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Experimental Dynamical Forecast of an MJO Event Observed during TOGA-COARE Period

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Abstract With a hybrid atmosphere-ocean coupled model we carried out an experimental forecast of a well documented Madden-Julian Oscillation (MJO) event that was observed during the period of Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE). The observed event, originated in the western Indian Ocean around 6 January 1993, moved eastward with a phase speed of about 6.2 m s^{-1} and reached the dateline around February 1. The hybrid coupled model reasonably forecasts the MJO initiation in the western Indian Ocean, but the predicted MJO event propagates too slow (~ 4.4 m s^{-1}). Results from previous observational studies using unprecedented humidity profiles obtained by NASA Aqua/AIRS satellite suggested that two potential physical processes may be responsible for this model caveat. After improving the cumulus parameterization scheme based on the observations, the model is able to forecast the same event one month ahead. Further sensitivity experiment confirms that the speed-up of model MJO propagation is primarily due to the improved convective scheme. Further, air-sea coupling plays an important role in maintaining the intensity of the predicted MJO. The results here suggest that MJO prediction skill is sensitive to model cumulus parameterization and air-sea coupling.

Keywords: MJO, dynamic forecast, cumulus parameterization, air-sea coupling, TOGA-COARE

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1 Introduction

The Madden-Julian Oscillation (MJO) is a dominant intraseasonal mode in the Tropics, which involves strong coupling between convective heating and large-scale circulations (Madden and Julian, 1972). It is usually originated in the Indo-western Pacific warm-pool and propagates eastward around the globe, which gives rise to a period of 30–60 days. The basic dynamics of MJO can be understood by the frictionally and convectively coupled equatorial Kelvin-Rossby waves (Wang, 1988; Wang and Rui, 1990). Because the MJO has a far reaching influence worldwide (Hsu and Huang-Hsiung, 1996; Donald et al., 2006), improved understanding and prediction of MJO are imperative for filling in the forecast gap between current weather forecast (~ one week) and seasonal outlook (> one month) and for making the so-called seamless forecast possible (WCRP COPES, 2005). Unfortunately, most state-of-the-art general circulation models (GCMs) still have a variety of problems in realistic simulation of MJO (Slingo et al., 1996; Lin et al., 2006), thus resulting in a limited MJO forecast skill (Jones et al., 2000; Seo et al., 2005; Kim et al., 2007).

A few GCMs including the ECHAM (ECMWF model at HAMburg, Germany) family coupled models have been recognized as the models that are capable of simulating a reasonable MJO (Lin et al., 2006; Kim et al., 2007; Sperber and Annamalai, 2008). In this study, we will take advantage of a hybrid coupled model which used ECHAM AGCM as its atmospheric component (Fu and Wang, 2004) to address some essential issues related to MJO forecast. The major objectives of this study are: i) to explore the practical predictability of MJO in this hybrid coupled model and ii) to test the sensitivity of MJO forecast to cumulus parameterization scheme and air-sea coupling.

The TOGA-COARE (Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment; Webster and Lukas, 1992) has conducted intensive observations of the atmosphere and ocean states from November 1992 to March 1993 over equatorial western Pacific. Two MJO events occurred and were well documented in this period (Lin and Johnson, 1996; Chen and Yanai, 2000). The following forecast experiments focus on the second event, which has been selected as target by previous forecast studies (e.g., Woolnough et al., 2007; Vitart et al., 2007).

2 MJO forecast experiments

The hybrid coupled model used in this study combined ECHAM-4 AGCM (Roeckner et al., 1996) with an intermediate upper ocean model (Wang et al., 1995; Fu and Wang, 2001) without heat flux correction (Fu and Wang, 2004). The simulated MJO and boreal-summer intraseasonal oscillations exhibit reasonable fidelity (Kemball-Cook et al., 2002; Fu et al., 2003). The potential predictability of tropical intraseasonal oscillation in this

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model reaches about one month on average over the tropical Asian-western Pacific sector (Fu et al., 2007).

As a starting point to examine the MJO practical predictability in this hybrid coupled model, an MJO event observed during TOGA-COARE period (Fig. 1a) was selected as our forecast target. This choice facilitates comparison with other dynamical forecasts which focused on the MJO events during TOGA-COARE (Woolnough et al., 2007; Vitart et al., 2007). In this study, all retrospective forecasts were initiated with NCEP (National Centers for Environmental Prediction) reanalysis on 1 January 1993. Three suites of forecasts were carried out: i) coupled forecast with model default cumulus parameterization; ii) coupled forecast with a revised cumulus parameterization; iii) uncoupled (atmosphere-only) forecast with revised cumulus parameterization. For each suite of forecast, one hundred ensembles have been carried out with perturbed initial atmospheric conditions. All forecasts have been integrated for two months from 1 January to 28 February 1993.

