Toward Seamless Weather-Climate Prediction with a Global Cloud Resolving Model

PI: Tim Li
IPRC/SOEST, University of Hawaii at Manoa
1680 East-West Road, POST Building 409B
Honolulu, Hawaii 96822
Phone: (808) 956-9427, fax: (808) 956-9425, e-mail: timli@hawaii.edu

PI: Dr. Shian-Jiann Lin
Geophysical Fluid Dynamics Laboratory, NOAA
Princeton, New Jersey 08542
Tel: (609) 452-6514, Email: Shian-Jiann.Lin@noaa.gov

Co-PI: Melinda S. Peng
Naval Research Laboratory
Monterey CA 93943-5502
Phone: (831) 656-4704, fax: (831) 656-4769, e-mail: melinda.peng@nrlmry.navy.mil

Award Number: N000141210450
Project Period: April 2012 – Sept 2015

LONG-TERM GOAL

The long-term goal of this project is to developing a seamless weather and climate prediction system that has capability to predict accurately both weather phenomena such as tropical cyclones (TC) and other extreme weather events and longer climate-scale phenomena such as the Madden-Julian Oscillation (MJO) and the El Nino-Southern Oscillation (ENSO). Organized moist convections in the tropical atmosphere have their origins at space scale of less than 10 km, and they play a key role in the initiation and maintenance of mesoscale weather events such as super cloud clusters and large-scale phenomena such as MJO. The Navy is in urgent need to develop such a global high resolution model that has a proper dynamic core and physics packages and is capable of representing realistically convection and clouds across a wide range of spatial and temporal scales and suitable for prediction of extreme events in regional and global scales.

OBJECTIVE

We aim to develop a new global model framework with the goal of reducing the uncertainty in moist convective processes. The Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) is proposed as a base framework for the next generation Navy global cloud resolving system. The HiRAM has a highly scalable finite volume dynamic core formulated on a cubed sphere. It is a non-hydrostatic, “cloud-resolving capable” global model designed to be applicable for a wide range of horizontal resolution from 100 km to 1 km. The objective of this project
is to systematically evaluate the model’s performance in weather (short and extended range) and climate (seasonal) predictions and provide a basis for the construction of next-generation Navy global cloud-resolving atmospheric forecast system suitable for operational requirements. We will in particular demonstrate the capability of this model in reproducing both short-range weather events such as mid-latitude synoptic systems and TCs and long-range climate variability such as MJO and ENSO teleconnection.

**APPROACH**

We proposed to conduct the following three sets of experiments using HiRAM:

**Weather forecast experiment.** The first experiment is daily 10-day forecasts at the 25-km for a continuous period of one years, starting from spring of 2012. The 12.5-km resolution can be done for shorter period (for example, at hurricane season) pending on the availability of computing resources at GFDL. This experiment is designed to evaluate the model performance in the conventional “weather forecast mode”. A systematic evaluation of the model short-range weather forecast capability will be conducted and results will be compared with current operational models such as the Navy NOGAPS/NAVGEM and NCEP GFS. A special attention will be to the forecast skill of TC track and intensity and winter mid-latitude synoptic-scale systems.

**AMIP-type experiment.** The second is an AMIP-type experiment. The model is run for 20 years (1990-2010) with monthly or weekly observed SST as a lower boundary condition. The inclusion of a longer period is needed in order to examine the model’s performance in reproducing the atmospheric internal modes such as MJO and teleconnection patterns associated with El Nino. This experiment may be identified as a “free run mode”. A 25 km or a 12.5 km resolution will be used for the AMIP run. The capability of reproducing the observed MJO and ENSO variability in the “free run mode” is crucial for extended-range weather forecast. It has been shown that TC and other synoptic wave activity are to a large extent controlled by low-frequency oscillations such as MJO and ENSO (Liebmann et al. 1994, Sobel and Maloney 2000, Fu et al. 2007, Hsu and Li 2011). Only when a model can capture realistic MJO structure and evolution in a free run, can this model predict the growth, propagation and phase transition of a real-case MJO event (otherwise the initial MJO signals would damp quickly with time).

**Seasonal prediction experiment.** The third is a seasonal prediction experiment similar to our TC forecast experiment. This may be termed as a “seasonal prediction mode”. Such type of experiment is one step further toward achieving the goal of seamless weather-climate forecast. Through the evaluation of the model’s seasonal forecast skill with forecasted SST (in which SST is determined based on the climatologic annual cycle plus a SST anomaly frozen at forecast initialization date), we will examine the model’s practical predictability in extended range weather and seasonal climate prediction. The model’s systematic bias in reproducing the seasonal mean state will be first examined, followed by the bias analysis in seasonal anomalies. The signal to noise ratio will be examined through multi-ensemble experiments. In addition to examining seasonal TC forecast skills in various basins, we will also examine the forecast skills in regional climate systems including the Asian monsoon, mid-latitude storm track, and the Pacific-North America pattern. The seasonal forecast experiments will be carried out for each season, in order to reveal the seasonal dependence of the model forecast capability.
We proposed to diagnose the experiments above, evaluate the model performance and assess the model forecast skills. Conventional diagnostic methods adopted at current operational centers are used to evaluate the model short-range weather forecast capability. Other diagnosis matrices such as the Wheeler-Hendon RMM based anomaly correlation coefficient (ACC) index and the signal-noise ratio based predictability index are used to assess the model extended-range forecast skill. A box difference index (BDI) is applied to evaluate the relationships between TC genesis and large-scale pattern in various basins (e.g., tropical North Atlantic, eastern North Pacific, and western North Pacific). Additionally we evaluate the model’s performance in reproducing the MJO variability and the ENSO teleconnection patterns.

