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Toward Better Intraseasonal and Seasonal Prediction: Verification and Evaluation of the NAVGEM Model Forecasts

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LONG TERM GOALS

The long-term goal of this project is to understand the key physical processes for realistic simulation and skillful prediction of the intraseasonal variability and to improve the intraseasonal to seasonal prediction skills of the Navy's global numerical weather forecast models.

OBJECTIVES

Intraseasonal and seasonal prediction provides important information for decision-making and resource management, and has received increasing attention in recent years. Despite substantial progresses in numerical modeling in the past few decades, skillful seasonal prediction remains a challenge for many models. Verification and evaluation of model forecasts can offer users necessary information on the model prediction skills and reliability and provide model development teams with useful information on model improvements. In-depth analysis of the model forecasts can also help to better understand the key physical processes involved in intraseasonal variability and to identify new sources of predictability.

In the past year, we have been focusing on the following specific areas

i) Continue developing diagnostic tools to assess the representation of tropical cyclones in a global model;

ii) Investigate the possible error sources related to tropical cyclone prediction, especially the deficiencies of model physics;

iii) Evaluate the predictability of tropical cyclones on the subseasonal and seasonal time scales; explore new sources of predictability or new sources of variability for Atlantic tropical cyclone activity.

APPROACH

We used the GEFS reforecasts to develop and test the diagnostic tools. The GEFS reforecasts have the forecast lead time up to 16 days and available from 1985 to the present. The long time period makes it possible to construct meaningful statistics for extreme weather events. The products developed based on the GEFS can also be applied to other models and to forecasts with a longer lead-time.

Tropical cyclone-like vortices in the GEFS reforecasts are identified and tracked using the GFDL vortex tracker (Marchok 2002; Gall et al. 2011). The TC forecasts are evaluated against the IBTrACS data (Knapp et al. 2010), and the large-scale environmental conditions are evaluated against the ERA-Interim reanalysis. Satellite data are also used to evaluate precipitation processes in the model.

Tropical cyclone formation is a multi-scale process. The role of the large-scale environmental conditions in tropical cyclogenesis biases is examined using the genesis potential index (GPI; Emanuel and Nolan 2004). GPI is a function of the environmental variables and can serve as a proxy for genesis probability. Following Emanuel and Nolan (2004), it is defined as:

$$GPI = |10^5\eta|^{\frac{3}{2}}\left(\frac{RH}{50}\right)^3\left(\frac{PI}{70}\right)^3(1+0.1VWS)^{-2}$$

where η is 850-hPa absolute vorticity, RH is 700-hPa relative humidity (units: %), PI is the potential intensity (Emanuel 1995), and VWS is the 850-200-hPa vertical wind shear (vector difference). The role of synoptic-scale disturbances was examined as well.

WORK COMPLETED

In the past year we focused on the variability and prediction of tropical cyclones and completed the following tasks.

i) We continued developing diagnostic tools to evaluate tropical cyclone forecasts and examined the error sources and model deficiency that contribute to the TC genesis biases. A manuscript has been prepared and will be soon submitted to *Weather and Forecasting*.

ii) We continued investigating the impacts of RWB on Atlantic tropical cyclones. A strong correlation between the basin-wide RWB frequency and Atlantic tropical cyclones was found, and the mechanism for the impacts of RWB on Atlantic tropical cyclones were investigated. A manuscript has been conditionally accepted by *the Journal of Atmospheric Sciences*.

RESULTS

a) Biases in the Tropical cyclogenesis climatology

Although the GEFS captures the seasonality of tropical cyclogenesis reasonably well in different basins, large quantitative errors or regional errors exist (Fig. 1). Over the western North Pacific (WNP) and the eastern North Pacific, tropical cyclone counts are under-predicted; the center of action is also displaced southwestward over the eastern North Pacific. Over the Atlantic, although the climatology of the basin-wide tropical cyclone counts are skillfully reproduced by the GEFS, large errors exist on the regional scale: genesis is substantially overpredicted near the Cape Verde Islands but under-predicted over the rest of the basin (Fig. 2a).

