JHT Year-1 Progress Report:
Improving Predictability of the Atlantic Warm Pool in Ocean Model for Assistance to Operational Hurricane Forecast

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1. Introduction

This report is a summary of research conducted by the project personnel during the last 12 months period (August 1, 2009 - July 31, 2010). The rationale for the current project is the recent scientific finding that the Atlantic warm pool (AWP) — a large body of warm water comprised of the Gulf of Mexico, the Caribbean Sea, and the western tropical North Atlantic — may add a value to improving the simulation of Atlantic tropical cyclone (TC) in operational hurricane forecast models. In particular, recent studies using both observations and models have shown that a large AWP reduces the vertical wind shear and increases the convective available potential energy over the main development region for Atlantic hurricanes, and thus facilitates the formation and development of Atlantic TCs (Wang et al. 2006; Wang et al., 2008a, 2008b). Therefore, our ultimate goal is to improve the forecast of the formation and intensification of Atlantic hurricanes in NCEP/EMC operational model, by improving the simulations of the AWP in that model during the Atlantic hurricane season of June to November.

2. Achievements

We have setup a low-resolution ($1^o \times 1^o$) HYCOM for the Atlantic domain between 20^oS and 70^oN using RTOFS-Atlantic as the basic platform. At this stage, we are mainly working with this low-resolution stand-alone HYCOM to facilitate implementation, testing and verification of various model schemes and codes. So far, we have (1) evaluated the surface flux bias in Global Forecast System (GFS), (2) successfully implemented and tested the atmospheric mixed layer model (AML) and the mixed layer heat budget diagnosis scheme into the HYCOM, (3) performed low-resolution HYCOM experiments using the GFS, NCEP1 and a bias-corrected surface flux datasets with and without coupling with the AML, and (4) performed heat budget analysis to diagnose potential sources of AWP bias in the low-resolution HYCOM simulations with and without coupling with the AML. Finally, we have (5) explored the time evolution of

AWP bias in the thermally coupled HYCOM simulations to determine whether the AWP bias inherent in HYCOM bias can emerge for short-term forecasts (from 6-hour to 1-week).

Our major findings are that (1) the shortwave radiative heat flux of the GFS dataset may not be realistic and add too much heat (about 40W/m^2 yearlong) into the AWP, (2) the low-resolution HYCOM tends to create a large cold bias in the AWP region due to its inherent oceanic heat flux errors, (3) when HYCOM is thermally coupled to the AML, the AWP cold bias can emerge during short-term simulations (1-week). Based on these findings, we have concluded that the thermally coupled HYCOM (AML-HYCOM), in combination with the mixed layer heat budget diagnosis scheme, is an effective and practical tool to identify and improve the inherent errors in HYCOM. Once the HYCOM bias is minimized to a satisfactory level, the AML-HYCOM forced with bias-correct surface fluxes could be used for RTOFS-Atlantic simulations in order to allow physically more realistic thermal interactions at the air-sea interface, thus to minimize thermodynamic inconsistency at the air-sea interface for initializing the HWRF-HYCOM. A brief summary of our achievements is provided here.

2.1. *Evaluation of surface flux bias in Global Forecast System* (*GFS*)

Earlier studies have demonstrated that HYCOM may have some limitations in simulating the thermodynamics of the AWP and thus requires some modifications and optimizations of model schemes and codes (Lee et al. 2005, 2007). Among others, the largest model uncertainty originates from the surface heat flux bias, since the magnitude of surface net heat flux into the AWP varies by as much as 100 W/m^2 among various observational surface flux products and model-based reanalysis products typically used in regional simulations (Enfield and Lee 2005, Lee et al. 2005). Therefore, since the operational RTOFS-Atlantic is driven by the 3-hour forecast Global Forecast System (GFS), our first task is to evaluate the air-sea flux variables from the 3-hour forecast GFS, which are available for only 2008 and 2009 in NOAA national operational model archive and distribution system (http://www.nomads.noaa.gov).

A preliminary analysis of the 2008-2009 GFS dataset suggests that the GFS surface net heat flux into the AWP is too large (Figure 1a). In comparison to the Coordinated Ocean Research Experiments version-2 (CORE2) surface flux product (Large and Yeager 2008), an observation-based bias-corrected surface flux product, the 3-hour forecast GFS adds up to 50 W/m^2 of extra heat flux into the AWP region yearlong. Further analysis suggests that the GFS surface heat flux bias largely comes from the shortwave radiative heat flux component (Figure 1b), whereas other surface heat flux components of GFS are consistent with those of bias-corrected surface flux product (Figure 1c). The short wave radiative heat flux bias is slightly improved in the 6 hour forecast GFS (Figure 1b).

2.2 *Implantation of atmospheric mixed layer model* (*AML*)

In ocean-only models, such as HYCOM, the model ocean is always forced by the prescribed atmospheric conditions. Thus, in a strict sense, ocean–only models are useful only over the regions where ocean is predominantly forced by the atmosphere. Typically, flux forms of atmospheric forcing, such as short and long wave radiative heat fluxes, precipitation rate and wind stress, are directly used to force the ocean model. For latent and sensible heat fluxes, however, bulk equations are typically used to compute them interactively using wind speed, air humidity and air temperature at 10m (or 2m) along with the model SST. The main reason for not using the observed turbulent heat flux is that any bias in surface heat flux or in ocean model leads to local accumulation or depletion of oceanic heat, resulting in an unrealistic simulation of the upper ocean heat content. Therefore, using bulk formula is equivalent to damping the model SST toward observation. The main point is that it is certainly improper to evaluate an ocean model's performance if the SST in that model is damped toward observation.

An effective way to allow an ocean-only model to have realistic heat and freshwater exchanges at the air-sea interface is to couple the ocean model with an atmospheric mixed layer model (AML) of Seager et al. (1995). The AML solves advection-diffusion equations for air temperature and humidity in the planetary boundary layer (PBL). The air temperature and humidity above the PBL and the wind vector in the PBL are needed and they can be provided from, in the case of RTOF-Atlantic, the Global Forecast System (GFS). The benefit of coupling the AML to RTOFS-Atlantic is to allow physically more realistic thermal interactions at the air-sea interface, thus to minimize thermodynamic inconsistency at the air-sea interface for HWRF-HYCOM. We have successfully implemented and tested the AML model of Seager et al. (1995) in the low-resolution HYCOM.

2.3 *Low-resolution HYCOM experiments with and without thermal coupling*

In order to force the low-resolution HYCOM with the GFS air-sea flux, we need a longer time series air-sea flux dataset. Therefore, we construct a pseudo-GFS dataset for 1949-2009 periods by combining the 6-hour forecast of GFS for 2008-2009 and NCEP reanalysis-1 (NCEP1) for 1949-2009. First, for each air-sea flux variable, we compute the difference between GFS and NCEP1 in 2008-2009. For each air-sea flux variable, the difference in each month of 2008-2009 is added to the NCEP1 for the entire period of 1949-2009 to construct a pseudo-GFS dataset. The main assumption here is that the difference in each air-sea flux variable between the GFS and NCEP1 in 2008-2009 repeats in all other years. Note that the GFS air-sea fluxes in 2008 and 2009 are not modified. Along with the pseudo-GFS and NCEP1, we construct a bias-corrected NCEP1 dataset for 1949-2009 periods by combining the CORE2 for 1971-2000 and NCEP1 for 1949-2009. In this case, for each air-sea flux variable, the NCEP1 climatology for 1971-2000 is simply replaced with the CORE2 climatology for 1971-2000 then the NCEP1 air-sea flux anomaly is added to the CORE2 climatology. The low-resolution HYCOM is forced with the three air-sea flux datasets, namely pseudo-GFS, NCEP1 and bias-corrected NCEP1 for 1949-2009 periods with and without thermal coupling to AML.

