AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL078606

Special Section:
Bridging Weather and Climate: Subseasonal-to-Seasonal (S2S) Prediction

Relative Impacts of Local and Remote Forcing on Tropical Cyclone Frequency in Numerical Model Simulations

Chuan-Chieh Chang[1] and Zhuo Wang[1]

[1]Department of Atmospheric Sciences, University of Urbana-Champaign, Urbana, IL, USA

Key Points:
- The remote forcing, in particular extratropical processes, plays an important role in modulating Atlantic tropical cyclone (TC) frequency, and the influence may even exceed that of local sea surface temperature (SST) in some years
- In contrast to the Atlantic basin, tropical SST plays a dominant role in modulating the total TC frequency in the northern tropics

Supporting Information:
- Supporting Information S1

Correspondence to:
Z. Wang,
zhuowang@illinois.edu

Citation:
Chang, C.-C., & Wang, Z. (2018). Relative impacts of local and remote forcing on tropical cyclone frequency in numerical model simulations. *Geophysical Research Letters*, *45*, 7843–7850. https://doi.org/10.1029/2018GL078606

Received 2 MAY 2018
Accepted 13 JUL 2018
Accepted article online 23 JUL 2018
Published online 11 AUG 2018

Abstract Numerical experiments are carried out to explore the impacts of local and remote forcing on the interannual variability of tropical cyclone (TC) frequency. The first two groups of experiments focus on the regional simulations of Atlantic TCs, and the lateral boundary conditions and sea surface temperature (SST) are specified to investigate the relative importance of remote and local forcing. The results suggest that remote processes outside the North Atlantic, particularly extratropical processes, play an important role in modulating Atlantic TC frequency and that the remote impacts may exceed the impacts of local SST in some years. The total TC frequency in the northern tropics is explored in the third group of experiments. In contrast to the North Atlantic, tropical SST plays a dominant role in modulating the total TC frequency in the northern tropics. The difference may help to explain the uncertainties in the projections of future Atlantic TC frequency.

Plain Language Summary Skillful seasonal prediction of tropical cyclones (TCs) can help storm preparedness and mitigate their destructive impacts and is thus of profound socio-economic value. TC activity on the seasonal time scale is subject to local forcing associated with variability in tropical sea surface temperature (SST) and remote extratropical influence. Numerical model experiments are carried out to explore the impacts of local and remote forcing on the interannual variability of TC frequency. The experiments suggest that the remote forcing, in particular, extratropical processes, plays an important role in modulating Atlantic TC frequency and tropospheric variability and that the influence may even exceed that of local SST in some years. In contrast to the Atlantic basin, tropical SST plays a dominant role in modulating the total TC frequency over the northern tropics. The sensitivity of Atlantic TCs to extratropical processes may help explain the uncertainties in the projections of future Atlantic TC frequency.

1. Introduction

Tropical cyclones (TC) are one of the most severe storm systems on the Earth. Skillful seasonal prediction of TCs can help storm preparedness and mitigate their destructive impacts and is thus of profound socio-economic value. Seasonal prediction of Atlantic TCs has proven skillful in both dynamic models and statistical models in recent years (e.g., Chen & Lin, 2013; Klotzbach, 2007; Vecchi et al., 2011). In most models, tropical sea surface temperature (SST) is an important source of predictability. The relative SST (the difference between local SST and the tropical mean) is a particularly useful predictor for TC seasonal prediction or projection of TC activity in a changing climate (e.g., Swanson, 2008; Vecchi & Soden, 2007; Zhao et al., 2010). The effectiveness of tropical SST as a predictor for TC activity resides in its strong influence on atmospheric circulation and convection. The seminal study by Gill (1980) emphasized the equatorial wave response of the free troposphere to diabatic heating, which is closely related to tropical SST anomalies (Neelin & Held, 1987), especially in the western Pacific-Indian Ocean warm pool region (Wang & Li, 1993). Over the eastern oceans, where SST is relatively cool and the marine boundary layer is topped by the trade wind inversion layer, the boundary layer wind and low-level convergence are strongly influenced by the SST gradient (Battisti et al., 1999; Lindzen & Nigam, 1987). In addition, SST fronts can modulate the low-level wind and convergence via changes in static stability and vertical mixing (Chelton et al., 2004; Wallace et al., 1989).

Despite its strong influence on TC activity, tropical SST alone does not fully explain the variability of TC activity. For example, the 2013 Atlantic hurricane season was characterized by warm sea surface temperature anomalies (SSTAs) in the Atlantic main development region (MDR) and cold SSTAs in the East Pacific, but turned out to be one of the quietest seasons since 1994 (Blake, 2014). Zhang et al. (2016, 2017) suggested that the suppressed TC activity in 2013 can be attributed to active extratropical Rossby wave breaking

Table 1
Summary of the Experiments and Correlation Analysis

Exp. group	Experiment name	Surface temp.	Lateral boundary condition	Corr. w/obv	Corr. w/CTRL
Exp1	Exp1-2005	2005	2005	—	—
	Exp1-2013	2013	2013	—	—
	Exp1-SST05LBC13	2005	2013	—	—
Exp2	Exp2-CTRL	2000–2016	2000–2016	0.63	1.00
	Exp2-SST05	2005	2000–2016	0.42	**0.48**
	Exp2-LBC13	2000–2016	2013	0.22	0.25
Exp3	Exp3-CTRL	2000–2016	2000–2016	0.37	1.00
	Exp3-SST05	2005	2000–2016	0.41	−0.12
	Exp3-LBC13	2000–2016	2013	0.23	0.79

Note. The column "Corr. w/obv" lists the correlations of TC counts between the IBTrACS and the experiments in Groups 2 and 3 from 2000 to 2016, and the column "Corr. w/CTRL" lists the correlations of TC counts between a sensitivity test and the control run of the same group from 2000 to 2016. Correlations exceeding the 99% (95%) confidence level are underlined (in bold).

