Effect of Ocean Mesoscale Variability on the Mean State of Tropical Atlantic Climate

Hyodae Seo

Scripps Institution of Oceanography, La Jolla, CA 92093

Markus Jochum

National Center for Atmospheric Research, Boulder, CO 80305

Raghu Murtugudde

ESSIC/DAOS, University of Maryland, College Park, MD 20742

Arthur J. Miller

Scripps Institution of Oceanography, La Jolla, CA 92093

Corresponding Author address:

Hyodae Seo

Scripps Institution of Oceanography

La Jolla, CA 92093-0224

Email: hyseo@ucsd.edu

ABSTRACT

A regional coupled ocean-atmospheric model is used to investigate the effect of oceanic mesoscale features on the mean climate of the tropical Atlantic. It is shown that, compared to a non-eddy resolving ocean model, resolving oceanic mesoscale variability leads to a cooler mean equatorial cold tongue and a cooler coastal upwelling zone. This changes the meridional SST gradient, and the resulting weaker low-level convergence reduces the mean of rainfall in the marine Inter-Tropical Convergence Zone (ITCZ). The reduced rainfall and the cooler coastal upwelling regions represent a clear improvement of the model solution.

1. Introduction

[1] The seasonal cycle of the marine Inter-Tropical Convergence Zone (ITCZ) in the tropical Atlantic (TA) Ocean is associated with seasonal sea surface temperature (SST) variability [*Nobre and Shukla*, 1996]. *Chiang et al.* [2002] discuss the nature of the TA ITCZ, suggesting that the two dominant mechanisms influencing variability of the ITCZ are the local meridional SST gradient and external forcing from ENSO.

[2] While the equatorial upwelling maintains the asymmetric positioning of the ITCZ most of the year [*Xie*, 2004], in boreal spring the meridional SST gradient is extremely weak which facilitates anomalous latitudinal positioning of the ITCZ. Thus it has been argued that a substantial improvement of seasonal rainfall forecast will be achieved if SST distribution in the TA could be predicted [*Nobre and Shukla*, 1996; *Ward and Folland*, 1991]. Unfortunately, most global coupled models fail to reproduce observed SST patterns in the TA, generally exhibiting a warm bias in the coastal upwelling region and incorrect seasonal cycles [*Davey et al.*, 2002].

[3] *Jochum et al.* [2005, 2004] argue that, because of their impact on the SST gradients, resolving mesoscale structures of the ocean such as Tropical Instability Waves (TIWs) and details of coastal upwelling along the African coast should improve simulations of TA SST. They show that in a forced ocean model the SSTs improve by going to an eddy-resolving model. A caveat of their study is that the winds were prescribed and did not adjust to this changed SST distribution. Thus, the benefits of increasing the resolution could be either lost or amplified in a coupled model.

[4] The present study is a follow up study to the work of *Jochum et al.* [2005] and simply tries to see if the improvements of the forced experiments are maintained in the coupled experiments. The main benefits (for SSTs) of increasing the resolution were that because of lower horizontal diffusion, higher, more realistic SST gradients could be maintained. The present short note illustrates that this is still the case in the coupled model and leads to improvements in the rainfall.

2. Model and experiment setup

[5] The model used for this study is the Scripps Coupled Ocean-Atmospheric Regional (SCOAR) model. It couples the Regional Spectral Model (RSM) for the atmosphere to the Regional Ocean Modeling System (ROMS) for the ocean. The model has already been shown to be capable of capturing the salient features of coupled ocean-atmosphere feedback in several regions of the eastern Pacific, including TIWs in the tropical Pacific [*Seo et al.,* 2006].

[6] RSM is a regional extension to the Global Spectral Model (GSM) used in the National Centers for Environmental Prediction (NCEP) / Department of Energy (DOE) Reanalysis [*Kanamitsu et al.,* 2002a]. It is thus dynamically and physically consistent with Reanalysis products, which are used for large-scale forcing to produce downscaled fields. The parameterization for deep convection is based on Relaxed Arakawa-Schubert scheme [*Arakawa and Schubert* 1974; *Moorthi and Suarez* 1992]. Further details about the model physics can be found in *Kanamitsu et al.* [2002b].

