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14. ABSTRACT
This is a renewal proposal to extend a previously funded ONR seasonal prediction DRI project. The overall objective of this project is to demonstrate the capability of a global high-resolution model in reproducing/predicting both short-range weather events such as tropical cyclones (TC) and long-range climate variability such as Madden-Julian Oscillation (MJO). The first task is to conduct extended-range (10-30-day) TC predictions for whole TC seasons during 2004-2013. Secondly, by conducting the same 10-year hindcast experiments, we intend to systematically evaluate the model performance in predicting MJO.

15. SUBJECT TERMS

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TOWARD SEAMLESS WEATHER-CLIMATE PREDICTION WITH A GLOBAL HIGH RESOLUTION MODEL

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LONG-TERM GOAL

The long-term goal of this ONR seasonal predictability DRI 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

This is a renewal project that extends our previously funded ONR seasonal prediction DRI project. The overall objective of this project is to demonstrate the capability of the HiRAM model framework in reproducing/predicting both short-range weather events such as tropical cyclones (TCs) and long-range climate variability such as Madden-Julian Oscillation (MJO) and El Nino-Southern Oscillation (ENSO). During the past three years, we systematically evaluated the model performance in simulating the MJO variability and ENSO teleconnection patterns through improved convective scheme. We also conducted extended-range (beyond 7 days) forecast of Hurricane Sandy (2012) in North Atlantic and super typhoon Haiyan (2013) in western North Pacific (WNP). The results indicate that the genesis of both the super storms can be well predicted at 11-day lead, with a high possibility of detection (POD) rate and a low false alarm rate. The timing of landfall can be also predicted one week ahead for Sandy and two weeks ahead for Haiyan. The predictability sources for the beyond weather scale TC forecast arose from successful prediction of MJO and easterly waves in the model. Although being a case study, this work demonstrates potential capability of beyond weather scale prediction of TCs.

The goal of this renewal project is to extend the scope of the aforementioned case study by conducting extended-range (10-30-day) TC predictions for a whole TC season. By doing so, we intend to obtain statistically robust extended-range TC forecast skills.

APPROACH

The previous Sandy (2012) and Haiyan (2013) forecast experiments were just a case study, showing the potential capability of the HiRAM in extended-range prediction. To achieve a statistically robust result, we plan to conduct 10-30-day TC forecasts during the TC season (June-November) in the global domain for the period of 2003-2013 (11 years).

A nudging method will be used to obtain the initial condition, following Xiang et al. (2014). The atmospheric nudging fields include wind, sea level pressure (SLP), and temperature, and they are derived from National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) analysis data (~28km, 6-hour interval). Similar to Zhang et al. (2014), sea surface temperature (SST) will be nudged toward a SST analysis field derived from National Oceanic and Atmospheric Administration

(NOAA) Optimum Interpolation 1/4 Degree Daily SST Analysis (OISST, v2) (Reynolds et al. 2007).

Both the atmospheric and SST nudging restart files were achieved every two hour so that 12 members of forecasts (00z, 02Z, ..., 22Z) can be generated for each day. For each ensemble, we integrate the model for 50 days. The forecasts are made for 6 times (1^{st}, 6^{th}, 11st, 16^{th}, 21^{st}, and 26^{th}) each month.

There are total 657 tropical storms during the 11-yr period. To quantitatively measure the model cyclogenesis prediction skill, two traditional verification statistics are used, namely, possibility of detection (POD, or named hit rate) and false alarm ratio (FAR). The 'correct' prediction is counted by the cyclogenesis within +/- 2.5 days around the observed genesis time (i.e., a 5-day window) in a 900km radius centered at the observed genesis location. The false alarm cases are defined when cyclogenesis happens 5 days before or 5 days after the 'correct' prediction window within 900 km radius of circle. For details, readers are referred to Xiang et al. (2015).

A TC tracking scheme developed by Lucas Harris is used, in which TCs are detected based on the primary variable SLP. Another way is to detect TCs in the model using 850hPa vorticity (Zhao et al. 2009). A comparison shows that the two results are quite similar. Here the cyclogenesis is defined as the time when the TC first develops into a tropical storm (with winds >17.5 m/s in observations and 15.2 m/s in the model).

WORK COMPLETED

1. 11-yr hindcast experiments with HiRAM

TC extended-range hindcast experiments for the period of 2003-2013 were completed, using the HiRAM coupled model with a double-plume convective scheme. We just completed the draft of a manuscript, and it will be submitted soon. The main result is summarized below.

The diagnosis of 11-yr hindcast result shows that the global TC forecast skill is much lower than that of Haiyan (2013) and Sandy (2012). If defining the 25% hit rate as useful skill, then the skill for the global domain is only up to 6 days. If good prediction skill is defined when the hit rate exceeds 65% for week 1 or 50% for week 2, then about 30% of TCs within the 11 year period have good prediction skill. Most of these good forecasts occur in the tropical western North Pacific, tropical eastern North Pacific and tropical North Atlantic. For these good forecasts, the hit rate in average exceeds 50% up to 7 days.

A further diagnosis indicates that the good forecasts occur when the TCs are co-located with the active phases of MJO and synoptic-scale wave trains in the all three basins. On other words, predictability of TC genesis is largely found over tropical regions where the MJO and tropical waves are active. Thus, the extended-range predictability sources of TC genesis are linked to model predictability of low-frequency large-scale fields, including low-level vorticity, mid-level moisture, and vertical wind shear.