(RWB). Despite a synoptic-scale process, frequent RWB can induce significant large-scale circulation anomalies on the seasonal time scale via enhanced tropical-extratropical mixing and modulate TC activity.

Atlantic RWB is not only sensitive to extratropical processes, but is also related to SSTAs over the tropical Atlantic (Zhang & Wang, 2018). Although RWB can modulate atmospheric conditions over the tropical Atlantic independent of tropical SST (Zhang et al., 2017), the relative importance of the local SST versus remote forcing (particularly extratropical processes) on TC activity is not entirely clear. This study will investigate this issue through numerical model experiments.

2. Model and Experiment Design

The Weather Research and Forecasting model (WRF; Skamarock et al., 2008) is used to conduct seasonal simulations. The model has 40 vertical levels in the terrain-following σ coordinates. The simulations adopt the Yonsei University planetary boundary layer parameterization (Hong et al., 2006), the rapid radiative transfer model of longwave radiation (Mlawer et al., 1997), and the shortwave radiation scheme developed by Dudhia (1989). The initial conditions, lateral boundary conditions (LBCs), and SST fields are derived from the National Centers for Environmental Prediction Final Operational Global Analysis (NCEP FNL) at $1° \times 1°$ resolution, and the LBCs and SST fields are updated every 12 hr.

Three groups of experiments are carried out (Table 1), denoted as Exp (*i*)-XX, where *i* is the experiment group number and XX indicates the surface temperatures and LBCs used for the experiment. The model is run at 9-km horizontal grid spacing without any cumulus parametrization over the North Atlantic-West Africa sector (2°–51°N, 112°W–2°E) in the first and second groups of experiments. The third group of experiments employs a tropical channel domain (0°–35° N) at a coarser grid spacing (18 km) with the Kain-Fritsch cumulus scheme (Kain & Fritsch, 1993), and the total TC frequency in the northern hemisphere is examined in addition to individual basins. In Group 1, Exp1-2005 and Exp1-2013 simulate the Atlantic hurricane seasons in 2005 and 2013, respectively. In contrast to 2013, the Atlantic hurricane season in 2005 had the record-breaking high TC activity, which can be attributed to warm SSTAs over the tropical Atlantic (supporting information Figure S1; Beven et al., 2008). A mixed experiment (Exp1-SST05LBC13), with LBCs taken from 2013 and surface temperature from 2005, is carried out to examine the relative impacts of local and remote forcing on Atlantic TC frequency. To test the robustness of the results, six ensemble simulations are carried out for each experiment with different initial conditions or microphysics schemes (see the supporting information). All members are integrated from late July to 31 October.

In the second group of experiments, the hurricane seasons during 2000–2016 are simulated to evaluate whether the findings derived from Group 1 experiments can be generalized for other years. For each hurricane season, the model is integrated from July 20 to October 31 with Goddard microphysics (Tao et al., 1989), which produces TC counts closest to the observation in Exp1-2005 and Exp1-2013 (not shown). The control experiment (Exp2-CTRL) is forced by the observed surface temperature and LBCs in each year. In Exp2-SST05, the surface temperature from 2005 is used to force the model while the LBCs are still taken

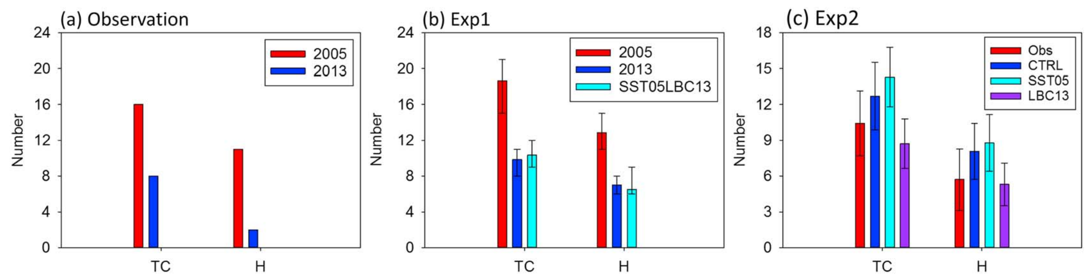

Figure 1. Tropical cyclone counts and hurricane counts from (a) the IBTrACS, (b) Experiment Group 1, and (c) Experiment Group 2. The bars in (b) are the ensemble mean with whiskers showing the ensemble range; the bars in (c) are the average over 2000–2016 with whiskers indicating the interannual standard deviation. IBTrACS = International Best Track Archive for Climate Stewardship.

from individual years during 2000–2016. In Exp2-LBC13, the LBCs from 2013 are used along with surface temperatures from 2000 to 2016. The three experiments in Group 3 are the same as those in Group 2 except that the tropical channel domain (0°–35°N) is used to further clarify the relative influence of tropical and extratropical processes on TCs. In the three groups of experiments, a buffer zone is used along the model lateral boundaries to mitigate the incompatibility when surface temperatures and LBCs from different years are used to force the model (see the supporting information).