WORK COMPLETED

The objective of this project is to systematically evaluate the GFDL High-Resolution Atmospheric Model (HiRAM) capability in capturing both high-impact weather (such as TC) events and low-frequency (MJO and ENSO) climate oscillations. In this year, a 10-yr (2003-2113) hindcast experiment was conducted, using the new version of HiRAM with a double-plume convective scheme. The diagnosis of 10-yr coupled model hindcast result shows that the model has a MJO forecast skill of up to 27 days. The forecast skill varies with initial/target MJO amplitude and phase.

In addition, we examined MJO propagation and non-propagation features across the Maritime Continent, and studied the MJO initiation processes over western Indian Ocean and MJO interaction with tropical cyclone.

RESULTS

1. A 10-yr MJO hindcast experiment and diagnosis of the model output

The coupled version of HiRAM with use of the new DP convective parameterization scheme was used to conduct 10-yr (2003-2013) hindcast experiment (Xiang et al. 2015). The coupled model initial condition was derived based on a nudging scheme in which the model prognostic variables such as U, V, SLP, geopotential height, air temperature and SST were nudged toward NCEP final analysis (FNL) fields. The hindcast period is November to April. The model was run once every five days (i.e., 1st, 6th, 11th, 16th, 21st, and 26th each month). There were 6 ensemble forecast members each run (00Z, 04Z, 08Z, 12Z, 16Z, and 20Z). The model was integrated for 50 days for each ensemble.

Figure 1 shows the bi-variate Anomaly Correlation Coefficient (ACC) and Root Mean Square Error (RMSE) of the model MJO prediction during the 10-yr period. The ACC for individual member (grey lines in Fig. 3a) drops rapidly for the first 20 days and the 6 members’ mean skill is about 19 days with the ACC exceeding 0.5. As expected, the ACC for the 6 members ensemble mean (red line in Fig. 3a) is superior to that from individual member with the skill reaching out to 25 days. This RMM skill is among top of current operational forecast models in the world.

In accordance with the decrease of the bivariate ACC, the RMSE increases rapidly during the first 20 days but keeps almost flat during the time range of 20-40 days (Fig. 3b). Using the same criterion of ACC in excess of 0.5, the prediction skills for RMM1 and RMM2 are estimated to be 28 and 22 days (not shown), respectively, suggesting that EOF1 is more predictable than EOF2 mode in this model.
forecast system. We also examine the prediction skill for individual variables. As expected, the prediction skill for OLR is lower (17 days) than the other two circulation variables U850 (24 days) and U200 (22 days).

Large contrasts are found for the MJO forecast skill between initially strong and weak cases (41 vs. 17 days), and also for target strong and weak cases (42 vs. 9 days). Meanwhile, the prediction skill is significantly higher during phases 2, 3, 4, and 5 compared to the other 4 phases, indicating that the propagation of wet anomalies is more predictable than the relatively dry anomalies. The amplitude and propagation speed are reasonably well predicted, ensuing the high prediction skill especially for initially strong cases.

![Figure 1 MJO prediction skill in boreal winter. (a) The bivariate ACC for individual member (grey) and 6 member ensemble mean (red) as a function of forecast lead days. (b) RMSE of individual member (grey) and ensemble mean (red), and the ensemble spread relative to the 6 member ensemble mean (blue).](image)

2. Mechanisms for propagating and non-Propagating MJO Events across Maritime Continent

The observed outgoing longwave radiation and ERA-I data during 1979-2008 (from November to April) were analyzed to reveal fundamental differences between eastward- propagating (EP) and non-propagating (NP) MJO events across the maritime continent. It was found that when the maximum MJO convection arrives near 120°E, a positive moisture tendency lies in a longitudinal zone (130°E -
170°E, 10°S - 10°N) for the EP cases whereas a negative tendency appears in the same region for the NP cases. For the latter there are clearly detectable westward-propagating Rossby-wave-type dry signals over the equatorial central-western Pacific. A moisture budget analysis shows that the positive tendency of specific humidity in the EP composite is mainly attributed to the advection of the mean moisture by intraseasonal ascending motion anomaly, whereas the negative tendency in the NP composite arises from the advection of anomalous dry air by the mean easterly and the advection of the mean moisture by the anomalous easterly.