Figure 2 shows the observed and HYCOM-simulated AWP SST during June-July-August (JJA) and September-October-November (SON) in 2009. The black solid line represents 27.5^{o}C isotherm in 2008 to be compared with the colored AWP region of 2009. It is clear from this figure that the simulated AWP in the case of HYCOM_GFS is too warm especially in the Gulf of Mexico during JJA suggesting that the GFS surface heat flux adds too much heat into the AWP formation region (This issue is further investigated later in this section). On the other hand, when the low-resolution HYCOM is forced with the bias-corrected NCEP1, the simulated AWP is too small (or too cold). If we treat the bias-corrected NCEP1 surface flux dataset as the truth, what this means is that the oceanic processes in the low-resolution HYCOM, such as vertical turbulent mixing and advection, tend to create a large cold bias in the AWP region. A common feature in all simulations is that the coastal upwelling region near the northern coasts of Columbia and Venezuela is too cold, suggesting that large-scale eddy mixing is not large enough in the model simulations to dissipate the cold upwelled water in the region.

Figure 3 is identical to Figure 2, except that the simulated AWP SSTs are derived from the thermally coupled HYCOM (AML-HYCOM) during JJA and SON in 2009. The black solid line represents 27.5^{o}C isotherm in 2008 to be compared with the colored AWP region of 2009. The simulated AWP in the case of AML_HYCOM_GFS is slightly colder than observations. This is quite surprising because the 6-hour forecast GFS put excessive heat into the AWP region due to its shortwave radiative heat flux bias as shown in Figure 1. When the low-resolution HYCOM is forced with the bias-corrected NCEP1, the simulated AWP is almost gone. As pointed out earlier, what this means is that the oceanic processes in the low-resolution HYCOM tend to create a large cold bias in the AWP region. The cold bias is much more intensified when the HYCOM is thermally coupled to AML in comparison to the forced HYCOM simulations. This means that the AML-HYCOM provides a much stringent test for the performance of HYCOM.

2.4 *Mixed Layer Heat budget analysis in the AWP region*

Figure 4 shows the HYCOM-simulated mixed layer heat budget (upper 40m) for 2008-2009 averaged in the AWP region (100^{o}W-40^{o}W; 5^{o}N-30^{o}N). The heat budget terms include vertical mixing at 40m (VTRMIX), vertical advection at 40m (VRTADV) surface net heat flux (SURFLX), heat storage rate (STORAG), numerical vertical mixing (HYBMIX), horizontal diffusion (HRZDIF), and horizontal advection (HRZADV). See Lee et al. (2007) for the heat budget equation. This figure clearly shows that the surface net heat flux is the main driving force for the onset and decay of the AWP whereas the oceanic mixing and advection terms play a secondary role and tend to cool down the AWP in boreal summer and fall months (Lee et al. 2007). Consistent with Figure 1 and 2, the surface net heat flux in HYCOM_GFS is larger than the other two cases. Figure 5 is the same as Figure 4 except that the simulated AWP heat budgets are derived from the thermally coupled HYCOM (AML-HYCOM) simulations. The overall heat budgets in the thermally coupled HYCOM simulations are similar to those of the forced HYCOM simulations.

Figure 6 shows the 2008-2009 surface flux components from two low-resolution HYCOM experiments, two AML-HYCOM experiments, and from two surface flux datasets (i.e., pseudo-GFS, and bias-corrected NCEP1). Note that the surface latent and sensible heat fluxes in the forced HYCOM simulations are recalculated by using the model simulated SST and bulk formulas. Similarly, the surface latent and sensible heat fluxes in the thermally coupled HYCOM simulations are recalculated by the model simulated SST and the AML model of Seager et al. (1995). Thus, the simulated heat flux is different from the original surface heat flux dataset used to force the HYCOM and AML-HYCOM. The latent heat flux in the original GFS dataset shows a reasonable range of values when it is compared with the bias-corrected NCEP1 dataset (Figure 6c). However, as pointed out in section 21, it is clear that the original GFS dataset adds up to 40 W/m^2 of extra shortwave radiative heat flux into the AWP region in comparison to the bias-corrected NCEP1 dataset (Figure 6b).

It is important to note that the simulated net surface flux into the AWP formation region is always too large in comparison to the bias-corrected NCEP1 net surface flux as shown in Figure 6a. This is largely due to the much-reduced surface latent cooling in the model simulations (Figure 6c) associated with the HYCOM's tendency to produces a large cold bias in the AWP formation region.

2.5 *Simulation of anomalous AWP SSTs in HYCOM with and without thermal coupling*

Figure 7 shows the anomalous AWP SST in June-November (JJASON) for the period of 1949-2009 simulated by HYCOM with and without thermal coupling to the AML. In the case of the forced HYCOM simulation, the correlation between the simulated and observed AWP SST anomaly is 0.79, which is larger than the case of the thermally coupled HYCOM (0.65~ 0.66). It is not surprising that the forced HYCOM simulation is better correlated with the observation than the thermally coupled HYCOM simulation because the AWP SST anomaly is basically relaxed to the observation in the forced HYCOM simulation. It is clear that the AML-HYCOM provides a much stringent test for the performance of HYCOM in capturing the AWP SST anomaly.

In order to better understand the regional pattern of model errors, the observed AWP SST anomaly in JJASON is regressed on to the observed and simulated SST anomalies in JJASON, as shown in Figure 8. As shown in Figure 8a, when the AWP is warm, the entire zonal strip of 10N-20N is warmed simultaneously. In the case of forced HYCOM simulations, the warming is largely located in the central tropical North Atlantic west of around 70W. The anomalous warming in the Caribbean Sea and off the West Africa is not well captured in the forced HYCOM simulation. In the case of thermally coupled simulations, in addition to the same problem, the warm SST anomaly is shifted southward around 10N. This means that the HYCOM has a tendency to generate a spatially inhomogeneous SST error pattern during anomalously warm and cold AWP events. Again, the AML-HYCOM truly reveals the inherent bias in the HYCOM, and thus provides a much stringent test for the performance of HYCOM in capturing the AWP SST anomaly.

2.6 *Time evolution of AWP SST bias in thermally coupled HYCOM*

We have shown here that HYCOM has a tendency to produce a large cold bias in the AWP region. Such tendency is mostly hidden in the forced simulations because the model SST is damped toward the observations in the forced simulations. The cold AWP bias is revealed only when HYCOM is thermally coupled to the AML. This is because nonphysical thermal interaction, which may be caused by the ocean model bias in the forced HYCOM simulations, is not allowed the thermally coupled HYCOM simulations.

