5.7 A STUDY OF TROPICAL INSTABILITY WAVES OVER THE ATLANTIC USING A COUPLED REGIONAL ATMOSPHERE-OCEAN MODEL

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1. INTRODUCTION

The tropical instability waves with wavelengths of about 1000 km and periods between 25 days and 40 days are frequently observed in the tropical regions of the Pacific and the Atlantic oceans. The generation of these waves trapped within the atmospheric boundary layer has been considered a direct response of the atmosphere to the SST variations (Small et al., 2003), resulting from advection of the SST front by instabilities of the near-surface equatorial ocean current (e.g. Philander 1978, Contreras 2002). Some previous numerical studies also indicate that such ocean instability waves are controlled to some extent by surface wind forcing, suggesting a feedback from the atmosphere to these ocean instability waves (e.g. Allen et al., 1995, Benestad et al., 2001).

These instability waves not only contribute to the climate variability over the Atlantic but also influenced by it. For example, these waves tend to be less active under El Nino conditions and more active during La Ninas (Halpern et al., 1988, Contreras 2002). Our regional climate model (RCM) forced by observed daily SSTs over the Atlantic has demonstrated the ability to realistically capture the tropical instability waves in the atmosphere, induced by SST perturbations due to the corresponding ocean instability waves. Preliminary result has shown that tropical instability waves over the Atlantic can cause some remote climate impacts near the west coast of Africa and the tropical Atlantic, e.g., intraseasonal variation of the precipitation of the Intertropical Convergence Zone (ITCZ).

To explore the air-sea interaction mechanisms for these instability waves, a coupled regional atmosphere-ocean model is developed by coupling RCM with a reduced gravity ocean model. Comparisons between the modeled waves forced by observed daily SST and those generated through coupled atmosphere-ocean model may help reveal how the air-sea interaction affects the evolution and properties of tropical instability waves. Further detailed diagnoses of the modeled waves may offer insights to the main mechanisms responsible for the generation and maintenance of these waves in the lower troposphere and ocean.

2. MODEL DEVELOPMENT AND SETUP

The regional coupled atmosphere-ocean model is developed by coupling a regional climate model with a reduced gravity ocean model. In this study, the fifth-generation Pennsylvania State University (PSU)-NCAR Meso-scale model MM5 is customized into a regional climate model suitable for seasonal or interannual simulations. To perform regional climate modeling, SST and surface soil moisture, two major lower boundary conditions, are updated to include the seasonal variation effect. The model is initialized at 0000UTC on 15 January by using climatological January conditions from the NCEP-NCAR reanalysis (Kalnay et al., 1996). Lateral boundary conditions for winds, temperature, geo-potential heights, and moisture at each vertical level are taken from the NCEP-NCAR reanalysis, updated every 12 h based on a linear interpolation between monthly means. The nonhydrostatic dynamics of MM5 with 24 vertical sigma levels and various convection schemes allows RCM to be valid for mesoscale simulations.

RCM forced by observed SST has shown to be able to capture tropical instability waves mainly trapped in the atmospheric boundary layer from some of our preliminary results (not shown). To cover the whole tropical Atlantic, the domain for our coupled model experiments extends from 112°W to 22°E and 31°S to 31°S. The horizontal grid spacing is 90 km, and 23 sigma levels are used in the vertical direction. The top fixed pressure of the atmosphere is set to 50 mb, and each model step is 2 minutes. The parameterizations used in the coupled run are simple ice moisture scheme, Blackadar (1979) planetary boundary layer scheme (Zhang and Anthes 1982), and the Community Climate Model Version 2 (CCM2) scheme for long wave radiation of the atmosphere. The Kain-Fritsch cumulus convection (1993) is chosen for cumulus parameterization, and shallow convection scheme (Grell et al. 1994) is used to handle non-precipitating clouds.