2.1 The impact of cumulus parameterization

It is well-known that MJO simulation is very sensitive to cumulus parameterization schemes (e.g., Tokioka et al., 1988; Wang and Schlesinger, 1999; Maloney and Hartmann, 2001; Liu et al., 2005). In this study, the impact of cumulus parameterization on MJO forecast has been explored. As a first step to assess the MJO practical predictability, the longitude-time cross-sections and projections onto the phase space (Wheeler and Hendon, 2004) are applied. Because MJO is an equatorial eastward propagating phenomenon with strong coupling between convection and large-scale circulations, both rainfall and zonal wind vertical shear associated with MJO are evaluated. Figures 1 and 2, respectively, show the rainfall and zonal wind vertical shear (U850 hPa−U200 hPa) averaged between 10°S and 10°N from the observations and forecasts. At initial time (1 January 1993), the observations indicate strong convection around the dateline which tends to stay there for a while (Fig. 1a). The emanated fast Kelvin wave triggers a MJO event (Chen and Yanai, 2000) in the western Indian Ocean around January 6. The MJO-related convection then gradually moves eastward and finally stops around the dateline on February 1 (Fig. 1a). The zonal wind vertical shear from NCEP reanalysis (Fig. 2a) shows consistent eastward propagation in association with the MJO convection. For the hybrid coupled model with default cumulus parameterization, the convection (Fig. 1b) and the associated circulations (Fig. 2b) of the forecast MJO do indicate eastward movement, but consistently falling behind the observations. Until February 1, the convection center only moves to around 120−150°E, which is about 30−40° west of the observations.

In recent observational studies with the unprecedented humidity profiles obtained by NASA Aqua/AIRS satellite, two peculiar MJO features are found being misrepresented or underestimated by contemporary GCMs (Fu et al., 2006; Tian et al., 2006; Yang et al., 2008): the salient lower-troposphere moisture preconditioning ahead of MJO convection and dryness underneath the convection. Both processes may strongly affect the MJO propagation. The misrepresentation of these processes may be responsible for the slow eastward propagation of the forecast MJO in this model (Figs. 1b and 2b) and for the too long MJO period noticed in many GCMs participated into the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4, Lin et al., 2006). To test this hypothesis, we revised the cumulus parameterization of ECHAM-4 with enhanced lowertroposphere moistening and convective downdrafts. As a result, the

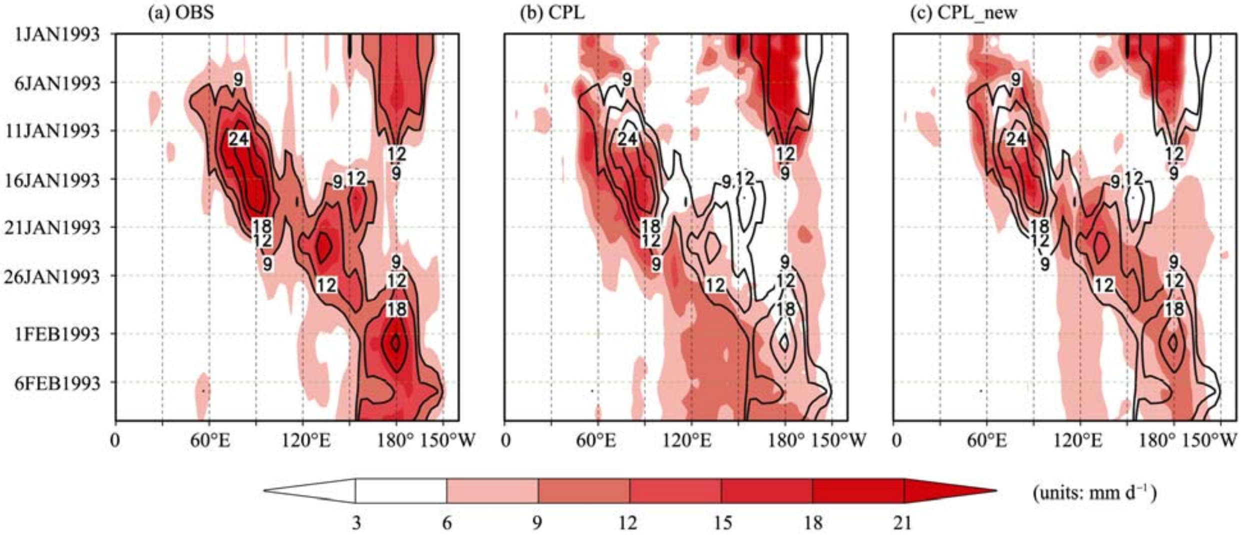

Figure 1 Time-longitude evolutions of precipitation (mm d^{-1}) averaged between 10°S and 10°N from the CMAP observations (a, OBS, both shading and contours), coupled forecast with default cumulus parameterization (b, CPL, shading; the OBS has been redrawn as contours), and coupled forecast with revised cumulus parameterization (c, CPL-new, shading; the OBS has been redrawn as contours). Both forecasts start from 1 January 1993 and are 100-ensemble means.