A tracker algorithm is used to detect TCs in the model simulations (see the supporting information). TCs are first tracked in individual simulations, and the TC statistics based on the ensemble mean in Group 1 or the long-term mean (2000–2016) in Groups 2 and 3 are presented in section 3. The International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al., 2010) and the FNL analysis are used to evaluate the model simulations. Since the model resolutions are not sufficient to resolve intense hurricanes, we mainly focus on TC frequency. Our analyses cover the time period from 1 August to 31 October, and the simulation in late July is excluded as the model spin-up stage.

For the convenience of discussion, we refer to the impacts of processes outside the model domains via LBCs as the remote forcing, and the direct impacts of the SST within the model domains as the local forcing, although SSTAs in a model domain may have remote impacts on the large-scale circulation outside the domain.

3. Results

3.1. Experiment Group 1: 2005 Versus 2013

The storm counts from the observation and model simulations are shown in Figures 1a and 1b, respectively. Compared to the observation, the model slightly overestimates TC and hurricane counts in both 2005 and 2013, which may be partly attributed to the lack of air-sea interaction (Bender & Ginis, 2000). Nevertheless, the model reasonably reproduces the observed contrast between 2005 and 2013. Few TCs originate from the western MDR in Exp1-2013 (Figure S2c), consistent with the observation (Figure S2a). The ensemble mean TC counts are 18.7 and 9.8 for 2005 and 2013, respectively, and the TC counts in ensemble members are well separated between the two years (Figure 1b). A similar contrast in hurricane counts is also reproduced by the model.

Surprisingly, TC frequency in Exp1-SST05LBC13 is similar to that in Exp1-2013 despite different SST and is substantially suppressed compared to Exp1-2005 (Figures 1b and S2). This suggests that the remote forcing via LBCs exerts a stronger influence on Atlantic TCs than the direct influence of local SST in this experiment.

To better understand the local versus remote impacts, the differences in vertical wind shear (VWS, defined as the magnitude of the vector wind difference between 200 and 850 hPa) and 600-hPa relative humidity (RH) between 2005 and 2013 are examined. According to the FNL analysis, the hurricane season in 2013, when compared to 2005, is characterized by enhanced VWS (with differences up to 7 m s^{-1}) over the Gulf of Mexico and the MDR and reduced RH over the central and western MDR and east of Florida (Figures 2a and 2b). Such differences contribute to the substantially suppressed TC activity in 2013. Exp1-2005 and