[7] ROMS solves the incompressible and hydrostatic primitive equations with a free surface on horizontal curvilinear coordinates, and utilizes stretched general sigma coordinates in order to enhance vertical resolution near the sea surface and bathymetry. In this study, we use 30 vertical sigma layers, with approximately 10 layers in the upper 100 m in the open ocean, and 20 layers below. Implicit diffusivity associated with 3rd-order upstream horizontal advection is used in the lateral plane as opposed to explicit diffusivity. Mixed layer dynamics are parameterized using a KPP scheme [*Large et al.,* 1994], with vertical mixing coefficient of 10^{-5} m^2 s^{-1} (see *Shchepetkin and McWilliams* [2005] for details).

[8] The flux coupler [*Seo et al.*, 2005] employs linear horizontal interpolations of surface flux fields (momentum, heat, and freshwater flux) from RSM to ROMS and SST fields from ROMS to RSM. The atmospheric boundary layer is based on bulk parameterization of *Fairall et al.* [1996], which is implemented in ROMS. In the bulk formula, the relative motion between surface winds and surface currents are calculated for better representation of wind stress near the equator.

[9] In this study, two coupled experiments are designed to isolate the impact of the oceanic mesoscale on TA climate. In the first run (hereafter L), both RSM and ROMS use low (1º) horizontal resolution. Therefore L does not resolve mesoscale features of the TA Ocean. In the second run (hereafter H), horizontal resolution of RSM remains 1º, but high (¼º) resolution is used for ROMS. Since the two experiments are identical except for their horizontal resolutions for ROMS, the differences between H and L represent the difference between mesoscale eddies in H and horizontal diffusion in L.

[10] ROMS is first spun up for 8 years forced with climatological atmospheric forcing obtained from COADS [*da Silva et al.*, 1994], and initial and boundary conditions from World Ocean Atlas 2001 [*Conkright et al.*, 2002]. The end state from the forced ocean run is used as an initial condition for the coupled runs. The large-scale (low wave-number) atmospheric components specified from NCEP for the period 1998-2004 are used as realistic forcing (downscaling). H and L are further spun up in coupled mode for 1-year of 1998 to allow for surface adjustment processes. Solutions from 1999 to 2004 (6 years) are analyzed in this study.

3. Results

[11] **Figures 1-3** show that both H and L are reasonably realistic representations of the TA. This is different from the results usually found in *global* coupled models, which have a reversed east-west SST gradient [*Davey et al.*, 2002]. A related global modeling study with a localized ocean-atmosphere coupling in the Atlantic also suggests that *regional* coupling leads to a more realistic zonal SST gradient both at the equator and south of it, although systematic SST errors similar to those found here are still present [*Huang et al*., 2004]. Thus, both the H and L solutions are controlled by the low-wavenumber components of the flow specified by the NCEP Reanalysis downscaling procedure. From this it can be speculated that the TA Ocean dynamics may only be of minor importance for TA climate. This reflects the fact that the Atlantic basin is relatively small compared to the tropical atmospheric Rossby radius. However, in spite of the close resemblance of the H and L solutions there are important differences, as discussed below.

[12] **Figure 1** shows that resolving mesoscale features in the ocean results in different SST patterns that are the most distinct near the equator and African coastal upwelling region. H is colder than L in both regions, with the greatest difference of 0.6°C in the upwelling zone of the African coast. Given that most global coupled models produce a too weak SST-gradient and too warm coastal upwelling [*Mechoso et al.*, 1995; *Davey et al.*, 2002], this result is a major improvement and attests to the importance of the ocean mesoscale in the coupled models for more realistic SSTs in upwelling regions. The larger SST gradients in H, and the resulting colder equatorial cold tongue (ECT) and upwelling have been explained for a forced ocean in *Jochum et al.* [2005]. They showed that by resolving the mesoscale eddies in the ocean, one removes the spurious horizontal diffusion of heat from the warm subtropical warmpool to the cold equator, and this increases the SST gradient and thus makes the ECT and coasts colder and the warmpool warmer. Consistent with their analysis, the subtropics are warmer in H. It is a major result of the present study that these results from the forced model still hold true in the coupled model. The resulting changes in tropical SST affect the trade winds and rainfall as discussed below.