An important question is how fast the cold bias emerges. For instance, if it takes several years to develop, it is not a critical problem for short-term forecasts (from 6-hour to 1-week) in the NCEP/EMC's operational models (RTOFS-Atlantic and HWRF-HYCOM). Therefore, we have performed three additional experiments. First, HYCOM is forced with the three surface flux products of pseudo-GFS, NCEP1 and bias-corrected NCEP1 for the period of 1949-2007. Then, the thermal coupling is initiated in HYCOM from Jan/2007 and continued until Dec/2009. Shown in Figure 9 is the time evolution of simulated AWP SST errors for 2007-2009. The upper panel shows the AWP SST difference between the AML-HYCOM simulation and observation (HADISST). The lower panel shows the AWP SST difference between the AML-HYCOM and forced HYCOM simulations. The AWP SST bias develops quite fast. It takes about only 5 months for 1degC of cold bias to develop. This amounts to about 0.1degC of cold bias within 14days. Thus, it may not be negligible in short-term forecasts. It is also interesting to note that the AWP SST bias has a seasonal dependency, with a larger bias in boreal summer and fall and smaller bias in boreal winter and spring.

Figure 10 shows the expected spatial pattern of the SST bias growth within 15days in the thermally coupled HYCOM simulations. Focusing on the AML-HYCOM forced by the bias-corrected NCEP1, the entire mid-latitude North Atlantic between 20N-40N has a large cold bias. The cold bas is extended to the Gulf of Mexico. Interestingly, the Columbia basin is characterized with a relatively large warm bias. A further study is required to understand the spatial pattern of the SST bias growth.

3. Recommendations and Future Plans

Based on our researches during the last 12 months period (August 1, 2009 - July 31, 2010), as summarized in this report, we provide the following three recommendations for the NCEP/EMC operational ocean model (RTOFS-Atlantic).

Suggestion-1). The 3-hour forecast GFS, which is used to force the RTOFS-Atlantic, has a large shortwave radiative heat flux bias in the AWP formation region. Therefore, *a bias correction of the GFS shortwave radiation is suggested*. This can be achieved by first constructing a pseudo-GFS climatology for 1971-2000 period then computing the difference between the pseudo-GFS climatology and the bias-corrected surface heat flux climatology of CORE2 following the methodology described in section 2.3. This difference is the bias-correction term to be added to the GFS shortwave radiative heat flux forecast. It is also suggested here that the 6-hour forecast GFS is used instead of the 3-hour forecast to reduce the shortwave radiative heat flux bias.

Suggestion-2). *It is recommended that the thermally coupled HYCOM (AML-HYCOM) with bias-corrected surface fluxes be implemented into RTOFS-Atlantic*. The thermally coupled RTOFS-Atlantic, in combination with the mixed layer heat budget diagnosis scheme, will provide an effective and practical tool to identify and improve the inherent errors in RTOFS-Atlantic. Ultimately, it will allow physically realistic thermal interactions at the air-sea interface, thus to minimize thermodynamic inconsistency at the air-sea interface for initializing the HWRF-HYCOM. However, it should be used as a diagnostic tool initially.

Suggestion-3). Although it is yet to be determined whether the cold AWP bias can emerge for short-term forecasts (from 6-hour to 1-week) in RTOFS-Atlantic, it seems highly plausible that HWRF-HYCOM, an experimental hurricane forecast system at NCEP/EMC, may suffer from SST drifts. In the light of new evidence of SST drifts in the thermally coupled model of AML-HYCOM, a diagnostic study is suggested to evaluate HWRF-HYCOM's predictability of the AWP. The primary targets of the proposed study are (1) to determine and quantify the inherent model bias in both HYCOM and HWRF, (2) to examine how local atmosphere-ocean processes amplify the HYCOM and HWRF biases, and (3) to ultimately provide a practical strategy to correct the AWP SST bias in coupled HWRF-HYCOM model. These objectives can be addressed by carefully designing numerical model experiments using HWRF-HYCOM, which can be run in several different setups including HWRF with fixed SST run (EXP_ATM); HYCOM with fixed surface flux run (EXP_OCN); thermally coupled AML-HYCOM run (EXP_AML) and fully coupled HWRF-HYCOM with its atmosphere model initialized with EXP_ATM and the ocean model with EXP_OCN (EXP_CPL).

In the second year of the JHT project, we will mainly focus on implementing the first two suggestions, and transferring the programs and codes developed during the last 12 months period to the NCEP/EMC.

4. References

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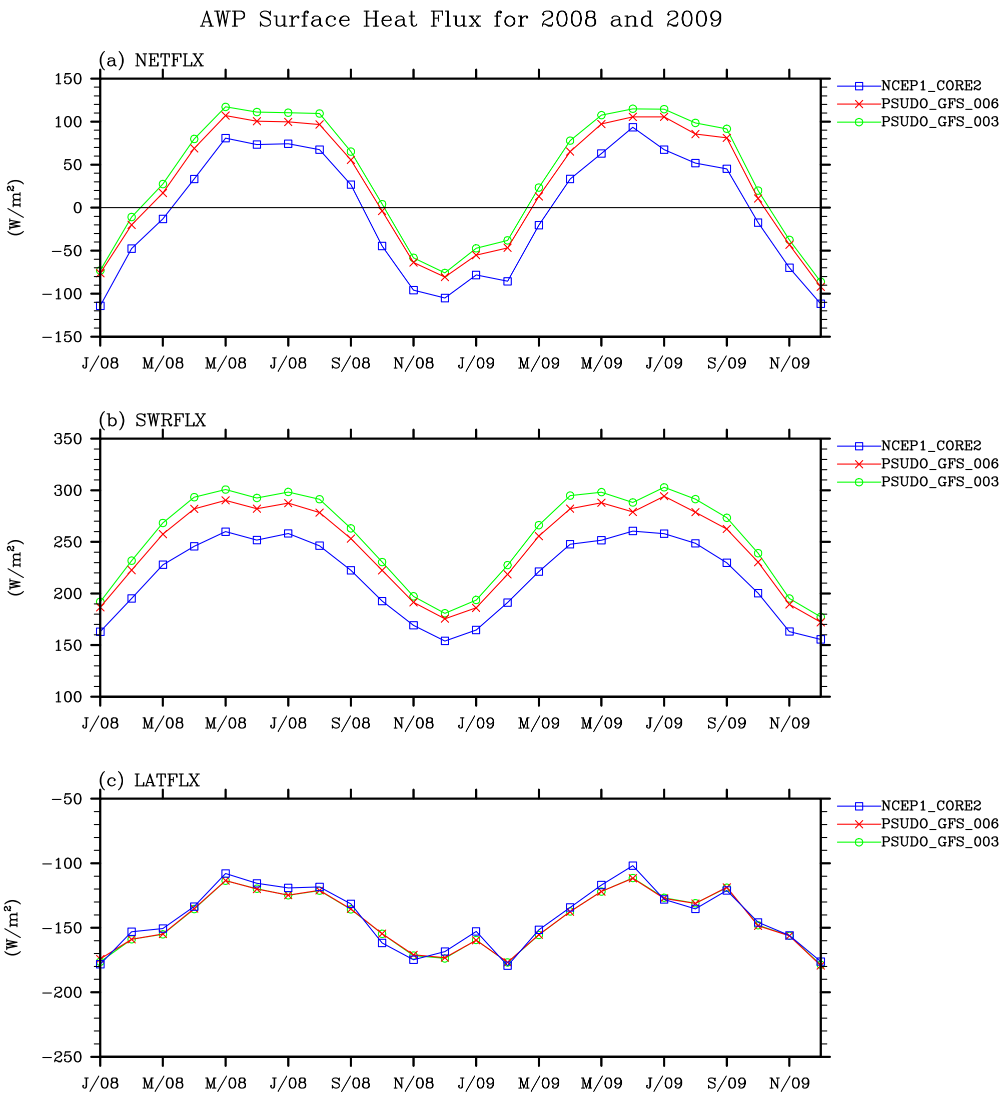

Figure 1. (a) Net surface heat flux, (b) shortwave heat flux, and (c) latent heat flux into the AWP formation region (100^{o}W-40^{o}W; 5^{o}N-30^{o}N) derived from the bias-corrected NCEP1, and 3-hour and 6-hour forecast of GFS for 2008-2009 period. Unit is W/m^2.