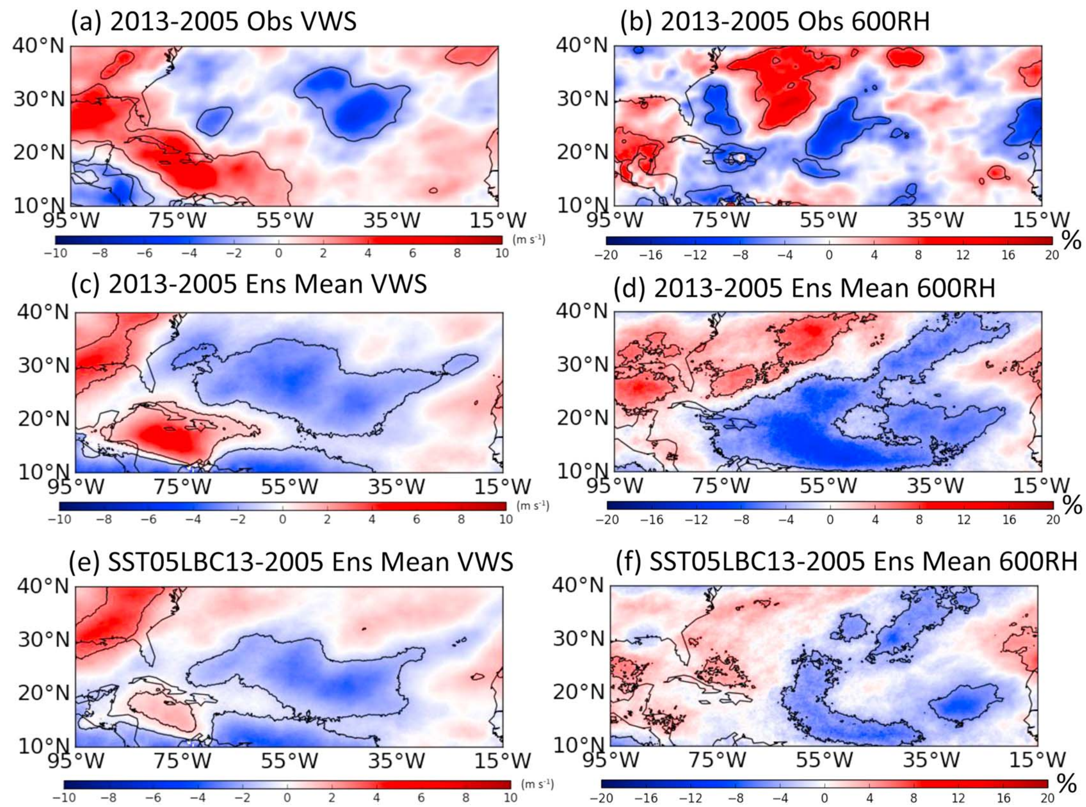

Figure 2. The difference in VWS (m s^{-1}) and 600-hPa RH (%) between 2005 and 2013 from the FNL analysis (top), between Exp1-2005 and Exp1-2013 (middle), and between Exp1-2005 and Exp1-SST05LBC13 (bottom). Black contours highlight the differences above the 99% confidence level.

Exp1-2013 broadly reproduce the observed differences between the two years, including the enhanced VWS in the Caribbean and reduced RH in the central and western MDR in 2013 (Figures 2c and 2d). However, the model fails to reproduce the VWS differences over the central MDR and underestimates the VWS differences over the West Atlantic. Furthermore, the RH differences over the central MDR are overestimated by the model.

The differences between Exp1-SST05LBC13 and Exp1-2005 are also examined (Figures 2e and 2f). The VWS in Exp1-SST05LBC13 generally resembles that in Exp1-2013, including the enhanced VWS over the southeastern United States and the Caribbean and the reduced VWS over the subtropical Atlantic compared to Exp1-2005, but Exp1-SST05LBC13 fails to reproduce the enhanced VWS in the central and eastern MDR. The pattern of RH difference resembles that in Figure 2d, but with a smaller magnitude. The differences between Exp1-SST05LBC13 and Exp1-2013 can be attributed to SSTAs, which modulate the atmospheric conditions, including local baroclinicity and humidity.

To quantify the role of remote forcing in modulating the North Atlantic circulation, pattern correlation coefficients (PCCs) of various variables are calculated between the simulations and the FNL analysis. A 7-day running mean filter is applied to the daily data to remove high-frequency fluctuations, and PCCs are then calculated on each day between 1 August and 31 October. The ensemble mean PCCs are shown in Figure 3a. Exp1-2013 is more skillful in reproducing the observed 200- and 850-hPa zonal winds (U) and 500-hPa RH than Exp1-2005, which can probably be attributed to the stronger lateral boundary forcing associated with a large-scale Rossby wave train spanning from North America to the North Atlantic in 2013 (Bell et al., 2014). Meanwhile, Exp1-2005 is more skillful in reproducing the 850-hPa RH, possibly owing to the influence of the strong SSTAs in 2005.

Furthermore, the PCCs of different variables in Exp1-SST05LBC13 are calculated with the FNL in 2005 and 2013, respectively, to assess the relative influences of remote and local forcing on the Atlantic atmospheric circulation. Specifically, if tropospheric variabilities are mainly controlled by the remote forcing, Exp1-

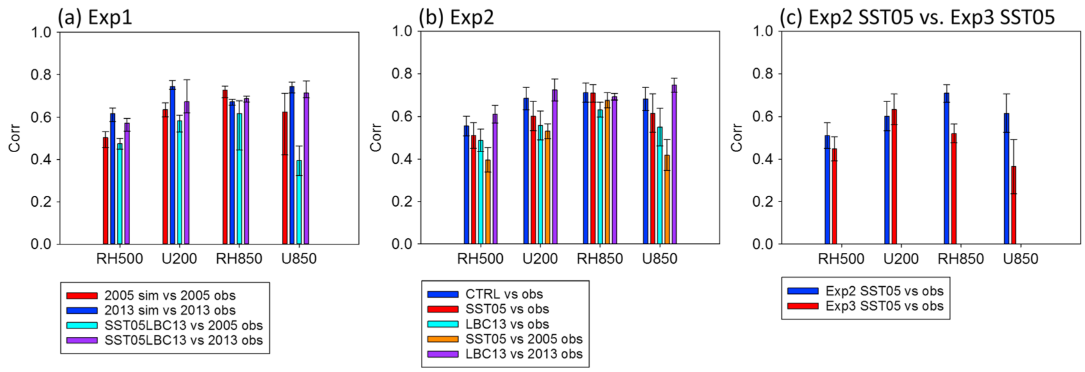

Figure 3. PCCs of various variables between the FNL analysis and model experiments from (a) Group 1, (b) Group 2, and (c) the comparison between Exp2-CTRL and Exp3-CTRL. All PCCs are calculated with 7-day running mean daily data over the tropical-subtropical Atlantic (10°–30°N, 20°–90°W) and averaged over 1 August to 31 October. The ensemble means are taken for Group 1, and the long-term means over 2000–2016 are taken for Groups 2 and 3. The whiskers indicate the ensemble range of PCCs in (a), and the interannual standard deviation in (b) and (c). PCC = pattern correlation coefficient.