[13] Changes in near-surface atmospheric winds (**Figure 2)** are directly connected to the underlying SST gradient by changing the meridional sea-level pressure gradient (not shown) [*Lindzen and Nigam*, 1987]. The meridional wind difference map shows that low-level wind convergence is weaker in H in the ITCZ, leading to less rain there (**Figure 3)**. Between the equator and 5°N mean rainfall is reduced by up to 20% and in the subtropics of both the northern (5°N - 20°N) and southern (5°S - 20°S) hemispheres, H increases precipitation by approximately 10%. Increases in mean rainfall in the subtropics are roughly compensated by the deficit in the ITCZ, resulting in mean rainfall over the entire basin from 20°S to 20°N remaining roughly the same (difference in rainfall from 20°S to 20°N is only -0.0373 mm day^{-1}). Thus changes in SST gradient associated with better-resolved oceanic eddies cause a basin-scale rearrangement of mean rainfall patterns across the equator. A comparison with the NCEP Reanalysis (**Figure 3c,d**) shows that model-mean rainfall of H in the marine ITCZ, especially east of 35°W is reduced compared to L and in better agreement with the observations. Therefore we argue that there is a significant improvement in the precipitation simulation over the open ocean by

going from L to H. Such changes in rainfall are consistent with those in winds, but the changes in the winds are not large enough (<5%) to judge whether they improved or not. Over land, the differences between the present model's and NCEP's land-sea mask and topography render judgments on improvement moot.

4. Summary and discussion

[14] A regional coupled model has been used to examine if resolving the oceanic mesoscale field is important in determining the mean climate in the TA. It was found, somewhat surprisingly to the authors, that the TA climate is largely controlled by the large-scale atmospheric background circulation specified in the model from Reanalysis fields and that TA Ocean dynamics is only of minor importance in most of the domain. However, resolving the oceanic mesoscale results in colder and more realistic coastal upwelling regions along the coast of Africa and in a colder ECT. As already explained by *Jochum et al.* [2005] for the ECT in a forced ocean model, the reason for colder ECT and upwelling regions is that increasing horizontal resolution in the ocean model removes a spurious horizontal diffusion of heat from the warm subtropical warmpool to the ECT and coastal waters.

[15] A direct effect of the increased SST gradient is a reduced low-level convergence along the ITCZ. It is found that H precipitation is suppressed in the marine ITCZ by 20% with similarly sized increases in precipitation statistics in the subtropics, indicating a basin-scale redistribution of mean rainfall patterns. Comparing with the observations (diagnosed from the NCEP Reanalysis), we conclude that by increasing the horizontal resolution in the ocean model, the rainfall simulation over the open ocean is improved. It should be noted that the precipitation differences between H and L are small (<1 mm day^{-1}) compared to the ranges in estimates of the available observations: annual mean precipitation is ~4 mm day^{-1} from Reanalysis fields, ~7 mm day^{-1} from CPC merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997], and ~6 mm day^{-1} from satellite measurement of Tropical Rainfall Measuring Mission (TRMM). We chose to compare model with the NCEP fields because they are consistent with the prescribed large-scale atmosphere and the physics of the RSM [*Kanamitsu et al.*, 2002b].

[16] Due to the short length of the analyzed runs (6 years), we limit the current analysis to the changes in mean structure of winds and ITCZ arising from resolving oceanic mesoscale features. However, we can speculate that any changes in SST are likely to affect not only the mean but also the variability of the marine ITCZ. The nature of the altered atmospheric variability by SST changes in the TA will need be addressed with longer-term runs, which are currently under way.

[17] The horizontal resolution of the atmospheric model used in this study is not much finer than that of most global coupled atmospheric models and therefore the atmosphere does not experience the full effects of oceanic mesoscale features. To quantify the importance of the atmosphere resolving oceanic mesoscale features we plan to use the RSM in ¼º resolution. This allows for a synchronous coupled feedback arising from ocean mesoscale eddies through the localized wind adjustment and corresponding advection of heat and moisture (as observed by *Chelton et al*. [2001] and *Hashizume et al*. [2001] and modeled recently by *Small et al*. [2003] and *Seo et al.* [2006]), which is absent in the current model study. This will be the next step in our modeling strategy toward a better understanding of the mean and variability of TA climate as a result of resolving the ocean mesoscale in the TA Ocean.

Acknowledgement

This work forms a part of the Ph.D. dissertation of HS. The authors thank anonymous reviewers for helpful suggestions. This research was partially funded by NOAA Grant "Impact of oceanic mesoscale variability on the coupled climate". We gratefully acknowledge additional funding support from DOE (DE-FG02-04ER63857) and NOAA (NA17RJ1231 through ECPC and CORC). The views expressed herein are those of the authors and do not necessarily reflect the views of these agencies. The TMI data are obtained from the Web site of Remote Sensing Systems.