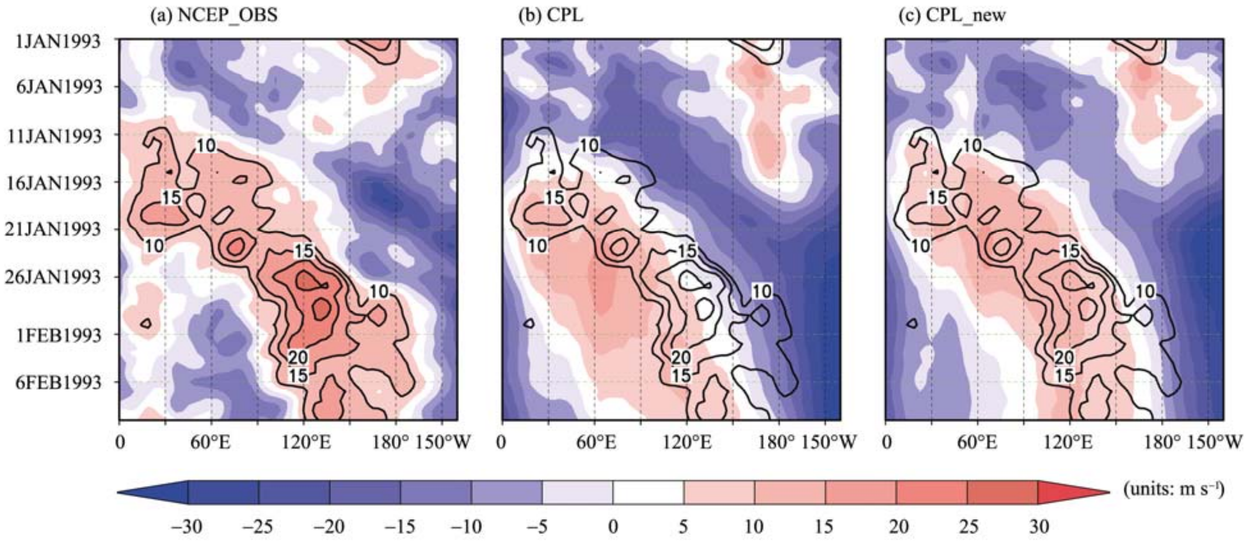

Figure 2 Time-longitude evolutions of zonal-wind vertical shear (U850 hPa−U200 hPa) averaged between 10°S and 10°N from the NCEP reanalysis (a, NCEP_OBS, both shading and contours), coupled forecast with default cumulus parameterization (b, CPL, shading; the NCEP_OBS has been redrawn as contours), and coupled run with revised cumulus parameterization (c, CPL-new, shading; the NCEP_OBS has been redrawn as contours). Both forecasts start from 1 January 1993 and are 100-ensemble means.

forecast MJO has speeded up significantly. Both rainfall and zonal wind vertical shear show very good agreement with the observations (Figs. 1c and 2c). The validation with TOGA-COARE in-situ sounding observations confirms our hypothesis and the details will be reported elsewhere considering the page limit of this short article.

A convenient graph describing MJO evolution is the phase-space map developed by Wheeler and Hendon (2004). In this study, 24-year (1982–2005) observed Outgoing-Longwave-Radiation (OLR) and NCEP reanalysis 850 hPa and 200 hPa zonal winds have been used to derive two leading combined Empirical Orthogonal Functions (EOFs). The observed and forecast anomalies of OLR, zonal winds after removing two-month means (from 1 January to 28 February 1993) have been projected onto the two leading EOFs to obtain a pair of PC time series for the observations and forecasts (Wheeler and Hendon, 2004). The resultant one-month trajectories are given in Fig. 3. The distance between the initial observation point and initial conditions of forecasts indicates further improvement of initialization is needed. On day 5, both observations and forecasts fall within phase 1. On day 10, observed MJO moves into the Indian Ocean between phase 2 and 3; the forecast MJO by original CouPLed model (CPL) still resides between phase 1 and 2; the revised coupled model (CPL-new) moderately helps the MJO move ahead. Toward day 20, both the observed MJO and the CPL-new forecast MJO reach the Maritime Continent; while the CPL forecast is still in Indian Ocean (phase 3). During day 25–30, both the observations and the CPL-new forecast quickly cross the Maritime Continent and enter the western Pacific; the CPL forecast is still meandering around the Maritime Continent. In terms of the intensity, both coupled forecasts tend to overestimate the MJO activity in the Indian sector.