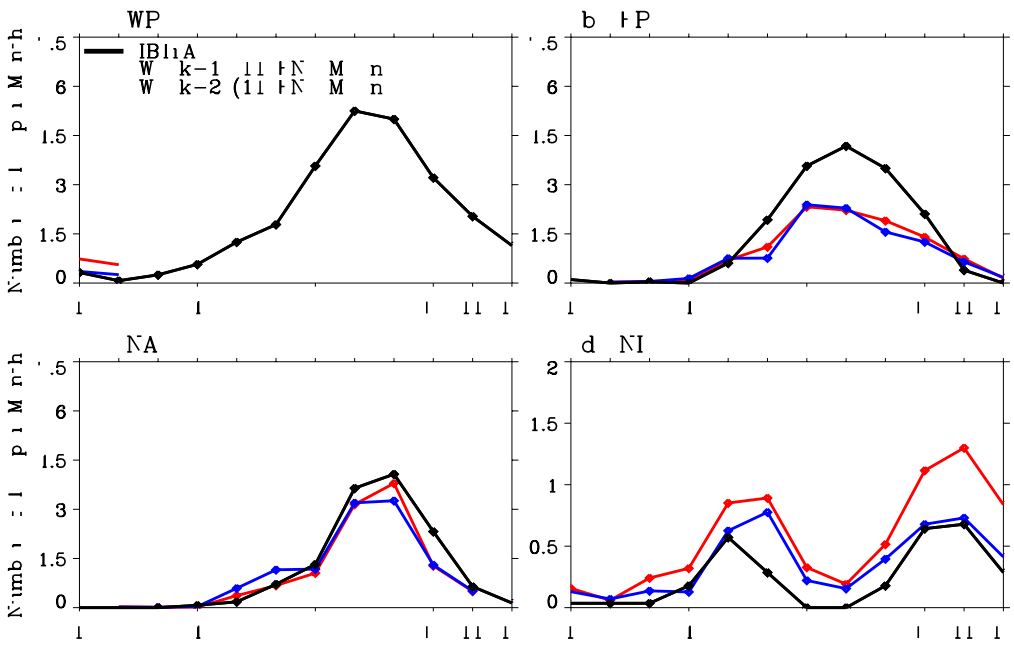


Figure 1 The seasonal variability of TCG frequency averaged over the period 1985-2012 . The black curves are the observed TC counts in the IBTrACS, and the red and blue curves show the GEFS Week-1 and -2 reforecasts.

The diagnosis using the GPI index suggests that the genesis biases over the WNP are associated with a weak monsoon trough in the GEFS (Fig. 2b). Over the WNP, 75% of tropical cyclones are generated under the monsoon trough environment, including the monsoon shear line, monsoon confluence region, and monsoon gyre (Ritchie and Holland 1999). The dynamic and thermodynamic conditions in a monsoon trough, such as the

low-level cyclonic vorticity and convergence, weak vertical wind shear, high midlevel relative humidity, are favorable to the formation and intensification of TCs (e.g., Holland 1995; Chen et al. 1996; Gray 1998). The negative biases in the low-level cyclonic vorticity and the mid-level relative humidity associated with the weak monsoon trough contribute to the negative genesis biases in the GEFS.

A primary genesis pathway over the eastern North Pacific is the ITCZ breakdown (*Wang and Magnusdottir 2005*). The eastern tip of the ITCZ is the most unstable region of the ITCZ, and plus interaction with topography, is a preferred location for genesis (Guinn and Schubert 1993; Zehnder and Powell 1999). The southwestward displaced genesis center can be attributed to the southward displaced ITCZ (Fig. 2c).