3. MJO initiation processes during DYNAMO period

During the DYNAMO campaign period, two strong MJO events occurred from middle of October to middle of December (referred to as MJO I and MJO II respectively). Both the events were initiated over the western equatorial Indian Ocean (WIO) around 50º-60ºE. Using multiple observational data products (ERA-Interim, ECMWF final analysis and NASA MERRA), we unveil specific processes that triggered the MJO convection in the WIO. It is found that 10 days prior to MJO I initiation, a marked large-scale ascending motion anomaly appeared in the lower troposphere over the WIO. The cause of this intraseasonal vertical motion anomaly was attributed to anomalous warm advection by a cyclonic gyre anomaly over the northern IO. The MJO II initiation was preceded by a low-level specific humidity anomaly. This lower-tropospheric moistening was attributed to the advection of mean moisture by anomalous easterlies over the equatorial IO. It was found that upper-tropospheric circumnavigating signals did not contribute the initiation of both the MJO events. Thus the EOF-based RMM indices should not be used to determine MJO initiation time and location because they are primarily used to capture large scale eastward-propagation signals, not localized features.

4. A Spatial-Temporal Projection Model for Extended-Range Forecast in the Tropics

A spatial-temporal projection model (STPM) was constructed for the extended-range (10-30-day) forecast (ERF) of tropical outgoing longwave radiation anomalies (OLRA). A 10-yr hindcast result shows that, different from previous statistical models, the skill scores of the STPM dropped slowly with forecast lead times. Useful skills can be detected at 30-35 day leads over most tropical regions. The highest temporal correlation coefficient (TCC) of 0.4-0.5 appears over the Maritime Continent (Indian and western North Pacific monsoon regions) in boreal winter (summer). The STPM is also able capable in predicting the spatial evolutions of convective anomaly, including the zonal and meridional propagation of OLRA. The forecast of the Real-time Multivariate MJO (RMM) indices shows that the STPM attains a higher skill than previous statistical models. The STPM shows comparable skills with the state-of-the-art dynamic models such as ECMWF during the DYNAMO campaign period.

5. Interactions between Typhoon Megi and a Low-frequency Monsoon Gyre

The WRF model is used to investigate the sharp northward turn of super typhoon Megi (2010) after it moved westward and crossed the Philippines. The NCEP analyzed fields during this period are separated into a slowly varying background flow component, a 10-60-day low frequency component representing the monsoon gyre, and a 10-day high-pass filtered component representing Megi and other synoptic-scale motion. It appears that the low-frequency (10-60-day) monsoon gyre interacted with Megi and affected its track. To investigate the effect of the low-frequency mode on Megi,
numerical experiments were designed. In the control experiment, the total fields of the analysis are retained in the initial and boundary conditions, and the model is able to simulate Megi’s sharp northward turn. In the second experiment, the 10-60-day monsoon gyre mode is removed from the initial and lateral boundary fields and Megi moves westward and slightly northwestward without turning north. Tracks of the relative positions between the Megi and the monsoon gyre centers suggest that a Fujiwhara effect may exist between the monsoon gyre and Megi. The northward turning of both Megi and the monsoon gyre occurred when the two centers are close to each other and the beta drift was enhanced.

6. Three Types of MJO Initiation Processes over the Western Indian Ocean

Thirty strong Madden–Julian Oscillation (MJO) events in boreal winter 1982–2001 are selected to investigate the triggering processes of MJO convection over the western equatorial Indian Ocean (IO). These MJO events are classified into three types, according to their dynamic and thermodynamic precursor signals in situ. In Type I, a remarkable increase in low-level moisture occurs, on average, 7 days prior to the convection initiation. This low-level moistening is mainly due to the advection of the background mean moisture by easterly wind anomalies over the equatorial IO. In Type II, lower-tropospheric ascending motion anomalies develop, on average, 4 days prior to the initiation. The cause of this ascending motion anomaly is attributed to the anomalous warm advection, set up by a suppressed MJO phase in the equatorial IO. In Type III, there are no clear dynamic and thermodynamic precursor signals in situ. The convection might be triggered by energy accumulation in the upper layer associated with Rossby wave activity fluxes originated from the mid-latitudes.

IMPACT/APPLICATIONS

The current effort may lead to the improved understanding of MJO dynamics and the development of next generation navy operational weather-climate prediction model.

TRANSITIONS

Results from this study may lead to the development of a base model for next-generation navy operational seamless weather-climate forecast system. The model dynamic core and physics package may be transitioned into NRL as a 6.4 project.

RELATED PROJECTS

This project is complementary to our NSF funding entitled “Upscale feedback of tropical atmospheric synoptic-scale variability to intra-seasonal oscillation” in which we are investigating two-way interactions between the synoptic-scale motion (including TC) and MJO.

PUBLICATIONS

The following are papers published in 2015 that are fully or partially supported by this ONR grant:


Chen L. T. Li, Y. Yu, 2015: Causes of Strengthening and Weakening of ENSO Amplitude under Global Warming in Four CMIP5 Models, J. Climate, 28 (8), 3250-3274.


Xiang, B., M. Zhao, X. Jiang, S.-J. Lin, T. Li, X. Fu, and G. Vecchi, 2015: 3-4 week MJO prediction skill in a GFDL Coupled Model, J. Climate, in press.


Mei, S., T. Li, and W. Chen, 2015: Three Types of MJO Initiation Processes over the Western Equatorial Indian Ocean, Advances in Atmospheric Sciences, in press.