Reference

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus ensemble with large-scale environment Part I, *J. Atmos. Sci.*, **31**, 674-704

Chelton, D. B, and Coauthors, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical Pacific, *J. Climate*, **14**, 17877-17904

Chiang J. C. H., Kushnir, Y., and Giannini, A., 2002: Deconstructing Atlantic Intertropical Convergence Zone variability: Influence of the local cross-equatorial sea surface temperature gradient and remote forcing from the eastern equatorial Pacific, *J. Geophys. Res.*, **107**

Conkright, M. E., R. A. Locarnini, H. E. Garcia, T. D. O'Brien, T. P. Boyer, C. Stephens, J. J. Antonov, 2002: World Ocean Atlas 2001: Objective Analysis, Data Statistics, and Figure, CD-ROM Documentation. *National Oceanographic Data Center, Silver Spring, MD, 17pp*

da Silva, A., Young, C., Levitus, S., 1994: Atlas of Surface Marine Data 1994. NOAA Atlas NESDIS 6-110, US Government Printing Office, Washington, DC, pp. 1-5

Davey, M., and coauthors, 2002: STOIC: A study of coupled model climatology and variability in tropical ocean regions. *Clim. Dynm.,* **18**, 403-420

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. D. Edson, and G. S. Young, 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean Global Atmosphere Coupled-Ocean Atmosphere Response Experiment, *J. Geophys. Res.*, **15**, 3747-3764

Hashizume, H., S.-P. Xie, W. T. Liu, and K. Takeuchi, 2001: Local and remote atmospheric response to tropical instability waves: A global view from space, *J. Geophys. Res.*, **106**, 10173-10185

Huang, B., P. S. Schopf, and J. Shukla, 2004: Intrinsic Ocean-Atmosphere Variability of the Tropical Atlantic Ocean, *J. Climate*, **17**, 2058-2077

Jochum, M., Murtugudde, R., Ferrari, R., Malanotte-Rizzoli, P., 2005: The impact of the horizontal resolution on the Equatorial Mixed Layer Heat Budget in Ocean General Circulation Models, *J. Climate*, **18**, 841-851

Jochum, M., Murtugudde, R., Manlanotte-Rizzoli, P., and Busalachi, A., 2004: Internal Variability of the Tropical Atlantic Ocean, *Geophys. Monogr. Ser.*, **147**, 181-187

Kanamitsu, M., W. Ebisuzaki, J. Woolen, J. Potter and M. Fiorino, 2002a: NCEP/DOE AMIP-II Reanalysis (R-2), *Bull. Amer. Met. Soc.,* **83**, 1631-1643

Kanamitsu, M., A. Kumar, H.-M. H. Juang, W. Wang, F. Yang, J. Schemm, S.-Y. Hong, P. Peng, W. Chen and M. Ji, 2002b: NCEP Dynamical Seasonal Forecast System 2000, *Bull. Amer. Met. Soc.*, **83**, 1019-1037

Large, M. W., McWilliams, J. C., Doney, S. C., 1994: Oceanic vertical mixing- a review and a model with a nonlocal boundary-layer parameterization, *Rev. Geophys*., **32** (4), 363-403

Lindzen, R. S, and Nigam S, 1987: On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics, *J. Atmos. Sci.,* **44**, 2418–2436

Nobre, P., and J. Shukla, 1996: Variations of sea surface temperature, wind stress and rainfall over the tropical Atlantic and South America, *J. Climate,* **9**, 2464-2479

Mechoso, C., and coauthors, 1995: The seasonal cycle over the tropical Pacific in general circulation model, *Mon. Wea. Rev.,* **123**, 2825-2838

Moorthi, S., and M. J. Suarez, 1992: Relaxed Arakawa-Schubert cumulus parameterization of moist convection for general circulation models, *Mon. Wea. Rev*., **120**, 978-1002

Seo, H., A. J. Miller, J. O. Roads, 2006: The Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model, with Applications in the Eastern Pacific Sector, *J. Climate*, *submitted*

Shchepetkin, A. F., and J. C., McWilliams, 2005: The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate ocean model, *Ocean Modell*., **9**, 347-404

Small, R. J., S-P. Xie, Y. Wang, 2003: Numerical Simulation of Atmospheric Response to Pacific Tropical Instability Waves, *J. Climate*, 16, 3723-3741