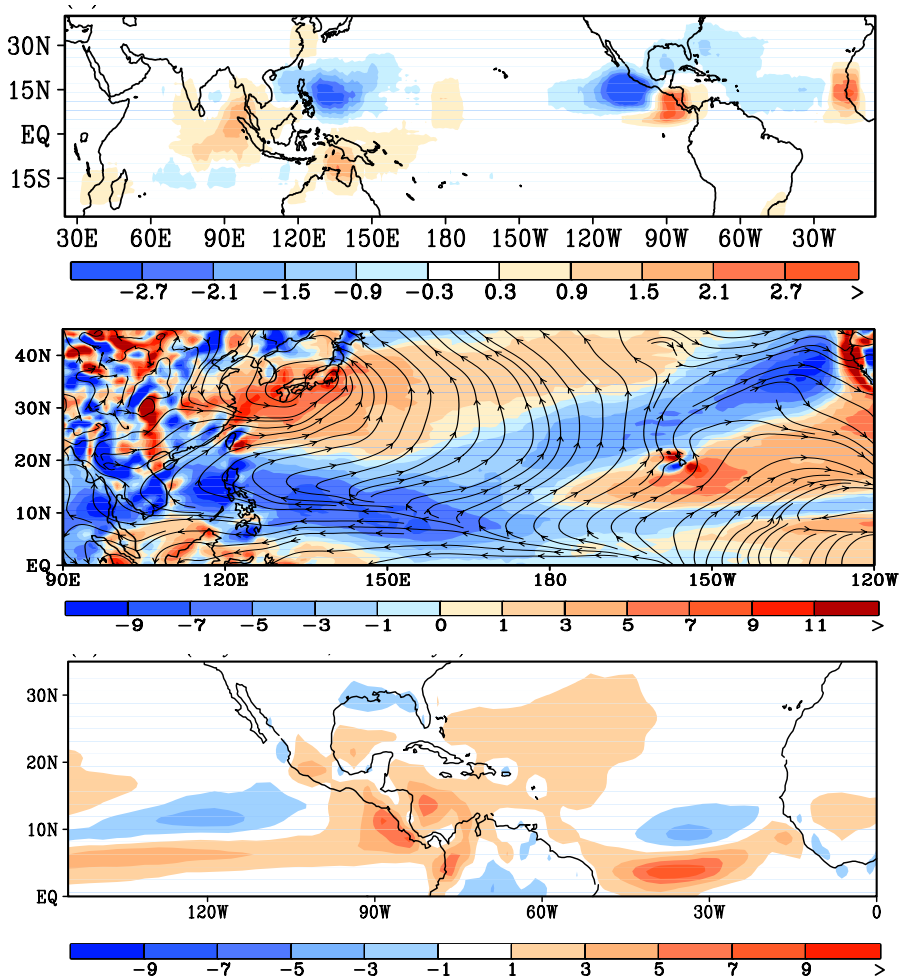


Figure 2 (top) Difference in the genesis density function between the GEFS Week-1 reforecasts and the IBTrACS; (middle) Difference in 850-hPa wind (streamlines) and relative vorticity (shading; 10^{-6} s^{-1}) between the GEFS 8-day forecasts and the ERA-Interim; (bottom) Difference in precipitation between the GEFS 8-day forecasts and GPCP (mm day^{-1}).

More than half of tropical cyclones over the Atlantic originated from African eastern waves (AEWs). AEWs play a particularly important role in genesis over the East Atlantic. We found that the positive biases near the Cape Verde Islands are closely related to errors in the structure of AEWs over West Africa. Compared to the ERA-Interim data, the GEFS analysis and forecasts both over-predict AEW activity in terms of the variance of the 850-hPa meridional wind (Fig. 3a). It was also found that AEWs have a deeper vertical structure and are associated with stronger diabatic heating in the GEFS than in the ERA-Interim (Fig. 3b-d). A wave of such a structure is more favorable for tropical cyclogenesis.