2.2 The impact of air-sea coupling

Many previous studies have suggested that air-sea coupling can improve the simulation of MJO (e.g., Krishnamurti et al., 1988; Waliser et al., 1999; Fu et al., 2003; Zhang et al., 2006; Dong et al., 2006) and even its forecast (Krishnamurti et al., 2007; Woolnough et al., 2007). To examine the possible impact of interactive air-sea coupling on MJO forecast in this hybrid coupled model, another suite of uncoupled (atmosphere-only) forecast with revised cumulus parameterization (UnCPL-

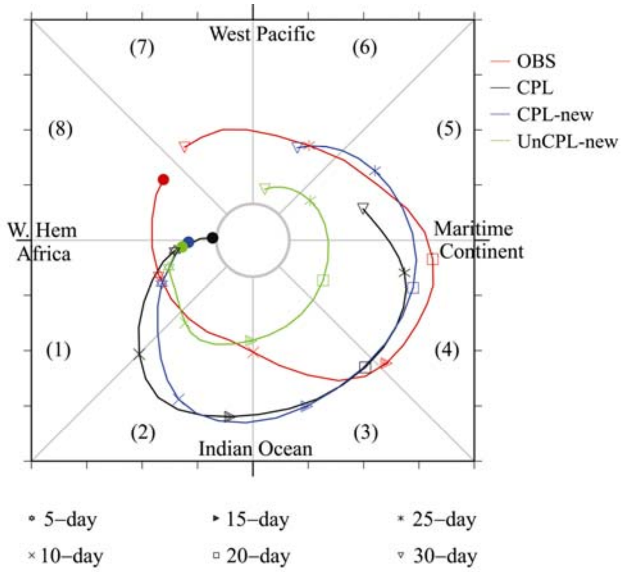

Figure 3 Phase-space projection of the observed (OBS) and forecasted MJO by the coupled model with default cumulus parameterization (CPL), coupled model with revised cumulus parameterization (CPL-new) and uncoupled (atmosphere-only) model with revised cumulus parameterization (UnCPL-new). All three forecasts start from 1 January 1993 and are 100-ensemble means.

new) has been carried out. In this case, the climatological monthly sea surface temperature has been used as lower boundary condition during the forecast period. The resultant phase-space trajectory of forecast MJO is also presented in Fig. 3. The associated eastward propagation speed is very similar with the corresponding coupled forecast (CPL-new) but with considerably weaker intensity.

3 Summary and discussion

In this study, the MJO practical predictability of a hybrid coupled model has been assessed with a prominent MJO observed during TOGA-COARE period. The hybrid coupled model combines an ECHAM-4 AGCM with an intermediate ocean model without heat flux correction. The coupled model with default cumulus parameterization captures the initiation and propagation of the observed MJO event but with too slow eastward propagation. Based on previous model validations with the unprecedented humidity profiles obtained by NASA Aqua/AIRS satellite (Fu and Wang, 2004; Fu et al., 2006; Tian et al., 2006; Yang et al., 2008), we found that the original cumulus parameterization underestimates the lower-troposphere moisture preconditioning ahead of the convection and the dryness underneath it. After revising the cumulus parameterization accordingly, the coupled model actually shows promising capability in tracking the eastward movement of the observed MJO beyond one month (Figs. 1−3). This demonstrates that running model in a forecast mode is a useful strategy to identify and remedy model errors (Boyle et al., 2005). Further uncoupled (atmosphere-only) experiment (Fig. 3) indicates that the speed-up of the MJO is basically a result of the revised cumulus parameterization. Using the monthly climatological sea surface temperature as an external forcing weakens the intensity of the forecast MJO, which agrees with the expectations from many previous modeling studies (e.g., Waliser et al., 1999; Dong et al., 2006; Fu et al., 2007; Woolnough et al., 2007).

The optimistic side of current case study encourages more experimental forecasts to be carried out with more boreal-winter MJO and boreal-summer intraseasonal oscillation events. Keeping in mind that many contemporary GCMs are still very poor even in simulating MJO, apparently more observational and modeling efforts are needed to better understand the physical processes governing the onset and evolutions of MJO. Finally, it is worth while to point out that the forecast MJO by this hybrid coupled model crosses the Maritime Continent from Indian to Pacific Oceans smoothly, while the forecast MJO by both NCEP climate forecast system (Vinzileos, 2007) and ECMWF seasonal forecast system (Vitart et al., 2007) experiences apparent predictability barrier at the Maritime Continent. Further inter-comparisons among these model forecasts will help identify the physical processes responsible for this difference and possibly make improvement.

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