Ward, M. N., and C. K. Folland, 1991: Prediction of seasonal rainfall in the north Nordeste of Brazil using eigenvectors of sea-surface temperature, *Int. J. Clima tol*., **11**, 711-743

Xie, S.-P., 2004: The shape of continents, air-sea interaction, and the rising branch of the Hadley circulation. The Hadley Circulation: Past, Present and Future, J. F. Diaz and R. S. Bradely. Eds. Springer-Kluwer Academic, 2005

Xie, P., and P. A. Arkin, 1997: Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs, *Bull. Am. Meteorol. Soc.,* **78**, No. 11, pp. 2539-2558

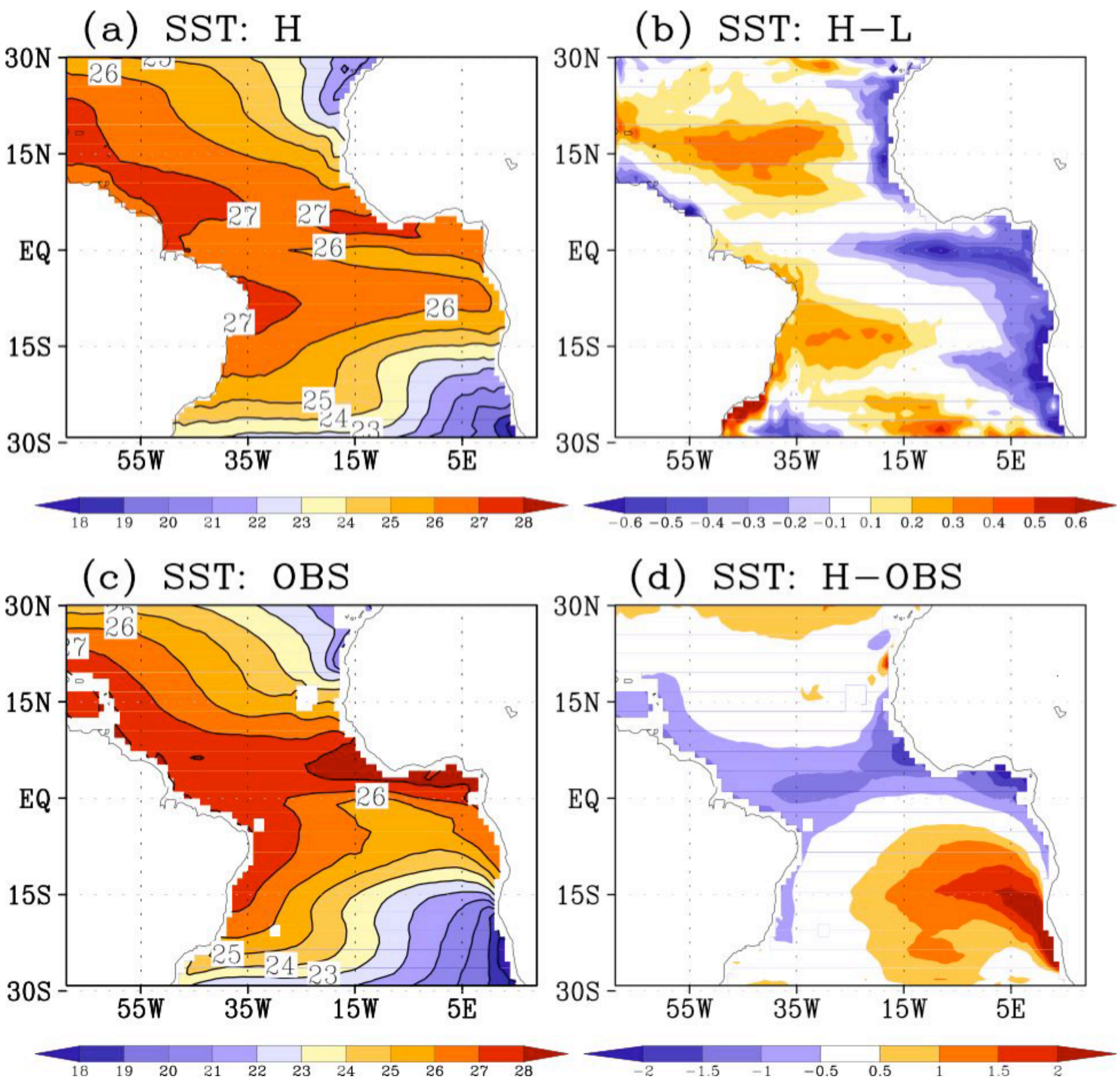

Figure 1. Mean SST (°C) from 1999 to 2004, (a) H, (b) H-L, and (c) observed SST from Tropical Rainfall Measuring Mission Microwave Image (TMI) (OBS), and (d) H-OBS. H SST is colder by up to 0.6°C in the equatorial cold tongue and African coastal upwelling region, while warmer in the extratropics.