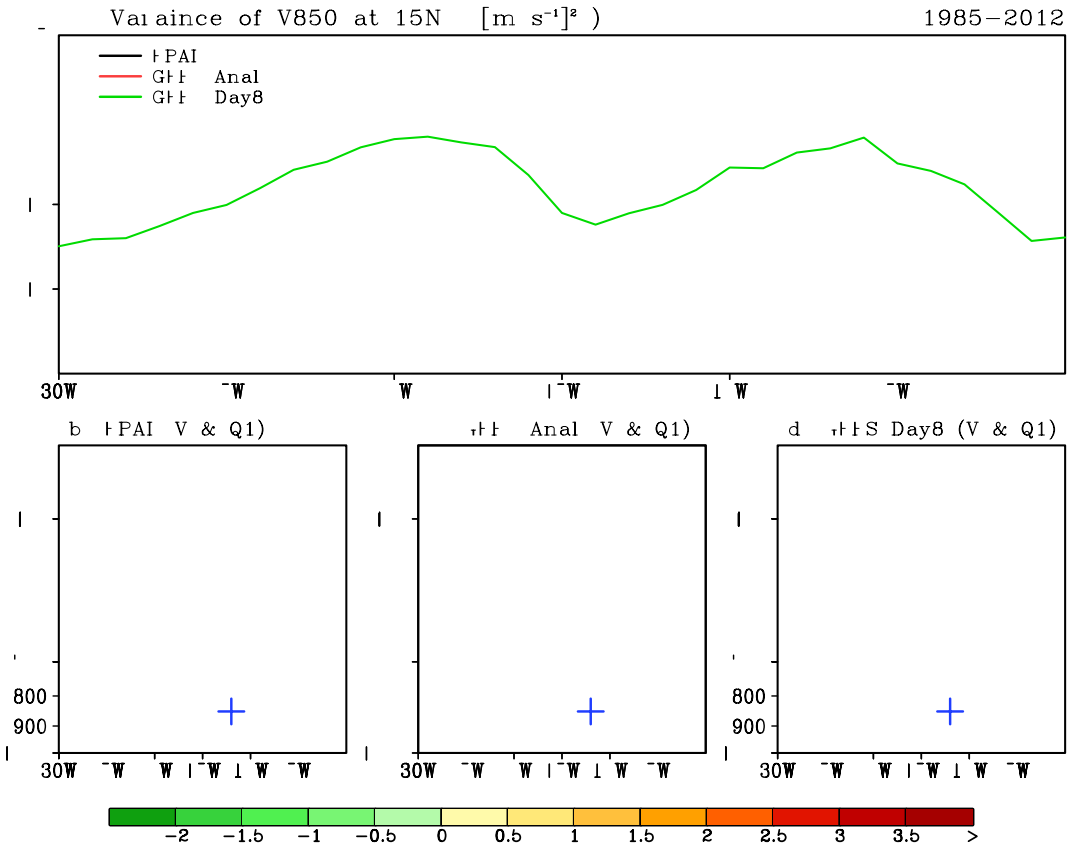


Figure 3 (a) the mean variance of daily 850-hPa meridional wind in the ERAI (black), the GEFS analysis (red), and the GEFS day-8 reforecast (green) in JASO for 1985-2012; (b) the longitude-height cross section of seasonal mean regressions of the daily meridional wind (shaded) and diabatic heating rate (Q1; contours starting at and with intervals of 0.4 K day^{-1} per m s^{-1}) against the daily 850-hPa meridional wind at a reference point (15ºN, 12ºW; in blue plus sign) in the ERAI; (c) and (d) as in (b) but for the GEFS analysis and day-8 reforecast.

In summary, tropical cyclogenesis is sensitive to both the large-scale circulation and the synoptic-scale precursors. As different tropical cyclogenesis pathways are dominant over different basins, the major error sources for tropical cyclone genesis and frequency are also different in different basins.

b) Possible error sources in the model physics

The evaluation of the moisture and precipitation in the GEFS suggest that precipitation initiates too early with respect to the column water vapor (CWV) (Fig. 4a), which explains the hyperactive convection over West Africa. Meanwhile, there is a substantial dry bias in the distribution of CWV (Fig. 4b). For example, the peak frequency occurs around 47 mm in the GEFS but around 57 mm in the observation. Given the nonlinear relationship between precipitation and the CWV, the negative biases in CWV lead to the significantly under-predicted frequency of occurrence of heavy precipitation in the GEFS. This leads to the negative precipitation biases and a weaker monsoon trough over the WNP.