2. Diagnosis of MJO propagation from 27 global GCMs

In addition to the TC forecast experiment study mentioned above, we also investigated the fundamental causes of differences in MJO eastward propagation among 27 GCMs that participated in WMO MJOTF organized mulit-model inter-comparison project. These models are categorized into good and poor groups characterized by prominent eastward propagation and non-propagation, respectively. Column integrated moist static energy (MSE) budgets are diagnosed for the good and the poor models. It is found that a zonal asymmetry in the MSE tendency, characteristic of eastward MJO propagation, occurs in the good group, while such an asymmetry does not exist in the poor group. The difference arises mainly from anomalous vertical and horizontal MSE advection. The former is attributed to the zonal asymmetry of upper-middle tropospheric vertical velocity anomalies acting on background MSE vertical gradient; the latter is mainly attributed to the asymmetric zonal distribution of low-tropospheric meridional wind anomalies advecting background MSE/moisture field. Based on the diagnosis above, a new mechanism for MJO eastward propagation that emphasizes the second-baroclinic-mode vertical velocity is proposed.

Idealized model experiments with prescribed diabatic heating were conducted to investigate the causes of vertical velocity and horizontal wind differences between the good and the poor models. The numerical experiments reveal that the presence of a stratiform heating at the rear of MJO convection is responsible for the zonal asymmetry of vertical velocity anomaly and is important to strengthening lower-tropospheric poleward flows to the east of MJO convection. Thus, a key to improve the poor models is to correctly reproduce the stratiform heating. The relative roles of Rossby and Kelvin wave components in MJO propagation are also discussed.

3. Dependence of Tropical Cyclone Intensification on Coriolis Parameter

A theoretical model was advanced to understand how tropical cyclone (TC) intensification depends on the Coriolis parameter. A number of dynamic processes through which the Coriolis parameter affects TC growth were considered. Among them are the effect of low-level inflow on cyclonic vorticity acceleration and the impact of vorticity at top of planetary boundary layer to Ekman pumping induced ascending motion, the latter of which further influences mid-tropospheric condensational heating and low-level vorticity growth. Under a set of realistic parameter values, the model predicts the most preferred latitude location around 5° for TC growth.

The result from the simple theoretical model is confirmed by high-resolution WRF model simulations under a resting environment and a constant SST condition on an f plane. Given an initial balanced weak vortex, the perturbation intensifies most rapidly at the reference latitude of 5°. Neither a smaller or larger Coriolis parameter environment would lead to such a growth rate. Thus, the WRF model simulations confirm the f-dependence characteristics of TC intensification rate predicted by the theoretical model.

IMPACT/APPLICATIONS

The current effort may lead to the improved understanding of TC dynamics and the development of a next generation seamless 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 extended-range TC forecast capability may be transitioned into JTWC as a 6.2 or a 6.4 project.

RELATED PROJECTS

This project is complementary to a NRL project entitled "Interaction between tropical cyclone and monsoon gyre" in which we investigate two-way interactions between the synoptic-scale motion (including TC) and low-frequency atmospheric oscillation.

PUBLICATIONS

The following are published papers supported by this ONR grant:

Wang, L., T. Li, E. Maloney, and B. Wang, 2017: Fundamental Causes of Propagating and Non-propagating MJOs in MJOTF/GASS models. *J. Climate*, **30** (10), 3743-3769.

Deng L., T. Li and M. Peng, 2017: Dependence of Tropical Cyclone Intensification on Coriolis Parameter: A Simple Theoretical Model. *Dynamics of Atmospheres and Oceans*, in press.

Li, T. and P.-C. Hsu, 2017: Fundamentals of Tropical Climate Dynamics, Springer, ISBN 978-3-319-59595-5.

Zhu, Z., T. Li, L. Bai, and J. Gao, 2017: Extended-range forecast for the temporal distribution of clustering tropical cyclogenesis over the western North Pacific *Theoretical and Applied Climatology*, doi: 10.1007/s00704-016-1925-4.

Deng, L., and T. Li, 2016: Relative Roles of Background Moisture and Vertical Shear in Regulating Inter-annual Variability of Boreal Summer Intra-seasonal Oscillations. *J. Climate*, 29 (19), 7009-7025, doi:10.1175/JCLI-D-15-0498.1.

Wang, L., and T. Li, 2016: Roles of Convective Heating and Boundary-layer Moisture Asymmetry in Slowing Down the Convectively Coupled Kelvin Waves. *Clim. Dyn.*, 48(7), 2453-2469. DOI: 10.1007/s00382-016-3215-3.

Zhu, Z.-W., and T. Li, 2016: Empirical prediction of the onset dates of South China Sea summer monsoon. *Climate Dynamics*, 48, 1633-1645.

Yang, S.-Y., and T. Li, 2016: Intraseasonal variability of air temperature over the mid-high latitude Eurasia in Boreal Winter, *Clim.* Dyn., 47, 2155-2175.

<u>Manuscripts that have been submitted and are currently in revision</u>:

Jiang, X.-A., B. Xiang, M. Zhao, T. Li, et al., 2017: Extended-Range Tropical Cyclogenesis Prediction in a Coupled Global High-Resolution Model System. *J. Climate*, in revision.