression (°C) of the Atlantic zonal mean temperature onto the normalized AMO index from the (b) SODA and (f) Ishii data, and regression (°C per °C) of the Atlantic temperature averaged between 8°N-20°N at each depth onto the SST on multidecadal (frequency lower than 7 years) and interannual (frequency higher than 7 years) timescales from the (c, d) SODA data, and (g, h) Ishii data. The AMO is defined by the detrended SST anomalies averaged in the North Atlantic Ocean (0° to 60°N, coast to coast) and smoothed by a 7-year low-frequency filter.

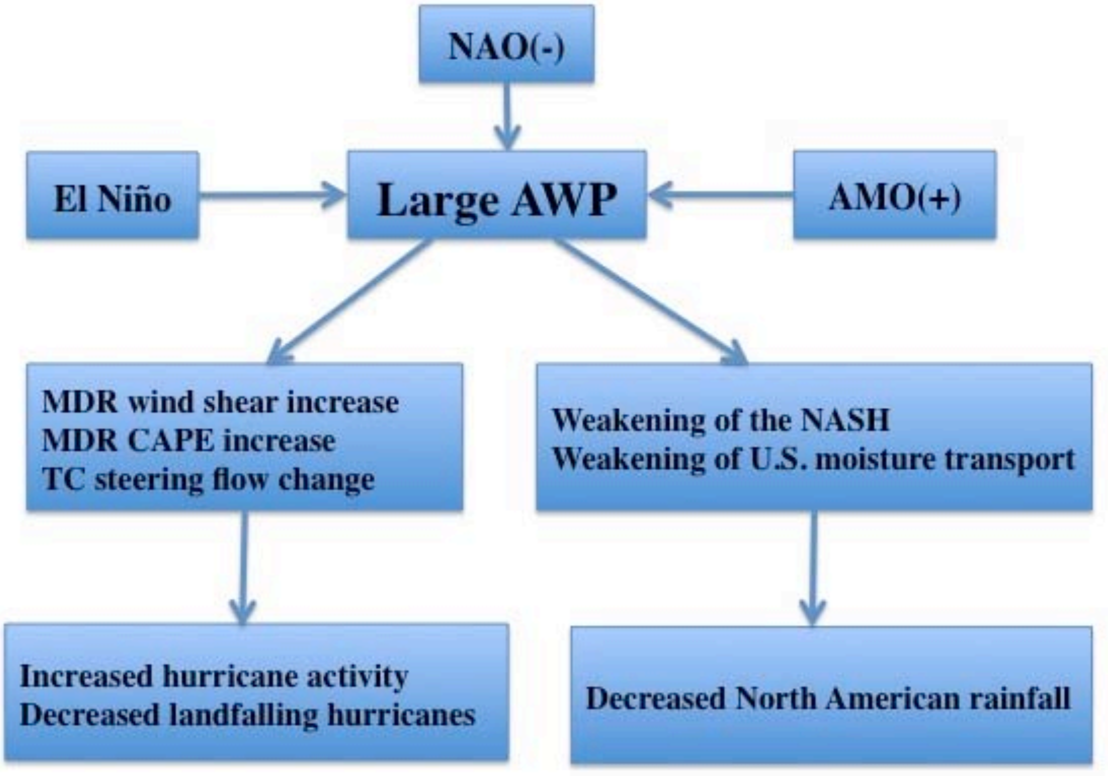


**Figure 9.** A diagram showing the relationships of the AWP with climate and influences of the AWP on Atlantic hurricanes and North American rainfall. NAO(-) represents the negative phase of the NAO and AMO(+) means the positive phase of the AMO. MDR: hurricane main development region; CAPE: convective available potential energy; NASH: North Atlantic subtropical high; and TC: tropical cyclone.

**Budget Details**

The proposed research is extensive, and we are requesting that the project lasts for a period of three years. The budget is developed from August 1, 2015 to July 30, 2018. C. Wang will work on this project for one month per year. C. Wang is a federal government employee, so he will carry on this project at no salary cost requested from NOAA/CPO. Salary requests from NOAA/CPO include funds for a Research Associate (12 months), S.-K. Lee (2 months), and an IT technician (0.6 months).

Two trips attending scientific meetings for dissemination of scientific results and collaboration with other scientists are budgeted each year. A personal computer is budgeted for the first year. Publication page charges are also budgeted.