The reduced gravity ocean (RGO) model

used in this study is a 2.5-layer model, consisting of two active layers: mixed layer and thermocline layer. The deep water below the thermocline layer is assumed to be infinitely deep and motionless. This RGO model is originally developed by Lee and Csanady (1999) with a relatively coarse horizontal resolution of 1° in both longitude and latitude. In their study, the effects of detrainment process and external forcing (i.e., Merdional overturning circulation (MOC)) over the tropical Atlantic are neglected. In order to include these processes important to the tropical Atlantic variability, the model is modified to include Kraus-tuner type entrainment parameterization (Kraus and Turner 1967, hereafter KT model) and open boundary condition (OBC) developed by Marchesiello et al. (2001). The KT model estimates both entrainment and detrainment rates in term of surface wind stress and heat flux. To resolve mesoscale eddy activities, a fine horizontal resolution of 0.25° grid spacing is used. The RGO model employs a Laplacian horizontal diffusion with the Smagorinsky diffusivity in the momentum equations. For the variables of temperature and layer thickness, no-flux boundary conditions are applied at all walls and open boundaries. All of the model equations are discretized using a 2nd order enstrophy-conserving finite difference scheme on the Arakawa C-grid in space and the leapfrog scheme in time (Sadourny, 1975).

RCM is coupled with RGO by providing the computed daily-average surface heat fluxes and wind stresses over the Atlantic to RGO and then daily average SST is computed by RGO as a lower boundary condition for RCM in the next time step. The SST over the Pacific is prescribed by observed daily SST. That is, there is no air-sea interaction over the Pacific region in our coupled model. The intended domain for RGO is designed to be slightly smaller than that of RCM, which ensures RGO to receive the modeled surface heat fluxes and wind stress completely from RCM over the Atlantic. From our testing experiments, it is found that excessive and unrealistic cloud liquid water is accumulated in the lower troposphere, which significantly blocks the incoming short wave radiation to the surface. To alleviate this problem, the cloud liquid water at the lowest 7 levels in RCM is set to zero.

3. RESULTS

Some results from the preliminary coupled simulations have shown the potential ability of this model to realistically capture the air-sea interaction phenomenon of tropical instability waves in both atmosphere and ocean. Figure 1 displays the summer background climatology averaged from June to August (JJA). As shown in Fig.1(a), the SST front associated with the equatorial cold tongue near the Gulf of Guinea appears to have shifted to the west, causing a relatively warmer condition to the east as compared with observations. Fig 1(b) shows the simulated Jun-July-August (JJA) mean precipitation and the streamlines at 945 hPa over the tropical Atlantic. The location and the concentration of ITCZ in summer are generally well simulated by the coupled model, suggesting the feasibility to explore the strong interaction between ocean and atmosphere within ITCZ through the coupled model experiments.

Figure 2 shows the composites of the tropical instability waves with periods between 25 days and 40 days in the ocean and the atmosphere. Composite SST perturbations and the surface wind vector at 10 m (U_{10} and V_{10}) are computed by selecting and averaging the filtered SST and perturbed surface winds with filtered SST at 25°W and 2°N greater than 0.1°C. Contours of SST perturbations north of the equator appear to tilt from southwest to northeast generally and northwest to southeast south of the equator, in agreement with the observational analysis from TRMM satellite data (not shown). The induced surface winds, U_{10} and V_{10}, diverge over the cold SST region regions and usually converge near the borders of warm and cold SST regions, suggesting a direct response of the atmospheric boundary layer to the perturbed SST near the equator. The estimated wavelength of these waves is approximately 11° in longitude near the equator (about 1100 km), in agreement with the results of many observational studies. In comparison with observations, its is found that the generation location of these simulated waves shifts to the west, which is associated with the westward shift of the equatorial cold tongue.