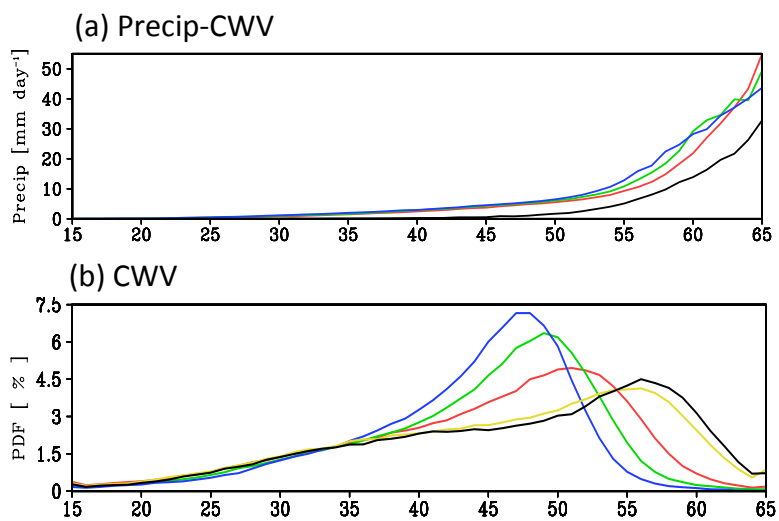


Figure 4 (a) The daily precipitation rate as a function of CWV over the Atlantic; (b) Histogram of CWV over the Atlantic. The black solid lines represent the SSM/IS, and the yellow, red, green and blue curves represent the GEFS analysis, 5-day, 10-day and 15-day forecasts, respectively.

Our analysis is consistent with the analysis by Chris Davis and Bill Kuo's work with the MPAS model using the same cumulus scheme, the simplified Arakawa-Schubert scheme (SAS). They also found that the SAS scheme produces too much transient, weak deep convection and too little intense, wide deep convection compared to the Tiedtke scheme (personal communication). Although other error sources may also contribute to the genesis biases, our diagnosis suggests that the deficiency in the cumulus scheme is likely the major culprit, and that an improved cumulus parameterization scheme will likely improve the basin-wide TC prediction and reduce the regional errors over the Atlantic.

c) Subseasonal Predictability of tropical cyclones

The Atlantic TC activity is significantly modulated by the MJO, which is the major source of subseasonal predictability (e.g., Maloney and Hartmann 2000; Mo 2000). The GEFS reforecasts out to 16 days provide a useful dataset to examine how well the inactive and active TC periods are captured by the model.

As an example, the time series of the weekly cyclone energy from the GEFS week-1 and week-2 reforecasts are compared with those derived from the IBTrACS in Fig. 5a. The Atlantic basin underwent three active periods of TC activity in 2000, mid-August, mid-September, and early-mid-October. The GEFS captures the peaks of weekly cyclone energy in August and early October but misses a primary peak in mid-September and a small peak mid-October. The overall performance can be objectively evaluated using the Pearson's correlation, which is 0.79 and 0.53 for the Week-1 and -2 reforecasts, respectively.

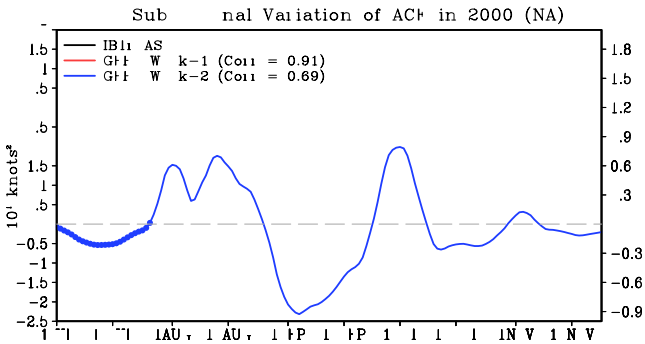


Figure 5 Subseasonal variations of the weekly cyclone energy from the IBTrACS (black curves), the GEFS Week-1 (red curves) and -2 (blue curves) reforecasts over the Atlantic.