**Project Title:** Atlantic Warm Pool (AWP)
**Primary PI:** Dr. Chunzai Wang

Year 1 FY15 | Year 2 FY16 | Year 3 FY17

## Salaries

| Name | Role/Title | Monthly Salary and Benefits (FY14) | Employee Type | Person Months (FY15) Funded in kind by institution | Person Months (FY15) Requested | FY15 Total In Kind | FY15 Total Requested | Person Months (FY16) Funded in kind by institution | Person Months (FY16) Requested | FY16 Total In Kind | FY16 Total Requested | Person Months (FY17) Funded in kind by institution | Person Months (FY17) Requested | FY17 Total In Kind | FY17 Total Requested |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dr. Chunzai Wang** | PI | **$14,857** | Federal | 1.00 | 0.00 | $14,857 | $0 | 1.00 | 0.00 | $15,451 | $0 | 1.00 | 0.00 | $16,069 | $0 |
| **Dr. Sang-ki Lee** | Co-PI | **$10,925** | Joint Institute | 0.00 | 2.00 | $0 | $21,850 | 0.00 | 2.00 | $0 | $22,724 | 0.00 | 2.00 | $0 | $23,633 |
| **Research Associate** | Analysis | **$6,188** | Joint Institute | 0.00 | 12.00 | $0 | $74,256 | 0.00 | 12.00 | $0 | $72,022 | 0.00 | 12.00 | $0 | $74,903 |
| **Jay Harris** | IT Support | **$13,768** | Federal | 0.00 | 0.60 | $0 | $8,261 | 0.00 | 0.60 | $0 | $8,591 | 0.00 | 0.60 | $0 | $8,935 |
| | | | | | | | | | | $0 | $0 | | | $0 | $0 |
| | | | ***Total Salaries*** | 1.00 | 14.60 | $14,857 | $104,367 | 1.00 | 14.60 | $15,451 | $103,337 | 1.00 | 14.60 | $16,069 | $107,471 |
| **Total Labor contribution (includes indirect costs)** | | | | | | **$22,731** | **$133,733** | | | **$23,795** | **$132,611** | | | **$24,907** | **$138,004** |

## Supplies and other expenses

| Description | Comments | FY15 Total Requested | FY16 Total Requested | FY17 Total Requested |
|---|---|---|---|---|
| Computer | | $3,000 | | |
| Publications | | $4,000 | $4,000 | $4,000 |
| | ***Total Supplies*** | $7,000 | $4,000 | $4,000 |

## Travel

| Destination/Purpose | Comments | FY15 Total Requested | FY16 Total Requested | FY17 Total Requested |
|---|---|---|---|---|
| Travel for Nat. Meeting | 2/yr @ $2500 each | $5,000 | $5,000 | $5,000 |
| | ***Total Travel*** | $5,000 | $5,000 | $5,000 |

## Indirect costs

| Description | Comments | FY15 Total In Kind | FY15 Total Requested | FY16 Total In Kind | FY16 Total Requested | FY17 Total In Kind | FY17 Total Requested |
|---|---|---|---|---|---|---|---|
| FTE | Salary & Benefits | $7,874 | $4,378 | $8,344 | $4,639 | $8,838 | $4,914 |
| Joint Instuitute | Salary & Benefits | $0 | $24,988 | $0 | $24,634 | $0 | $25,619 |
| | ***Total Indirect costs*** | $7,874 | $29,366 | $8,344 | $29,273 | $8,838 | $30,534 |
| | ***Total Budget Request*** | $22,731 | **$145,733** | $23,795 | **$141,611** | $24,907 | **$147,004** |

| Indirect Cost | FTE | Joint Inst. |
|---|---|---|
| FY15 | 53% | 26% |
| FY16 | 54% | 26% |
| FY17 | 55% | 26% |

## Biographical Sketch (Chunzai Wang)

**Education:**

Ph.D., Physical Oceanography, University of South Florida, 1995.
M.S., Atmospheric Sciences, Oregon State University, 1991.
B.S., Marine Meteorology, Ocean University of China, China, 1982.

**Professional Experience**:

Oceanographer, NOAA Atlantic Oceanographic and Meteorological Laboratory, 2000 – Present.
Associate Scientist, CIMAS/RSMAS, University of Miami, 1999 – 2000.
Research Associate, College of Marine Science, University of South Florida, 1997 – 1999.
Postdoctoral Associate, College of Marine Science, University of South Florida, 1995 – 1997.

**Service:**

Co-chair, Intra-Americas Study of Climate Processes (IASCLIP) Program, 20014 – Present.
Editor, Journal of Geophysical Research (Oceans), 2009 – Present.
Associate Editor, Journal of Climate, 2006 – Present.
American Geophysical Union Books Board, 2005 – 2010.

**Recent Publications (last three years):**

Zhang, L., C. Wang, Z. Song, and S.-K. Lee, 2014: Remote effect of the model cold bias in the tropical North Atlantic on the warm bias in the tropical Southeastern Pacific. *J. Adv. Model. Earth Syst.*, in press.

Ling, Z., G. Wang, and C. Wang, 2014: Out-of-phase relationship between tropical cyclones generated locally in the South China Sea and non-locally from the northwest Pacific Ocean. *Clim. Dyn.*, in press.