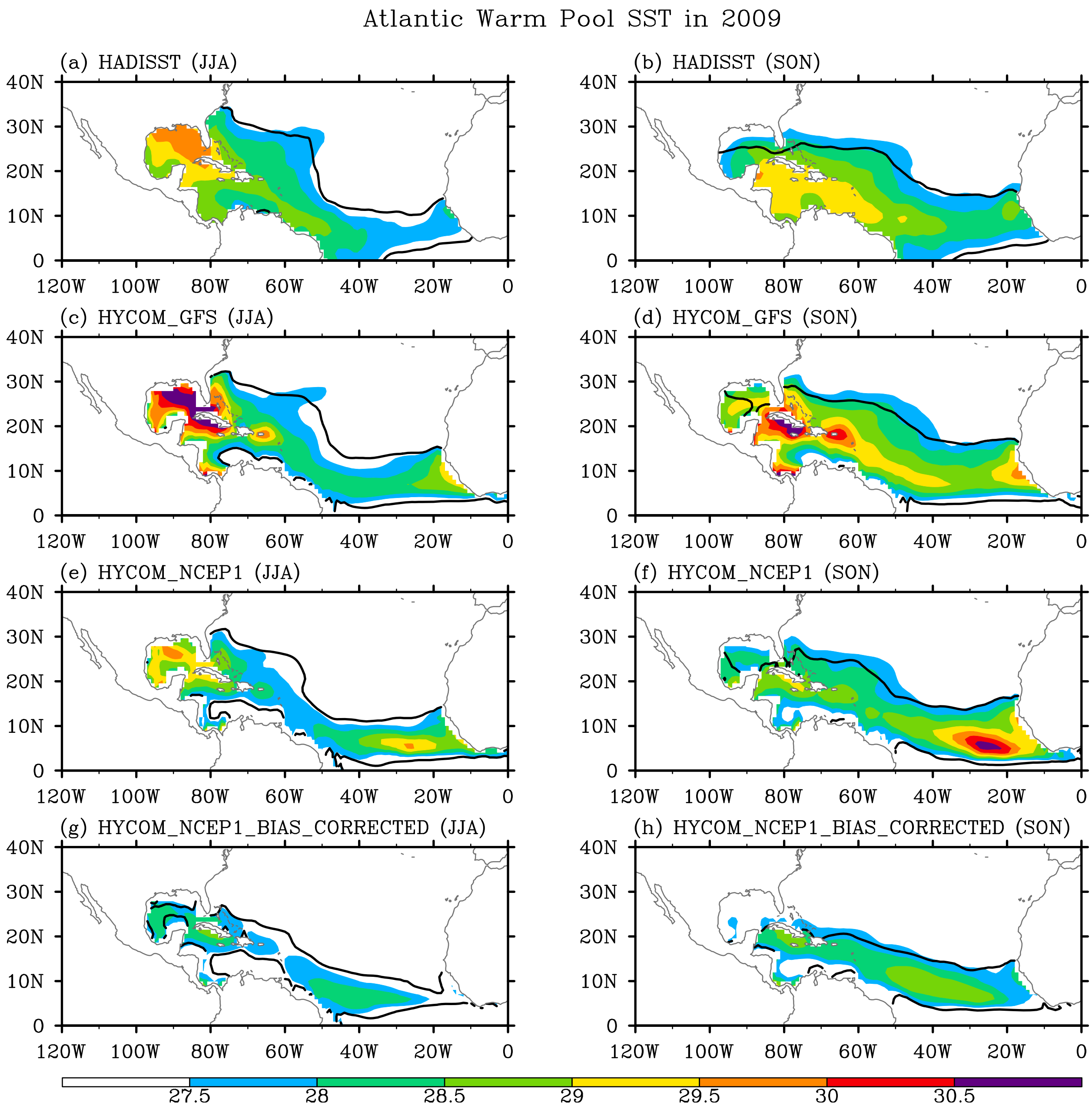

Figure 2. Observed and HYCOM-simulated AWP SST during June-July-August (JJA) and September-October-November (SON) in 2009. The black solid lines represent 27.5^{o}C isotherm in 2008 to be compared with the colored AWP region of 2009. Unit is degC.