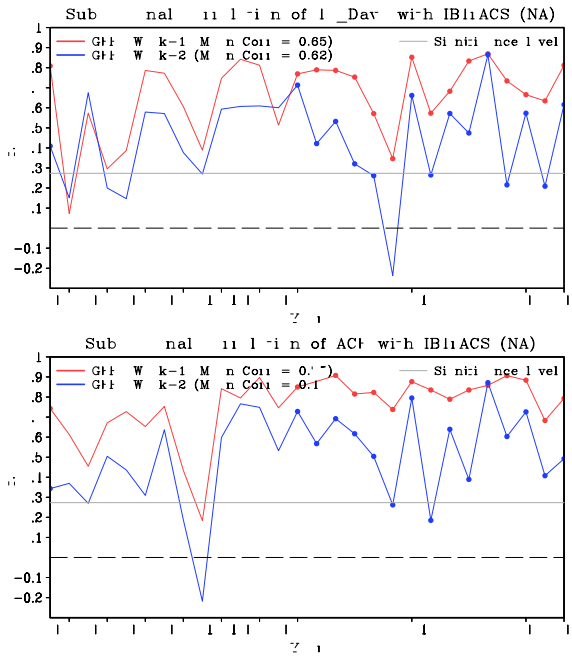
We can evaluate other years similarly, and the model skill is summarized by the Pearson's correlations between the observed and forecast time series of TC days or cyclone energy in each year (Fig. 6). The mean correlations of TC days (ACE) between the GEFS and the observation are 0.65 (0.75) in the Week-1 reforecasts, and 0.62 (0.49) in the Week-2 reforecasts. This suggests that the model has reasonable skill in predicting the active/inactive TC periods with lead time up to 7-14 days.

To examine how the prediction skill of TC subseasonal variation is modulated by different climate modes, Figure 7 shows the mean correlations stratified by different climate indices. It is shown that the prediction skill of the subseasonal TC variations is higher in years of active MJO and lower in years of inactive MJO for both the Week-1 and -2 reforecasts. The model tends to have higher skill during strong ENSO events, especially in the La Niña years. Strong an AMM year also tends to have higher correlations of the ACE in both Week-1 and -2 reforecasts. These results suggest that the low-frequency climate models provide a window of high predictability for the subseasonal variability of Atlantic tropical cyclones.

d) Impacts of RWB on Atlantic tropical cyclones

With warm SST anomalies in the tropical Atlantic and cold SST anomalies in the East Pacific, the unusually quite hurricane season in 2013 was a surprise to the hurricane community. Our analyses suggest that the substantially suppressed Atlantic tropical cyclone (TC) activity in August and early September can be attributed to frequent breaking of midlatitude Rossby waves, which led to the equatorward intrusion of cold

and dry extratropical air. The resultant middle to upper tropospheric dryness and strong vertical wind shear hindered TC development.



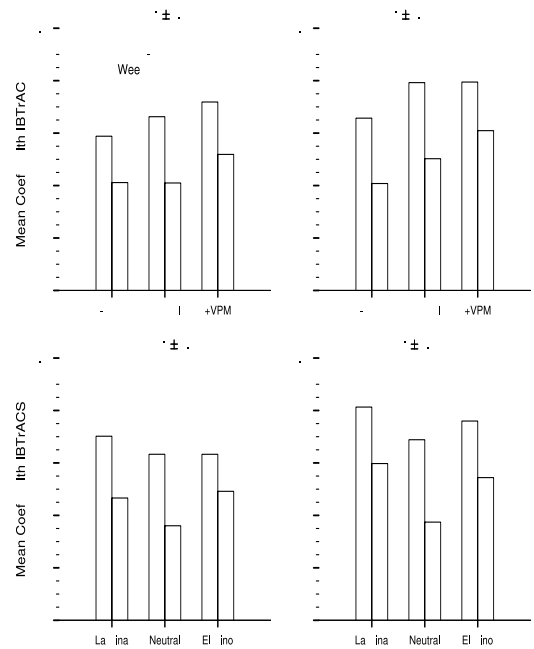


Figure 6 (Left) Time series of the Pearson's correlation of (top) TC days and (bottom) ACE between the GEFS Week-1 (red) and -2 (blue) reforecasts and the IBTrACS for each year from 1985-2012. The grey lines indicate the significance level using two-tailed t-test with 95% confidence. The degree of freedom was adjusted by "modified Chelton" method due to autocorrelation (Pyper and Peterman 1995).