SST05LBC13 should have stronger PCCs with the FNL in 2013 than in 2005, and vice versa. As shown in Figure 3a, the PCCs between Exp1-SST05LBC13 and the FNL in 2013 are consistently higher than those between Exp1-SST05LBC13 and the FNL in 2005. It is also found that TC genesis locations in Exp1-SST05LBC13 are similar to those in Exp1-2013 (Figure S2). Overall, the first group of experiments suggests that remote processes may have a strong influence on the atmospheric circulation and TC frequency over the Atlantic.

3.2. Experiment Group 2: Regional Simulations (2000–2016)

To test whether the finding of the strong remote influence can be generalized for other years, the hurricane seasons from 2000 to 2016 are simulated in the second group of experiments. The observed surface temperature in 2005 and LBCs in 2013 are chosen to represent strong local and remote forcing, respectively, and three experiments are carried out (Table 1). The cyclogenesis pattern in Exp2-CTRL is broadly consistent with that observed (Figures S3a and S3b). Although Exp2-CTRL slightly overestimates TC and hurricane counts (Figure 1c), it reproduces the TC interannual variability skillfully. The correlation of TC counts between Exp2-CTRL and the IBTrACS is 0.63 (Table 1), above the 99% confidence level. As expected, TC and hurricane counts are both reduced when the LBCs in 2013 are used (Exp2-LBC13) and are increased when the SST in 2005 are specified (Exp2-SST05). The reduced TC genesis in Exp2-LBC13 mainly occurs in the MDR (Figure S3d). The correlation of TC counts is reduced to 0.42 between Exp2-SST05 and the IBTrACS and is even weaker (0.22) between Exp2-LBC13 and the IBTrACS (Table 1). This suggests that both the local SST and remote forcing modulate Atlantic TC frequency and that remote forcing exerts a stronger influence than the local SST in the context of the model setup. Further calculations show that RWB occurrence is enhanced in Exp2-LBC13 (Figure S4), in agreement with the reduced TC activity (Zhang et al., 2017).

PCCs are calculated between the experiments and the FNL to assess the relative impacts of remote and local forcing on the tropospheric variability (Figure 3b). PCCs are reduced in both Exp2-LBC13 and Exp2-SST05 compared to Exp2-CTRL, but the reduction is larger in Exp2-LBC13, again suggesting that the remote forcing has a stronger influence on Atlantic tropospheric variability than the local SST. This point is further supported by the PCCs between Exp2-LBC13 and the FNL in 2013 and the PCCs between Exp2-SST05 and the FNL in 2005: The former set of correlations are much stronger than the latter.

It is generally accepted that climate modeling is strongly dependent on the lower boundary conditions (especially SST), which are an important source of predictability for the atmosphere on the subseasonal and seasonal time scales (Branković et al., 1994). Accordingly, the realistic representation of SST is regarded essential for the skillful seasonal TC prediction (e.g., Vecchi et al., 2014; Zhao et al., 2010). However, our results suggest that remote forcing (both extratropical and tropical) might play a more important role than local SST in modulating Atlantic TC activity in some years, at least in the context of the model setup.

3.3. Experiment Group 3: Tropical Channel Simulations (2000–2016)

In the previous two subsections, we simply refer to the processes outside of the model domain as remote forcing. This remote forcing includes extratropical processes from the north, tropical forcing from the east and west, and the possible influence from the South Atlantic. The lack of predictors in the South Atlantic in statistical models (e.g., Gray et al., 1993) implies that the influence from the South Atlantic is likely weak. A recent study suggests that African easterly waves do not affect the seasonal mean, basin-wide Atlantic TC activity (Patricola et al., 2018). However, the forcing via the west boundary includes the influence of the El Niño–Southern Oscillation and is not negligible (e.g., Goldenberg & Shapiro, 1996). To further investigate the tropical versus extratropical influence on TC frequency, we adopt the tropical channel configuration of the WRF (e.g., Ray et al., 2012) in Group 3 and carry out three experiments similar to those in Group 2 (Table 1). The total TC activity in the northern tropics enclosed by the model domain is modulated by tropical SST and the processes from the northern extratropics and the Southern Hemisphere. The latter is collectively referred to as the remote forcing, although these processes may be affected by SST in the northern tropics.

The model reproduces the long-term mean TC counts over the North Atlantic, the East Pacific, and the Indian Ocean generally well (not shown). Due to biases in the large-scale circulation, TC frequency over the western North Pacific is overestimated by ~200% (a similar issue also found in Ray et al., 2012). To mitigate this issue, we first rescale the basin-wide TC counts over individual basins based on observation (see the supporting information) and then calculate the total TC counts using the rescaled TC counts over individual basins. In the following analysis, we will focus on the TC interannual variability.