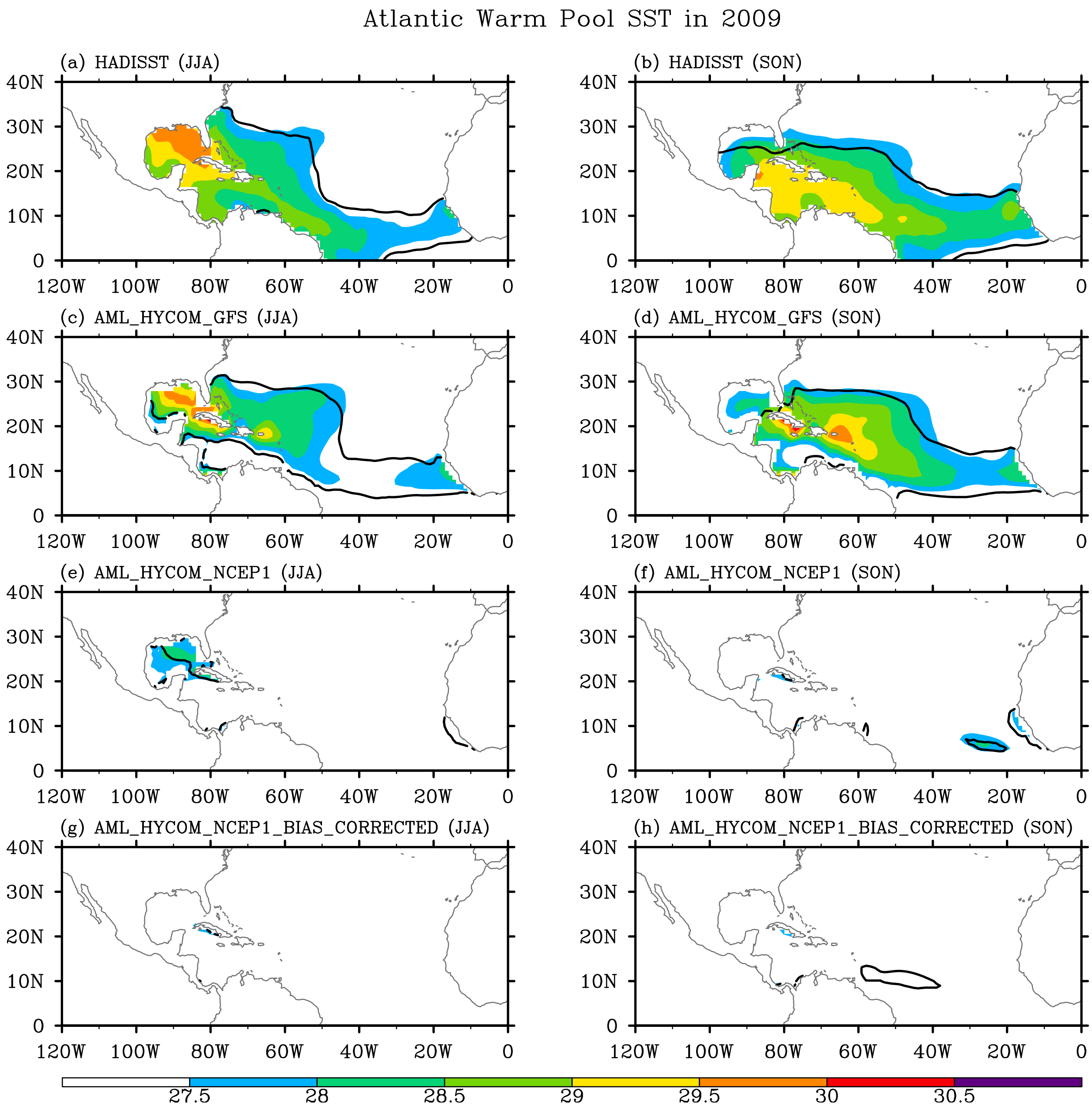

Figure 3. Observed and AML-HYCOM-simulated AWP SST during June-July-August (JJA) and September-October-November (SON) in 2009. The black solid lines represent 27.5^{o}C isotherm in 2008 to be compared with the colored AWP region of 2009. Unit is degC.

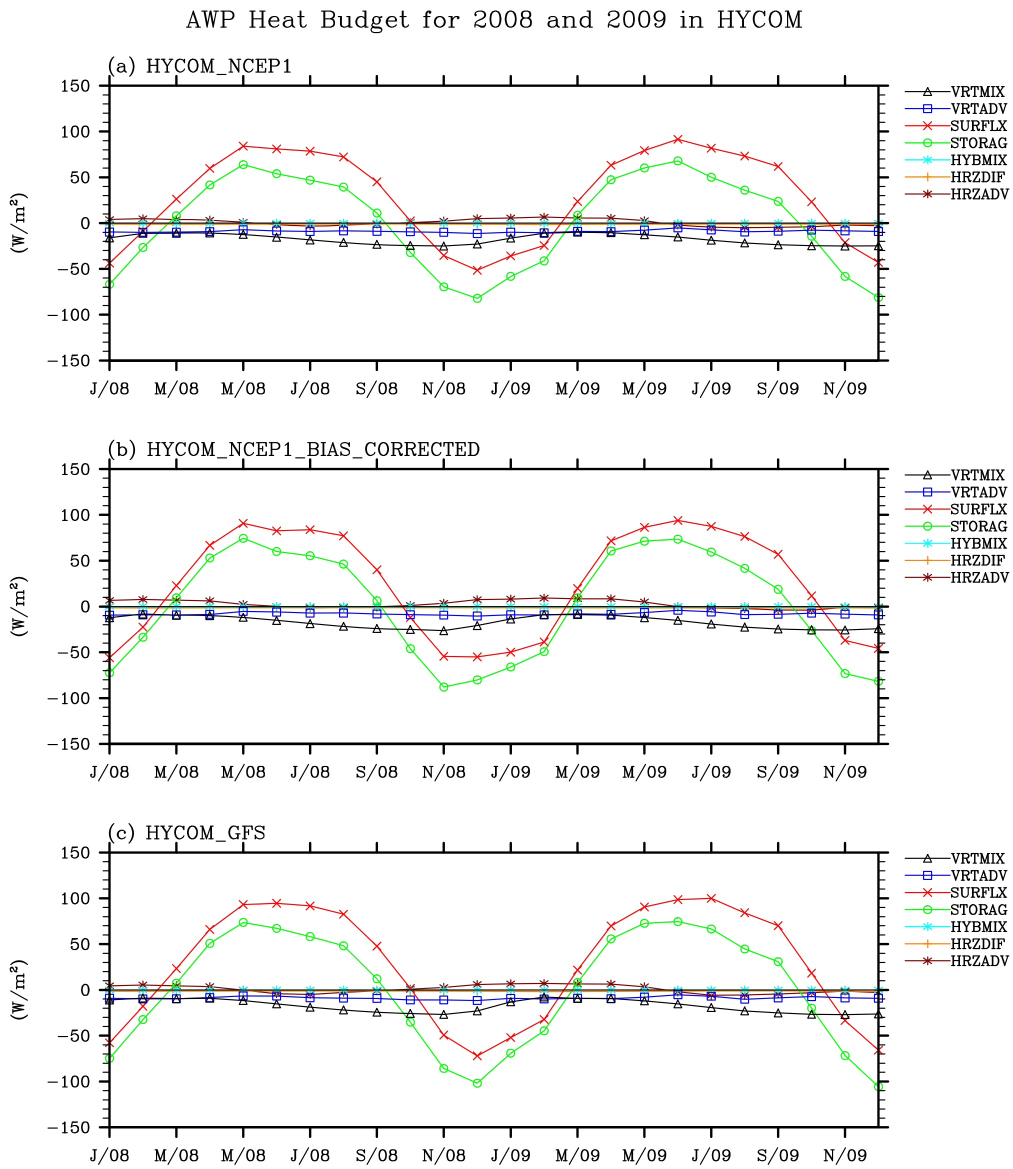

Figure 4. HYCOM-simulated mixed layer heat budget (upper 40m) for 2008-2009 averaged in the AWP region (100°W-40°W; 5°N-30°N). The heat budget terms include vertical mixing at 40m (vrtmix), vertical advection at 40m (vrtadv) surface net heat flux (surflx), heat storage rate (storag), numerical vertical mixing (hybmix), horizontal diffusion (hrzdif), and horizontal advection (hrzadv). See Lee et al. (2007) for the head budget equation. Unit is W/m^2.