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Maloney, E. D., et al., 2014: North American climate in CMIP5 experiments: Part III: Assessment of 21st Century projections. *J. Climate*, **27**, 2230-2270.
Wang, C., L. Zhang, S.-K. Lee., L. Wu, and C. R. Mechoso, 2014: A global perspective on CMIP5 climate model biases. *Nature Climate Change*, **4**, 201-205.
Wang, X., and C. Wang, 2014: Different impacts of various El Niño events on the Indian Ocean dipole. *Climate Dynamics*, **42**, 991-1005, DOI 10.1007/s00382-013-1711-2.
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Song, Z., F. Qiao, X. Lei, and C. Wang, 2012: Influence of parallel computational uncertainty on simulations of the coupled general climate model. *Geoscientific Model Development*, **5**, 313-319.

Li, W.-W., C. Wang, D. Wang, L. Yang and Y. Deng, 2012: Modulation of low-latitude west wind on abnormal track and intensity of tropical cyclone Nargis (2008) in the Bay of Bengal. *Adv. Atmos. Sci.*, **29**, 407-421.

**Biographical Sketch (Sang-Ki Lee)**

**Education:**

| | |
|---|---|
| PhD, Old Dominion University, Norfolk, VA (Oceanography) | 1995 |
| MSc, Old Dominion University, Norfolk, VA (Oceanography) | 1993 |
| BSc, Inha University, Incheon, South Korea (Oceanography) | 1991 |

**Professional Service:**

| | |
|---|---|
| Research Scientist, CIMAS, University of Miami | 2011 - Present |
| Associate Research Scientist, CIMAS, University of Miami | 2007 - 2010 |
| Assistant Research Scientist, CIMAS, University of Miami | 2005 - 2007 |
| Postdoctoral Research Associate, CIMAS, University of Miami | 2002 - 2004 |
| Associate Scientist: Maritime Research Institute, Samsung Heavy Industries | 1996 - 2001 |
| Graduate Research Assistant, Old Dominion University | 1991 - 1995 |

**Refereed publications (last three years):**

Cheon, W. G., Y.-G. Park, J. R. Toggweiler, and S.-K. Lee, 2014: The relationship of Weddell polynya and open-ocean deep convection to the Southern Hemisphere westerlies. *J. Phys. Oceanogr.*, 44, 694-713. doi: http://dx.doi.org/10.1175/JPO-D-13-0112.1

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Liu Y., S.-K. Lee, B. A. Muhling, J. T. Lamkin and D. B. Enfield, 2012. Significant reduction of the Loop Current in the 21st century and its impact on the Gulf of Mexico. *J. Geophys. Res*, 117, C05039, doi:10.1029/2011JC007555.

Wang, C., S. Dong, A. T. Evan, G. R. Foltz, and S.-K. Lee, 2012. Multidecadal co-variability of North Atlantic sea surface temperature, African dust, Sahel rainfall and Atlantic hurricanes. *J. Climate*, 25, 5404-5415, doi:10.1175/JCLI-D-11-00413.1.

**Five other publications:**

Lee S.-K., W. Park, E. van Sebille, M. O. Baringer, C. Wang, D. B. Enfield, S. Yeager, and B. P. Kirtman, 2011. What caused the significant increase in Atlantic Ocean heat content since the mid-20th century? *Geophys. Res. Lett.*, doi:10.1029/2011GL048856.

Lee, S.-K., D. B. Enfield and C. Wang, 2011. Future impact of differential inter-basin ocean warming on Atlantic hurricanes. *J. Climate*, 24, 1264-1275.

Lee, S.-K., C. Wang and D. B. Enfield, 2010: On the impact of central Pacific warming events on Atlantic tropical storm activity. *Geophys. Res. Lett.*, 37, L17702, doi:10.1029/2010GL044459.

Lee, S.-K. and C. Wang, 2010: Delayed advective oscillation of the Atlantic thermohaline circulation. *J. Climate*, 23, 1254-1261.

Lee, S.-K., C. Wang and B. E. Mapes, 2009: A simple atmospheric model of the local and teleconnection responses to tropical heating anomalies. *J. Climate*, 22, 272-284.

## Current and Pending Support

(1). NOAA/CPO MAPP Program: "Variability and predictability of the Atlantic warm pool and its impacts on extreme events in North America" PIs: C. Wang, S.-K. Lee and D. B. Enfield, $442.2K, August 1, 2012 to July 31, 2015, current.

(2). NOAA/CPO MAPP Program: "Toward developing a seasonal outlook for the occurrence of major U.S. tornado outbreaks", PIs: S.-K. Lee, R. Atlas, C. Wang, D. B. Enfield, and S. Weaver, $430.0K, August 1, 2012 to July 31, 2015, current.

(3). Present proposal.