The correlation of the TC counts between the Exp3-CTRL/Exp3-SST05/Exp3-LBC13 and the IBTrACS are all below the 95% confidence level (Table 1). However, the strong correlation of TC counts between Exp3-CTRL and Exp3-LBC13 (0.79), in contrast to the much weaker correlation between Exp-CTRL and Exp3-SST05 (−0.12), suggests that the total TC frequency over the northern tropics are strongly modulated by tropical SST while the impacts of the remote forcing are negligible. Regarding the individual basins, Exp3-CTRL better reproduces the TC variability over the North Atlantic ($r = 0.54$) and the East Pacific ($r = 0.63$) than over the western North Pacific ($r = 0.40$; Table S1). In addition, the strong positive correlation (0.93) of TC counts between Exp3-CTRL and Exp3-LBC13 over the East Pacific, in contrast to the negative correlation between Exp-CTRL and Exp3-SST05 (−0.28), indicates the prominent influence of tropical SST on TC variability over the East Pacific, which is different from the Atlantic basin. The remote forcing plays an important role in modulating Atlantic TC frequency, as indicated by the higher correlation of Atlantic TC counts ($r = 0.32$) between Exp3-CTRL and Exp3-SST05 than the nearly zero correlation ($r = -0.03$) between Exp3-CTRL and Exp3-LBC13 (Table S1).

To further investigate the tropical versus extratropical remote forcing on Atlantic TCs, the PCCs between Exp2-SST05 and the FNL are compared to those between Exp3-SST05 and the FNL over the Atlantic (Figure 3c). The Atlantic atmospheric circulation in Exp2-SST05 and Exp3-SST05 is both forced by the SST in 2005 and the year-to-year varying remote forcing from the north and south boundaries (although the latitudinal locations of the boundaries are not the same in the two experiments). The major difference lies in the west and east boundaries of the Atlantic basin, which are specified in Exp2-SST05 and generated by the model in Exp3-SST05. Similarity between the experiments and the FNL, as evaluated by PCCs, can be attributed to the remote forcing via the north and south boundaries. Additionally, similarity between the two experiments, which can also be evaluated in terms of their PCCs with the FNL, would imply a minor role of the remote forcing from the west and east. As shown in Figure 3c, Exp2-SST05 and Exp3-SST05 have similar PCCs for RH500 and U200, but a large reduction of PCC is found for RH850 and U850 in Exp3-SST05. This suggests that the remote forcing from the east and west has a stronger influence in the lower troposphere while extratropical processes have a stronger influence in the middle and upper troposphere.

4. Summary and Discussion

Three groups of numerical experiments are carried out to investigate the importance of local and remote forcing on TC frequency. The first two groups of experiments focus on the regional simulations of Atlantic TCs, and the third group examines the TC activity in the northern tropics using a tropical channel configuration. The first group of experiments reproduce the active hurricane season in 2005 and the inactive season in 2013 when driven by the observed surface temperature and LBCs from the corresponding years. The mixed simulations, with surface temperature from 2005 and LBCs from 2013, resemble the 2013 simulations, which implies the strong influence of remote forcing on Atlantic TCs. The hurricane seasons from 2000 to 2016 are simulated in the second group of experiments. The interannual variability of Atlantic TC frequency is skillfully simulated by the control run as indicated by the correlation between the observed and simulated TC counts (r = 0.63). The correlation is reduced when the LBCs are set to 2013 (r = 0.22) or the surface temperature is set to 2005 (r = 0.42). This suggests that the remote and local impacts both modulate Atlantic TC frequency, and the larger reduction of correlation in Exp2-LBC13 suggests that the remote forcing may have stronger impacts on Atlantic TCs than the local SST. Pattern correlation analysis further suggests that the tropospheric variability is strongly modulated by remote forcing. The tropical channel experiments in Group 3 fail to skillfully simulate the interannual variability of the total TC counts in the northern tropics. However, the strong correlation of TC counts between Exp3-CTRL and Exp3-LBC13, which have the same SST forcing but different LBCs, suggests that tropical SST plays a dominant role in modulating the total TC activity over the northern tropics, in contrast to the Atlantic basin.

The experiments suggest that the remote forcing plays an important role in modulating Atlantic TC activity and that the influence may even exceed that of local SST in some years. However, the results should not be interpreted as that the influence of tropical SST on Atlantic TC activity is not important. It is worth noting that 2013 is characterized by very active RWB over the North Atlantic and that such strong extratropical influence does not exist in every year.

Some results in this study may be sensitive to the model configuration. In particular, it is conceivable that LBCs may have a weaker control on regional model simulations if the model domain is larger. This helps to explain the difference in the local versus remote control on TC activity between the Atlantic basin and the northern tropics, but we suspect that the differences are also tied to the forcing mechanisms of TC variability in different basins. For example, TC variability tends to be out-of-phase between the North Atlantic and the East Pacific (e.g., Wang & Lee, 2009; Zhang & Wang, 2015). Such TC variations are partly canceled when the northern tropics is considered as a whole, so the regional TC variability may not be closely related to the global TC variability. In addition, TCs are strongly modulated by the El Niño–Southern Oscillation in the East Pacific (e.g., Jin et al., 2014; Zhang & Wang, 2015) and are closely tied to the monsoon activity over the western North Pacific (e.g., Ritchie & Holland, 1999). Extratropical influence may thus be relatively weak in these basins. The sensitivity of Atlantic TCs to extratropical processes may help to explain the uncertainties in the projections of future Atlantic TC activity.

Acknowledgments
The study is supported by NOAA grant NA16OAR4310080 and NRL grant N00173-15-1-G004. Computational resources were provided by the National Center for Atmospheric Research, Computational and Informational Systems Laboratory. The NCEP FNL is available at https://rda.ucar.edu/datasets/ds083.2. The authors thank two anonymous reviewers for their constructive comments that helped improve the manuscript.