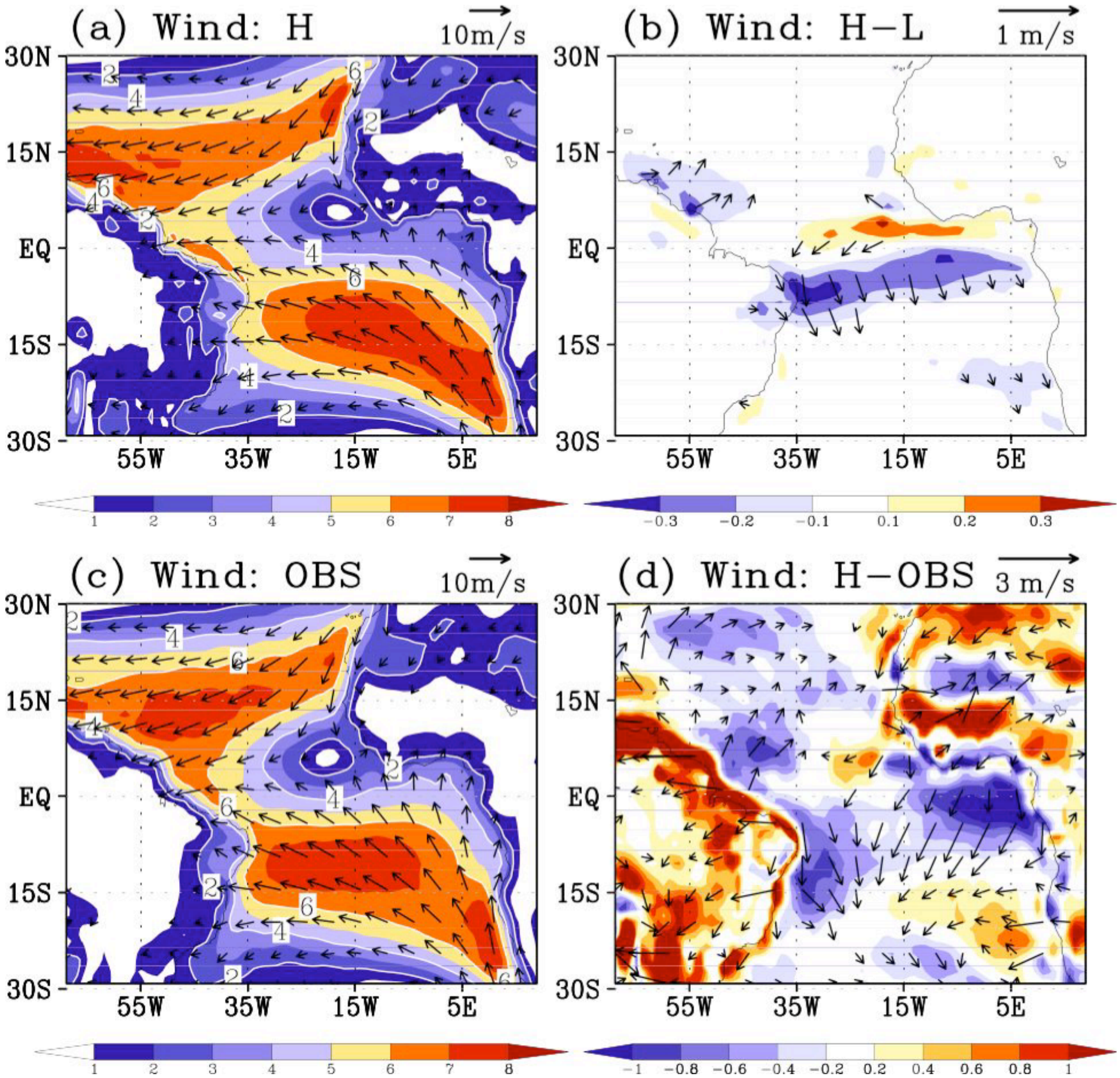

Figure 2. Same as Figure 1, except for 10 m wind speed (m s^{-1}) and vectors. OBS is the observed wind from NCEP Reanalysis. Difference in wind near the equator shows that wind-convergence is weaker in H, thus weaker ITCZ.