Figure 3 displays the time-longitude plot of tropical instability waves shown by the filtered SST (Fig.3a) and surface zonal wind (U_{10}) (Fig.3b) with periods between 25 days and 40 days along 2°N. The 25-40-day SST perturbations are initiated around mid-May and gradually diminish near the end of October. The filtered surface zonal wind U_{10} shows a similar trend to the perturbed SST signals, which also suggests a close relation between these two quantities. The westward phase speed of these SST perturbations, estimated by calculating the average slope of the contours, is around 0.6 ms^{-1}. In contrast, a slower group speed calculated by estimating the slope of the line connecting the contour maxima and minima appears to be eastward, suggesting that the energy flux is transported eastward although the propagation of these waves is westward.

4. SUMMARY AND CONCLUSIONS

The preliminary results in this study show that near ITCZ the air-sea interaction mechanisms of tropical instability waves may be further investigated through realistic simulations performed by the coupled atmosphere-ocean model (RCM-RGO). Some defects of the simulated results may be improved by performing the model simulation far beyond the spin-up period of the coupled model. To improve the modeled background climatologies of the atmosphere and the ocean, numerous experiments need to be conducted with various parameterization adjustments in both RCM and RGO.

Some studies have suggested that surface wind forcing may control the ocean instability waves to some extent, suggesting that the instability waves in the atmosphere may also affect the evolution of SST perturbations. A diagnosis of the energetics of these instability waves may provide more insights to the main air-sea interaction mechanisms of these waves in the ocean and the atmospheric boundary layer.

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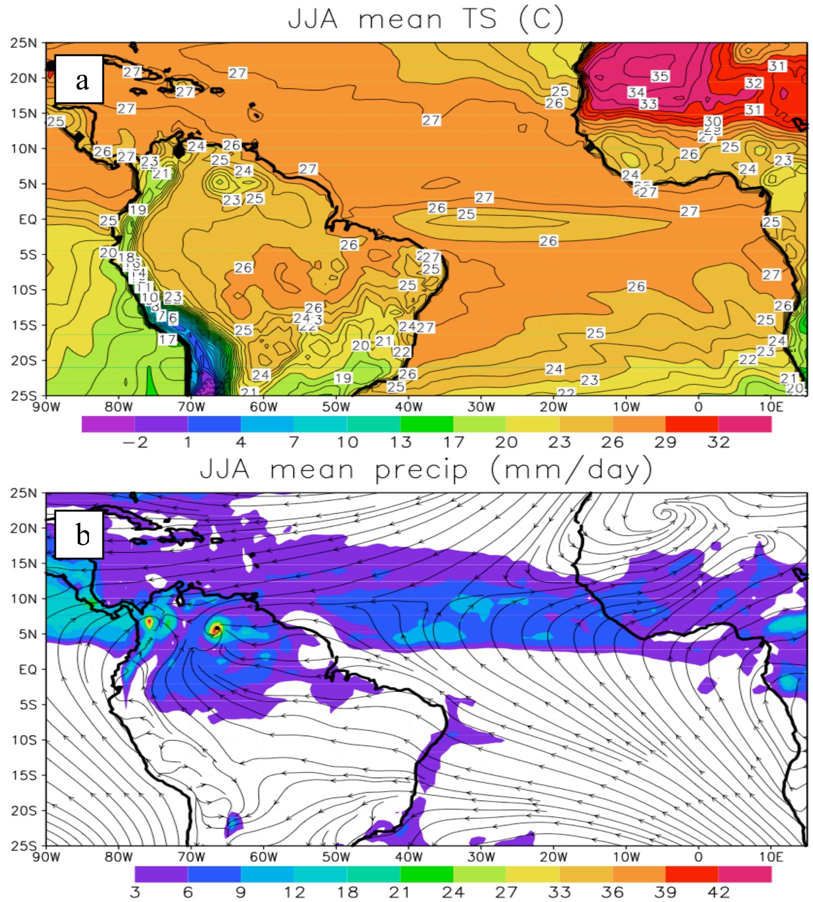

Figure 1. Simulated Jun-July-August means of (a) surface temperature (°C), (b) precipitation (mm.day)