References

Battisti, D. S., Sarachik, E. S., & Hirst, A. C. (1999). A consistent model for the large scale steady surface atmospheric circulation in the Tropics. *Journal of Climate*, *12*(10), 2956–2964. https://doi.org/10.1175/1520-0442(1999)012<2956:ACMFTL>2.0.CO;2

Bell, G. D., Landsea, C. W., Goldenberg, S. B., Pasch, R. J., Blake, E. S., Schemm, J., & Kimberlain, T. B. (2014). The 2013 North Atlantic hurricane season: A climate perspective [in "State of the Climate in 2013"]. *Bulletin of the American Meteorological Society*, *95*(7), S86–S90.

Bender, M. A., & Ginis, I. (2000). Real-case simulations of hurricane—Ocean interaction using a high-resolution coupled model: Effects on hurricane intensity. *Monthly Weather Review*, *128*(4), 917–946. https://doi.org/10.1175/1520-0493(2000)128<0917:RCSOHO>2.0.CO;2

Beven, J. L., Avila, L. A., Blake, E. S., Brown, D. P., Franklin, J. L., Knabb, R. D., et al. (2008). Atlantic hurricane season of 2005. *Monthly Weather Review*, *136*(3), 1109–1173. https://doi.org/10.1175/2007MWR2074.1

Blake, E. S. (2014). 2013 Atlantic hurricane season. *National Hurricane Center Annual Summary* (9 pp.).

Branković, Č., Palmer, T. N., & Ferranti, L. (1994). Predictability of seasonal atmospheric variations. *Journal of Climate*, *7*(2), 217–237. https://doi.org/10.1175/1520-0442(1994)007<0217:POSAV>2.0.CO;2

Chelton, D. B., Schlax, M. G., Freilich, M. H., & Milliff, R. F. (2004). Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, *303*(5660), 978–983. https://doi.org/10.1126/science.1091901

Chen, J.-H., & Lin, S.-J. (2013). Seasonal predictions of tropical cyclones using a 25-km-resolution general circulation model. *Journal of Climate*, *26*(2), 380–398. https://doi.org/10.1175/JCLI-D-12-00061.1

Dudhia, J. (1989). Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of the Atmospheric Sciences*, *46*(20), 3077–3107. https://doi.org/10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2

Gill, A. E. (1980). Some simple solutions for heat-induced tropical circulation. *Quarterly Journal of the Royal Meteorological Society*, *106*(449), 447–462. https://doi.org/10.1002/qj.49710644905

Goldenberg, S. B., & Shapiro, L. J. (1996). Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *Journal of Climate*, *9*(6), 1169–1187. https://doi.org/10.1175/1520-0442(1996)009<1169:PMFTAO>2.0.CO;2

Gray, W. M., Landsea, C. W., Mielke, P. W., & Berry, K. J. (1993). Predicting Atlantic Basin seasonal tropical cyclone activity by 1 August. *Weather and Forecasting*, *8*(1), 73–86. https://doi.org/10.1175/1520-0434(1993)008<0073:PABSTC>2.0.CO;2

Hong, S.-Y., Dudhia, J., & Chen, S.-H. (2004). A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Monthly Weather Review*, *132*(1), 103–120. https://doi.org/10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2

Hong, S.-Y., & Lim, J.-O. (2006). The WRF Single-Moment 6-class Microphysics Scheme (WSM6). *Journal of the Korean Meteorological Society*, *42*, 129–151.

Hong, S.-Y., Noh, Y., & Dudhia, J. (2006). A new vertical diffusion package with explicit treatment of entrainment processes. *Monthly Weather Review*, *134*(9), 2318–2341. https://doi.org/10.1175/MWR3199.1

Jin, F.-F., Boucharel, J., & Lin, I.-I. (2014). Eastern Pacific tropical cyclones intensified by El Niño delivery of subsurface ocean heat. *Nature*, *516*(7529), 82–85. https://doi.org/10.1038/nature13958

Kain, J. J., & Fritsch, J. M. (1993). Convective parameterization for mesoscale models: The Kain–Fritsch scheme. In *The representation of cumulus convection in numerical models, meteor. monogr., no. 46*, *Amer. Meteor. Soc.* (pp. 165–170). Boston, MA: American Meteorological Society.

Klotzbach, P. J. (2007). Revised prediction of seasonal Atlantic Basin tropical cyclone activity from 1 August. *Weather and Forecasting*, *22*(5), 937–949. https://doi.org/10.1175/WAF1045.1

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2010). The International Best Track Archive for Climate Stewardship (IBTrACS). *Bulletin of the American Meteorological Society*, *91*(3), 363–376. https://doi.org/10.1175/2009BAMS2755.1

Knutson, T. R., Sirutis, J. J., Garner, S. T., Held, I. M., & Robert, E. T. (2007). Simulation of the recent multidecadal increase of Atlantic hurricane activity using an 18-km-grid regional model. *Bulletin of the American Meteorological Society*, *88*(10), 1549–1565. https://doi.org/10.1175/BAMS-88-10-1549

Lindzen, R. S., & Nigam, S. (1987). On the role of sea surface temperature gradients in forcing low-level winds and convergence in the Tropics. *Journal of the Atmospheric Sciences*, *44*(17), 2418–2436. https://doi.org/10.1175/1520-0469(1987)044<2418:OTROSS>2.0.CO;2

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., & Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research*, *102D*, 16,663–16,682.