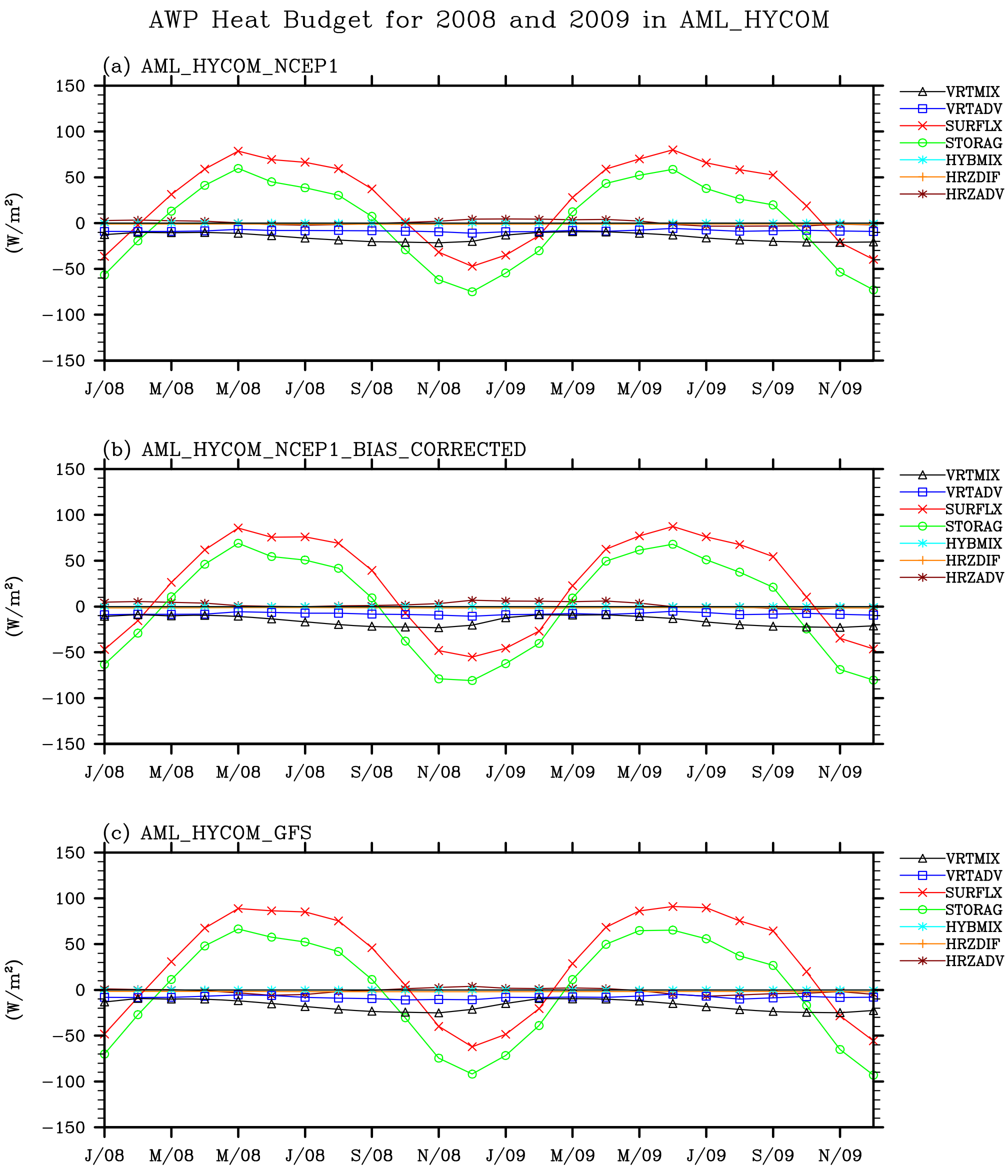

Figure 5 is same as Figure 4 except that the simulated AWP heat budgets are derived from the thermally coupled HYCOM (AML-HYCOM) simulations. Unit is W/m^2.

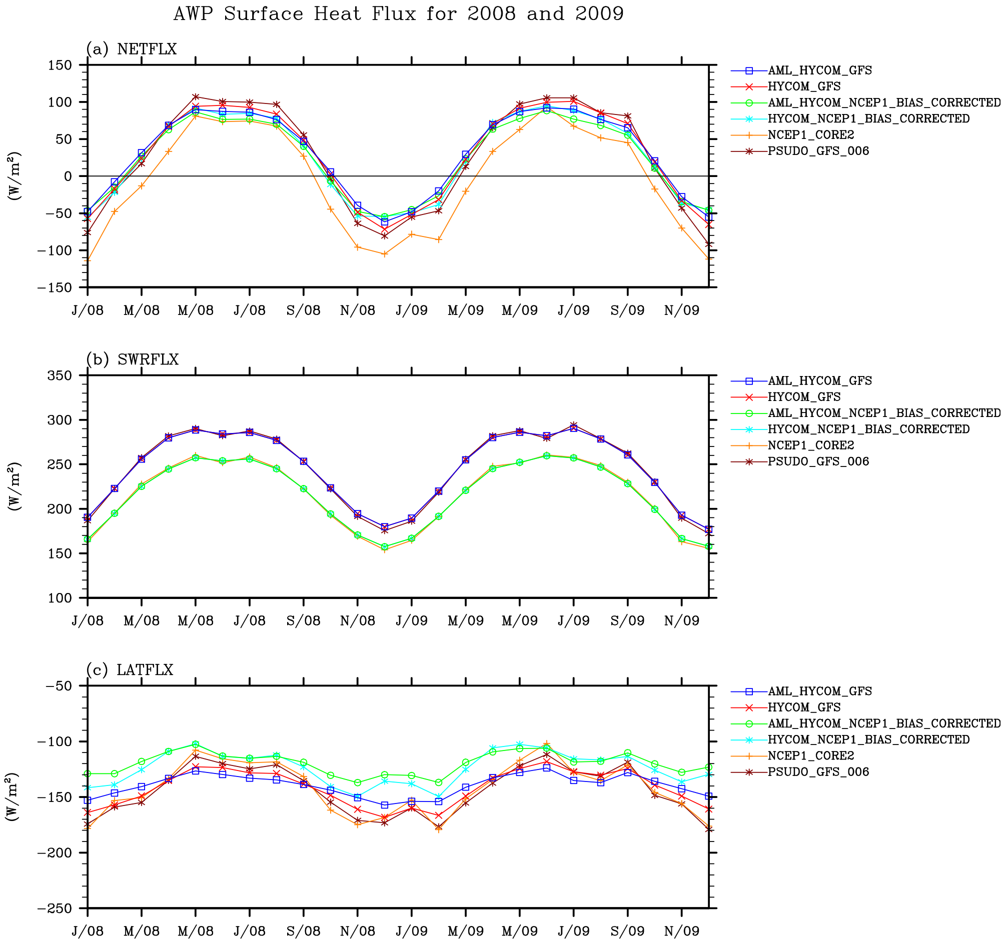

Figure 6. (a) Net surface heat flux, (b) shortwave radiative heat flux and (c) latent heat flux in 2008-2009 averaged in the AWP region (100^{o}W-40^{o}W; 5^{o}N-30^{o}N) from two low-resolution HYCOM experiments, two AML-HYCOM experiments, and from two surface flux datasets (i.e., pseudo-GFS, bias-corrected NCEP1). Unit is W/m^2.