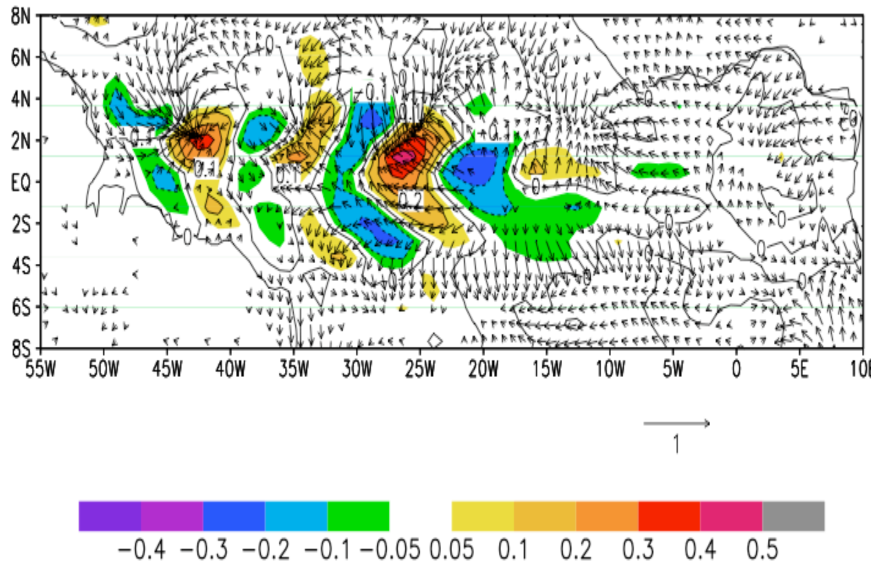

Figure 2. Composites of the filtered surface winds U_{10} and V_{10} (m/s) and SST perturbations (°C) or periods between 25 days and 40 days. Contour interval is 0.1 °C. Regions with amplitudes greater than 0.05 °C are shaded.

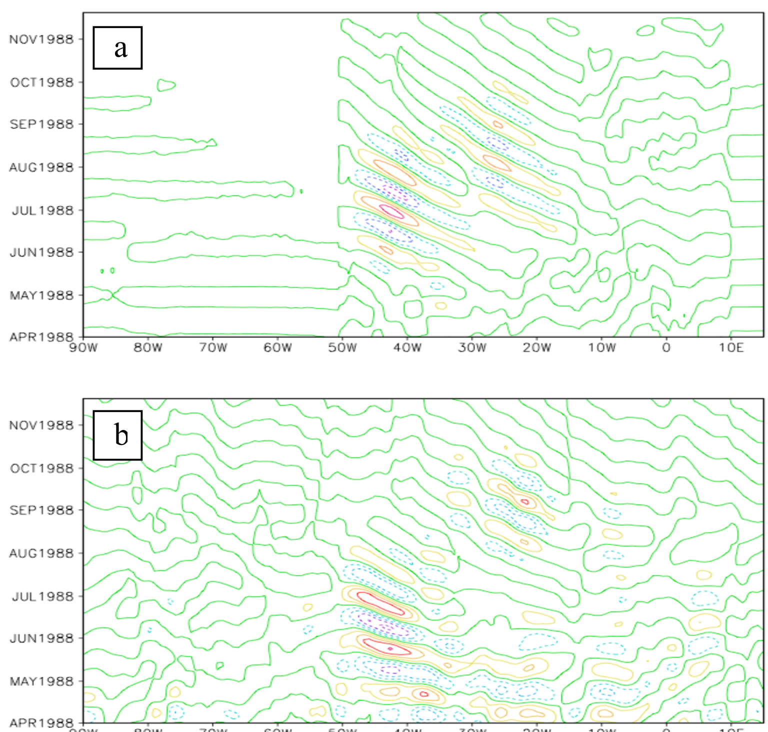

Figure 3. Time-longitude plot of 25-40-day tropical instability waves along latitude of 2°N for (a) SST (°C), contour interval is 0.3 °C, and (b) U_{10} (m/s). Contour interval 0.3 m/s