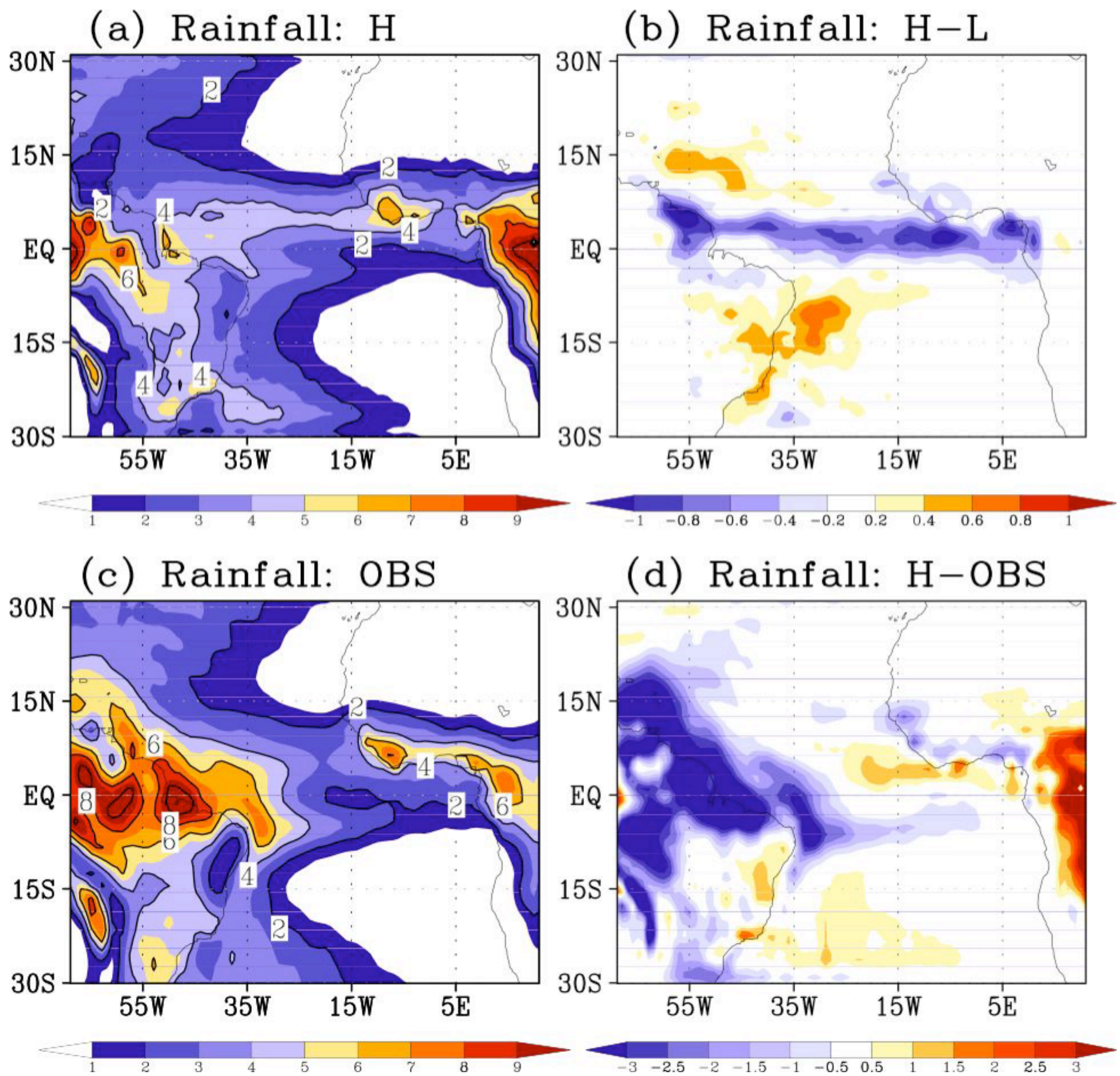

Figure 3. Same as Figure 1, except for precipitations (mm day^{-1}). OBS is the observed precipitation from NCEP Reanalysis. Rainfall deficit in H near the equator amounts to nearly 20% compared to its mean. Comparing with the observations, rainfall simulation is improved in H over open ocean.