Figure 7 (Right) The prediction skills stratified based on the MJO index and the Nino3.4 index.

An index was defined based on the basin-wide RWB frequency over the North Atlantic. A robust relation was found between the RWB frequency and Atlantic tropical cyclone activity during 1979-2012 using the ERA-Interim reanalysis and IBTrACS data. Frequent RWB over the North Atlantic leads to a significant reduction in the column water vapor and an increase in the vertical wind shear over the Atlantic MDR, and thus a decrease in the basin-wide hurricane count and accumulated cyclone energy. The composites based on the RWB index show a strong contrast between the active and inactive RWB years in tropical cyclone frequency, intensity and duration (Fig. 8). The correlation between the RWB index and Atlantic hurricane count is comparable to the correlation of Atlantic hurricane count with the MDR relative SST, and higher than that with the Niño 3.4 index (Table 1).

IMPACT/APPLICATIONS

Our studies contribute to a better understanding of the key physical processes for the intraseasonal and seasonal variability of tropical cyclones, which helps to improve the intraseasonal and seasonal prediction skill of the Navy's global models.

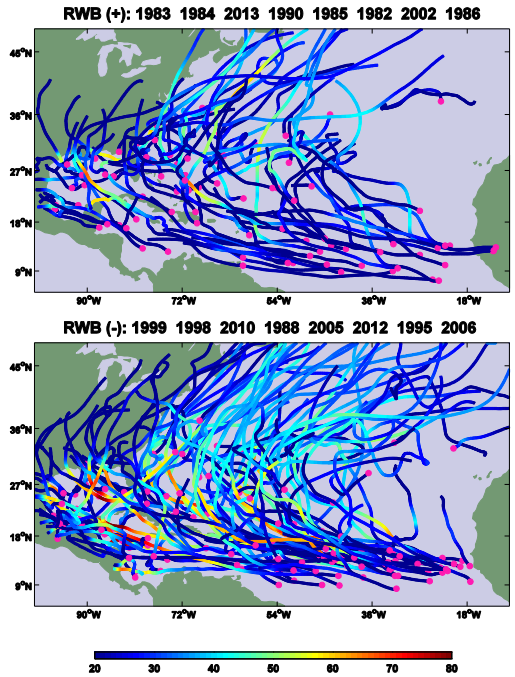


Table 1 TC and hurricane counts

	RWB+	RWB-
TC #	86	127
HURR#	29	70

Table 2 Correlation during July-Oct (1979-2013)

1979-2013	Hurr #	ACE
RWB	-0.68	-0.74
MDR SST	0.64	0.65
Nino3.4	-0.42	-0.37
AMO	0.60	0.61

Figure 8 Composites of tropical cyclones based on the RWB frequency index. Shading along tracks indicates the storm intensity.

TRANSITIONS

We worked with Dr. James A. Ridout, Dr. Ming Liu and Mr. Tim Whitcomb at the NRL, Monterey, and have transferred some diagnostic codes to the NRL modeling team. More diagnostic tools will be transferred to the NRL after proper documentation.

RELATED PROJECTS

This project is related to the other projects under the "Seasonal and Unified Parameterization" and "Seasonal Prediction" DRIs. The model evaluation tools developed can be used by other groups to diagnose the model physical processes and to evaluate the new parameterization schemes.

PUBLICATIONS

Zhang G., Z. Wang, T. Dunkerton, M. Peng and G. Magnusdottir, 2015: Extratropical Impacts on Atlantic Tropical Cyclone Activity, *J. Atmos. Sci.*, accepted after revision.

Li, W., Z. Wang and M. S. Peng, 2015: Evaluation of Tropical Intraseasonal Variability and Moist Processes in the NOGAPS Analysis and Short-Term Forecasts. *Wea. Forecasting*, to be submitted.

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