Neelin, J. D., & Held, I. M. (1987). Modeling tropical convergence based on the moist static energy budget. *Monthly Weather Review*, *115*(1), 3–12. https://doi.org/10.1175/1520-0493(1987)115<0003:MTCBOT>2.0.CO;2

Patricola, C. M., Saravanan, R., & Chang, P. (2018). The response of Atlantic tropical cyclones to suppression of African easterly waves. *Geophysical Research Letters*, *45*, 471–479. https://doi.org/10.1002/2017GL076081

Payne, A. E., & Magnusdottir, G. (2014). Dynamics of landfalling atmospheric rivers over the North Pacific in 30 years of MERRA reanalysis. *Journal of Climate*, *27*(18), 7133–7150. https://doi.org/10.1175/JCLI-D-14-00034.1

Ray, P., Wang, C., Dudhia, J., Li, T., & Moncrieff, M. W. (2012). Tropical channel model. In L. M. Druyan (Ed.), *Climate models* (pp. 3–18). London: InTech.

Ritchie, E. A., & Holland, G. J. (1999). Large-scale patterns associated with tropical cyclogenesis in the western Pacific. *Monthly Weather Review*, *127*(9), 2027–2043. https://doi.org/10.1175/1520-0493(1999)127<2027:LSPAWT>2.0.CO;2

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., et al. (2008). A description of the advanced research WRF version 3 (pp. 1–113).

Strong, C., & Magnusdottir, G. (2008). Tropospheric Rossby wave breaking and the NAO/NAM. *Journal of the Atmospheric Sciences*, *65*(9), 2861–2876. https://doi.org/10.1175/2008JAS2632.1

Swanson, K. L. (2008). Nonlocality of Atlantic tropical cyclone intensities. *Geochemistry, Geophysics, Geosystems*, *9*, Q04V01. https://doi.org/10.1029/2007GC001844

Tao, W.-K., Simpson, J., & McCumber, M. (1989). An ice-water saturation adjustment. *Monthly Weather Review*, *117*, 231–235.

Vecchi, G. A., Delworth, T., Gudgel, R., Kapnick, S., Rosati, A., Wittenberg, A. T., et al. (2014). On the seasonal forecasting of regional tropical cyclone activity. *Journal of Climate*, *27*(21), 7994–8016. https://doi.org/10.1175/JCLI-D-14-00158.1

Vecchi, G. A., & Soden, B. J. (2007). Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature*, *450*, 1066–1070.

Vecchi, G. A., Zhao, M., Wang, H., Villarini, G., Rosati, A., Kumar, A., et al. (2011). Statistical–dynamical predictions of seasonal North Atlantic hurricane activity. *Monthly Weather Review*, *139*(4), 1070–1082. https://doi.org/10.1175/2010MWR3499.1

Wallace, J. M., Mitchell, T. P., & Deser, C. (1989). The influence of sea-surface temperature on surface wind in the Eastern Equatorial Pacific: Seasonal and Interannual Variability. *Journal of Climate*, *2*(12), 1492–1499. https://doi.org/10.1175/1520-0442(1989)002<1492:TIOSST>2.0.CO;2

Wang, B., & Li, T. (1993). A simple tropical atmosphere model of relevance to short-term climate variations. *Journal of the Atmospheric Sciences*, *50*(2), 260–284. https://doi.org/10.1175/1520-0469(1993)050<0260:ASTAMO>2.0.CO;2

Wang, C., & Lee, S.-K. (2009). Co-variability of tropical cyclones in the North Atlantic and the eastern North Pacific. *Geophysical Research Letters*, *36*, L24702. https://doi.org/10.1029/2009GL041469

Zhang, G., & Wang, Z. (2015). Interannual variability of tropical cyclone activity and regional Hadley circulation over the northeastern Pacific. *Geophysical Research Letters*, *42*, 2473–2481.

Zhang, G., & Wang, Z. (2018). North Atlantic extratropical Rossby wave breaking during the warm season: Wave life cycle and role of diabatic heating. *Monthly Weather Review*, *146*(3), 695–712. https://doi.org/10.1175/MWR-D-17-0204.1

Zhang, G., Wang, Z., Dunkerton, T. J., Peng, M. S., & Magnusdottir, G. (2016). Extratropical impacts on Atlantic tropical cyclone activity. *Journal of the Atmospheric Sciences*, *73*(3), 1401–1418. https://doi.org/10.1175/JAS-D-15-0154.1

Zhang, G., Wang, Z., Peng, M., & Magnusdottir, G. (2017). Characteristics and impacts of extratropical Rossby wave breaking during the Atlantic hurricane season. *Journal of Climate*, *30*(7), 2363–2379. https://doi.org/10.1175/JCLI-D-16-0425.1

Zhao, M., Held, I. M., & Vecchi, G. A. (2010). Retrospective forecasts of the hurricane season using a global atmospheric model assuming persistence of SST anomalies. *Monthly Weather Review*, *138*, 3858–3868.