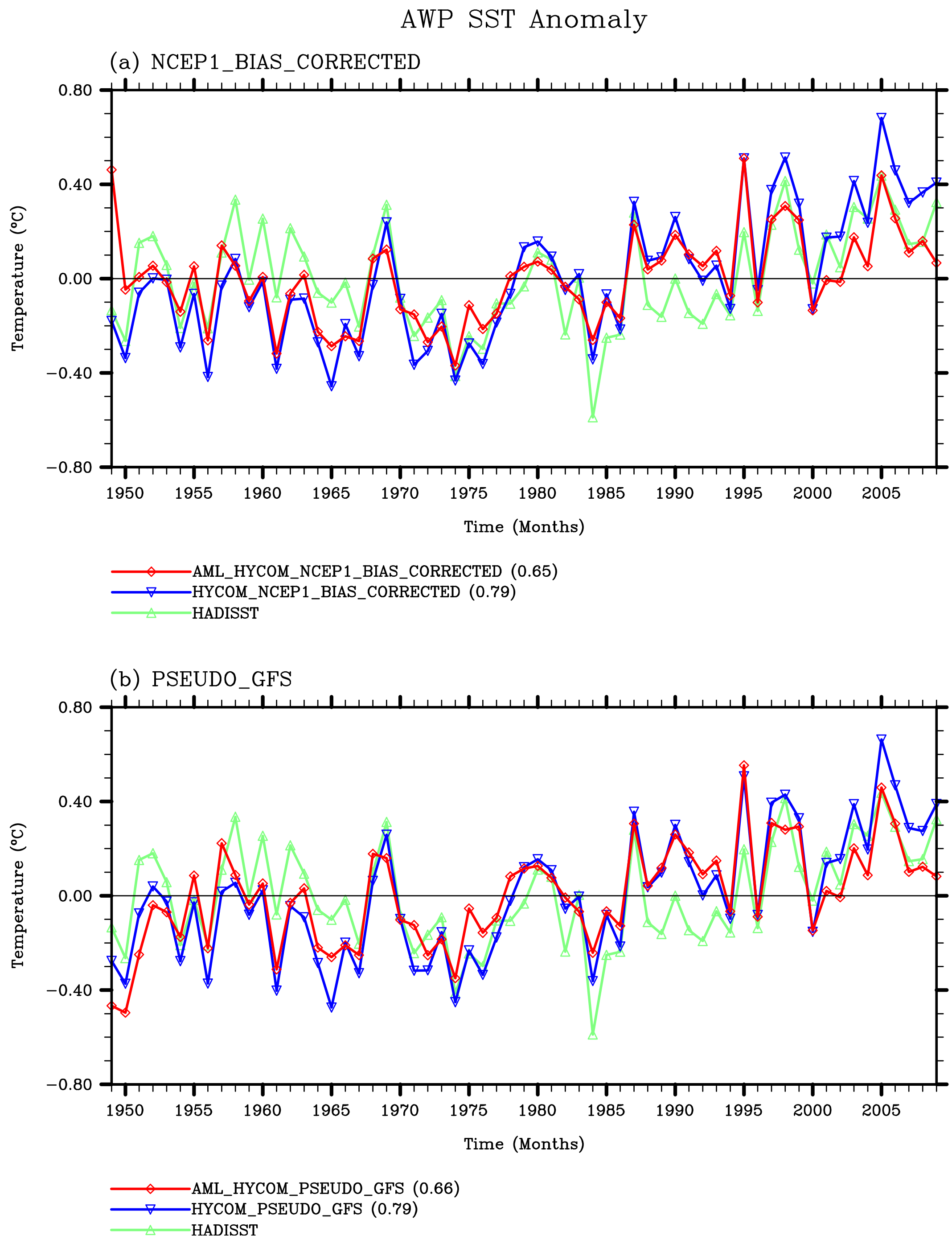

Figure 7. Anomalous AWP SST in June-November (JJASON) for the period of 1949-2009 simulated by HYCOM with and without thermal coupling to the AML forced with (a) the bias corrected NCEP1 and (b) pseudo-GFS. Unit is degC.

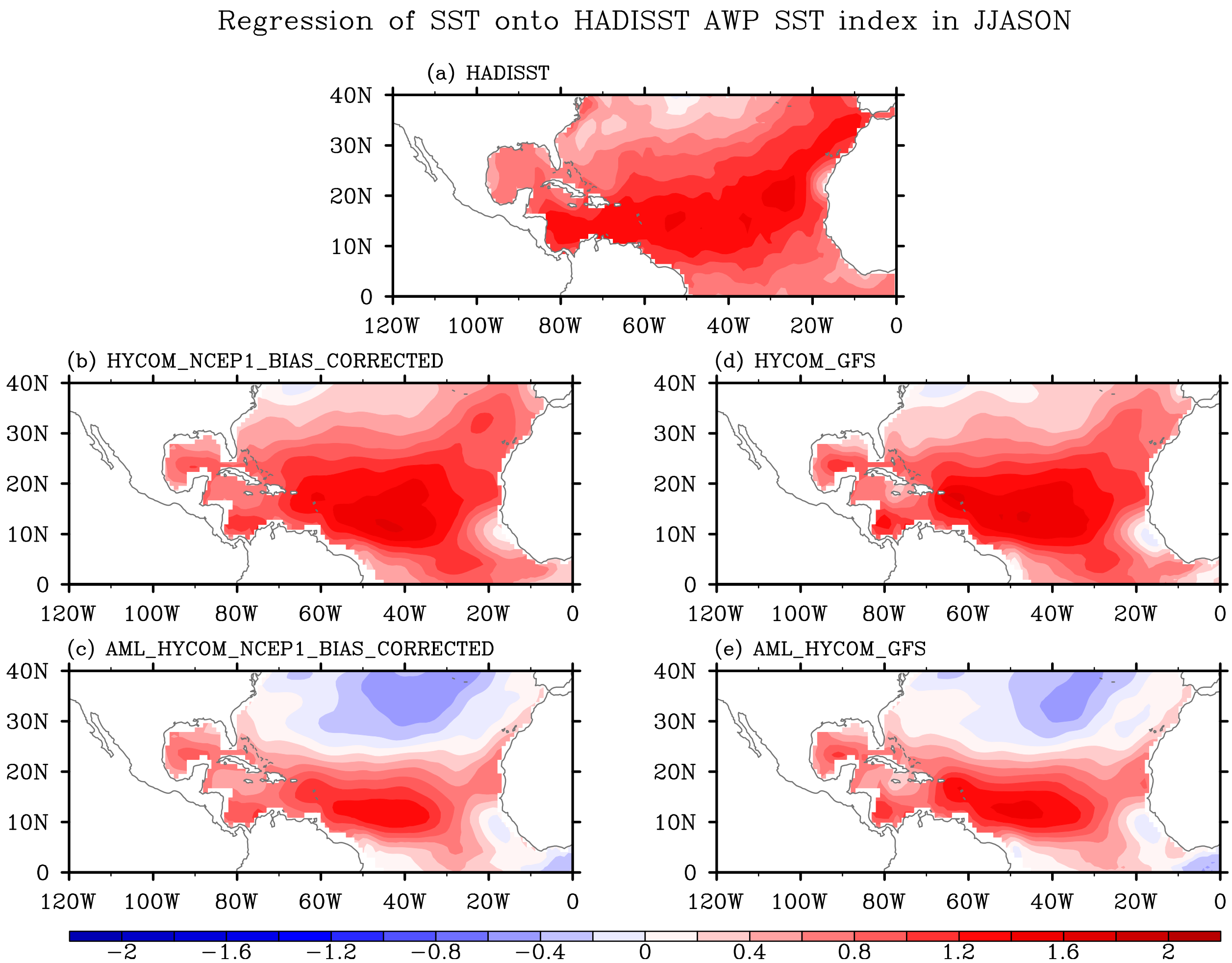

Figure 8. Regression coefficients of observed and simulated SST onto the observed AWP SST anomaly in JJASON. Unit is degC/degC.

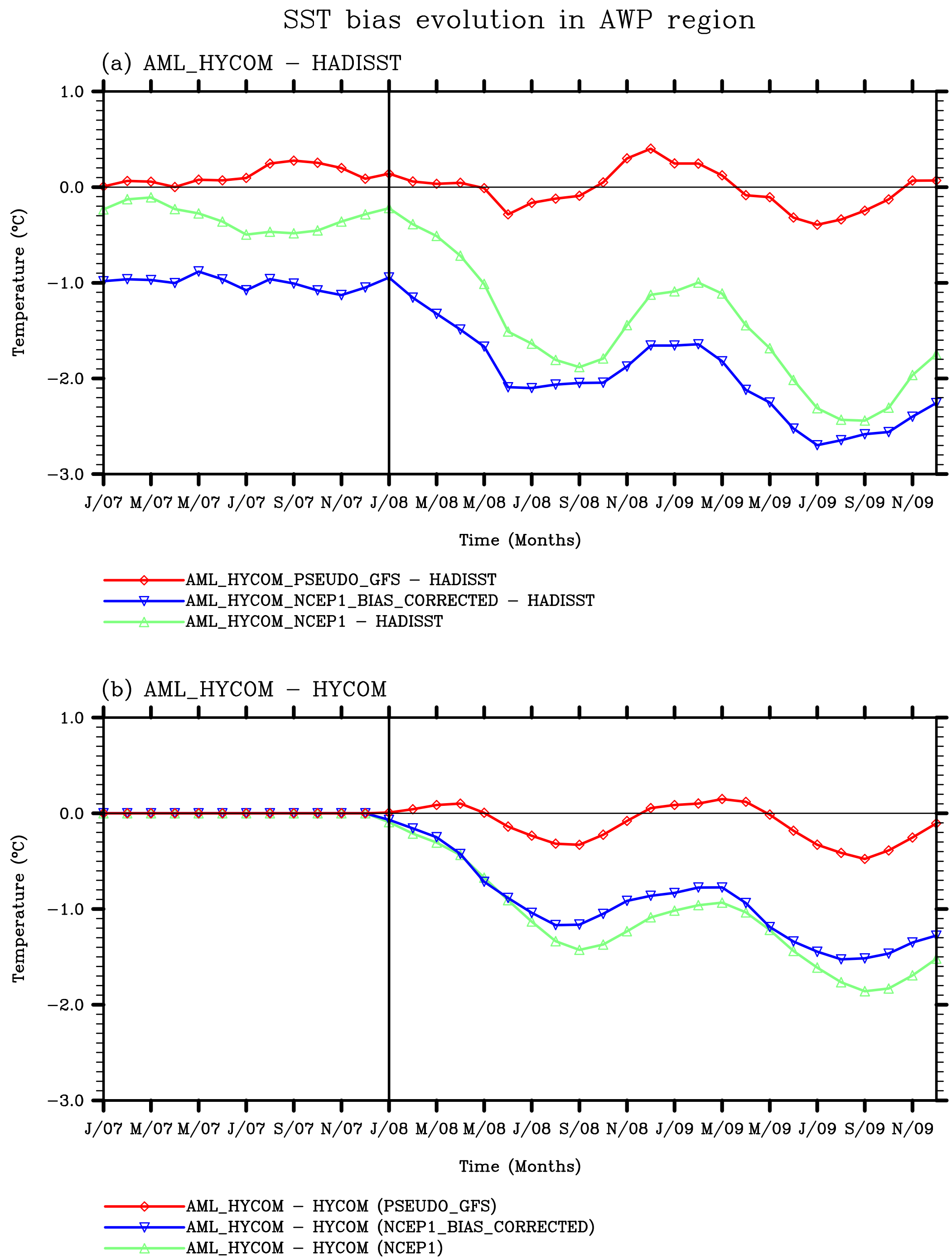

Figure 9. Time evolution of simulated AWP SST errors for 2007-2009. The upper panel shows the AWP SST difference between the AML-HYCOM simulation and observation (HADISST). The lower panel shows the AWP SST difference between the AML-HYCOM and forced HYCOM simulations. See text for details. Unit is degC.

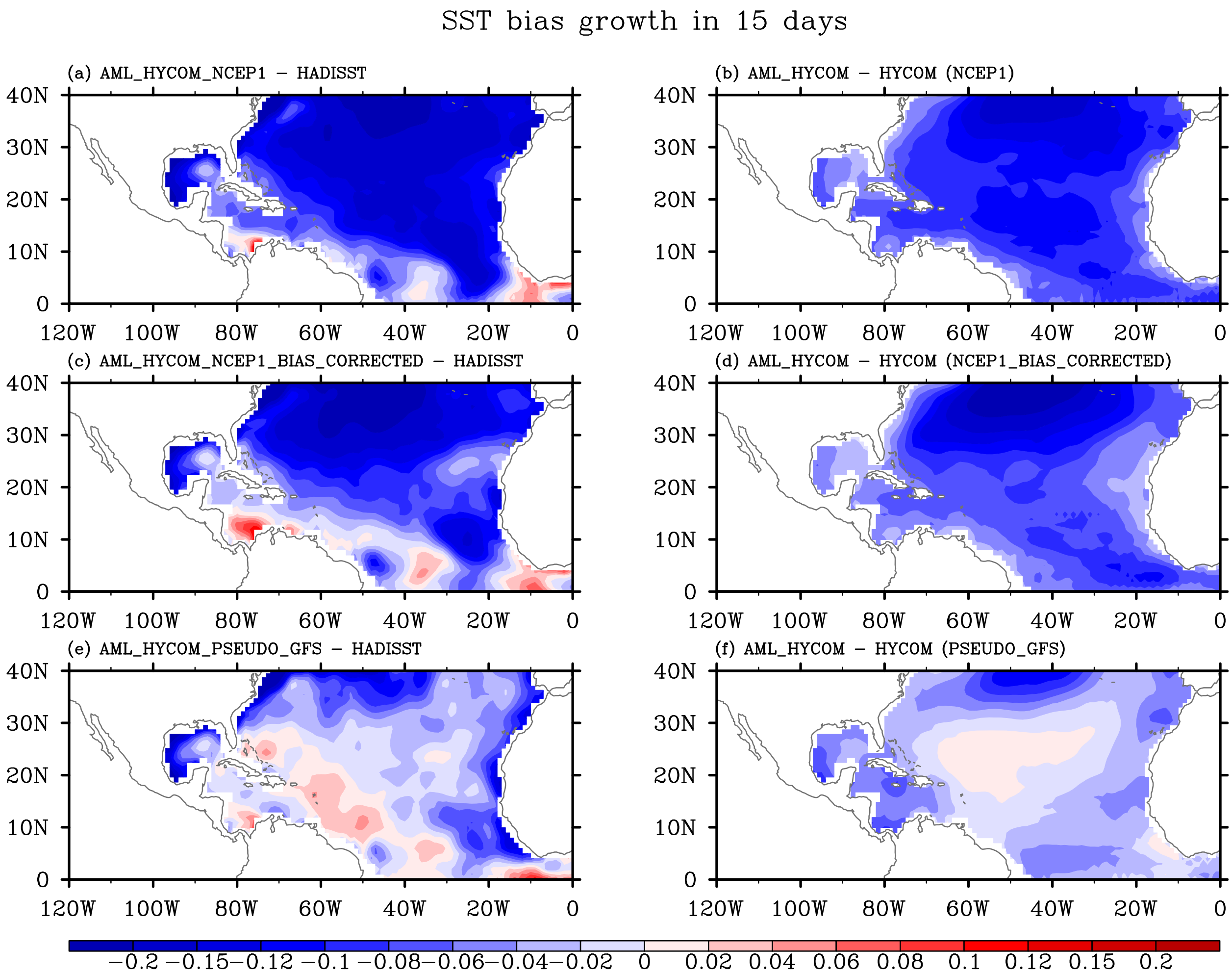

Figure 10. Spatial pattern of the expected SST bias growth within 15 days in the thermally coupled HYCOM simulations. Unit is degC.