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LETTER

Impacts of ENSO and Madden–Julian oscillation on the genesis of tropical cyclones simulated by general circulation models and compared to observations

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Abstract

Using the Seoul National University Earth System Model Version 0 (SEM0) and Community Earth System Model version 1 (CESM1), we analyzed the impacts of El Niño–Southern oscillation (ENSO) and Madden–Julian oscillation (MJO) on the genesis of tropical cyclones (TG). SEM0 is known to simulate ENSO, MJO, and TG reasonably well, all of which are difficult to simulate with general circulation models (GCMs). Observational analysis revealed that both ENSO and MJO have substantial impacts on global TG and that the impact of ENSO (MJO) on regional TG varies in a complex manner depending on the phase of MJO (ENSO). Both GCMs underestimated the observed TG over the North Atlantic and have relatively poor performance for simulating the TG anomalies associated with ENSO compared to simulating those associated with MJO. Overall, SEM0 shows much better performance than CESM1 in terms of reproducing the observed impacts of MJO and combined impacts of ENSO and MJO on TG. Therefore, SEM0 can serve as a useful tool for studying the interactions among them to improve the forecasting of tropical cyclones.

1. Introduction

Tropical cyclone (TC) activity is influenced by various atmospheric and oceanic variability modes at different time scales. The El Niño–Southern oscillation (ENSO) and Madden–Julian oscillation (MJO; [1]), which are the main modes of natural variability in the tropics on the interannual and subseasonal time scales, respectively, are known to exert significant effects on TC activity. Numerous observational studies have documented the impacts of ENSO ([2–7]) and MJO ([8–12]) on TC activity in various ocean basins. Reference [13] reported that El Niño promotes the genesis of TCs (TG, hereafter) in the southeast portions of the western North Pacific (WNP) and central North Pacific, and inhibits TC activity in the northwest portion of the WNP and northern Atlantic Ocean. In the case of MJO, TG during convectively active MJO phases is enhanced by up to four times compared to TG during suppressed MJO phases ([10, 12, 14]). Several studies have also examined the combined effects of ENSO and MJO on TC activity. The results revealed that the effects of ENSO and MJO cannot be added linearly because the modulation of TG by MJO under ENSO conditions is asymmetric (e.g. [15]).

Additionally, there have been efforts to reproduce and understand observed ENSO-TC and MJO-TC relationships using dynamical models. Observed ENSO-TC relationships have been reproduced by various general circulation models (GCMs), which enables the dynamical seasonal forecasting of TC, at least qualitatively ([16–22]). However, modeling studies on MJO-TC relationships are very limited because most GCMs have difficulty in reproducing the observed amplitude and phase of MJO ([23, 24]) and TC patterns ([25]), mainly due to the problems in parameterized moist convection processes. Reference [26] documented the impact of MJO on the statistics of TCs in the ECMWF forecasting model, and [27] and [28] conducted similar works based on high-resolution models. These studies adopted hindcast simulations targeting two to four weeks of MJO predictability, such that their results can be sensitive to

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errors in initial conditions. Reference [29] examined MJO-TC relationships utilizing a few atmospheric GCMs, but only over the WNP.

Here, we investigate the impacts of ENSO and MJO on TG using a set of long-term coupled GCM simulations produced by the Community Earth System Model version 1 (CESM1; [30]) and Seoul National University Earth System Model Version 0 with a unified convection scheme (SEM0-UNICON; [31]). The results are then compared to observations. SEM0-UNICON is one of the very few GCMs that simulates observed ENSO, MJO, and their teleconnections reasonably well ([32, 33]), as well as TG and the diurnal cycle of precipitation ([31]). To the best of our knowledge, our study is one of the very few attempts to investigate the combined effects of ENSO and MJO on TG utilizing GCMs, which can contribute to improving short-term TC forecasting and understanding changes in TC activity in the future.

2. Data and analysis methods

For observational analysis, for the period of January of 1979 to December of 2016 (38 years), TG over the eastern North Pacific and Atlantic oceans was obtained from the TC track data of the National Oceanic and Atmospheric Administration’s National Hurricane Center. TG in other regions was obtained from the TC track data of the US Navy’s Joint Typhoon Warning Center ([34]). The monthly sea surface temperature (SST) used for defining ENSO came from HadISST/OLI.v2 observations ([35]). Daily outgoing longwave radiation (OLR) and horizontal wind vector at levels of 850 and 200 hPa, which are used for defining MJO, came from observations of the Advanced Very-High-Resolution Radiometer satellite ([36]) and the NCEP-NCAR reanalysis product ([37]), respectively. In terms of GCMs, we conducted 400 years of coupled simulations at a 0.95° latitude × 1.25° longitude horizontal resolution (nominally, 1° in the pre-industrial period with the CESM1 and SEM0-UNICON ([31]) driven by the forcing data obtained from phase six of the Coupled Model Intercomparison Project (CMIP6; [38]). Although not sufficient for reproducing the observed strength of TCs, 1° GCM simulations have been used in previous studies to examine the interannual and intraseasonal variations of the genesis of tropical cyclones ([26, 39, 40]). The atmospheric model of SEM0 is the Seoul National University Atmosphere Model Version 0 with a UNICON (SAM0-UNICON) and the other components of SEM0 (e.g. land, ocean, and sea ice models) are identical to those of CESM1. SAM0-UNICON is one of the international GCMs participating in the CMIP6 and is based on the Community Atmosphere Model Version 5 (CAM5; [41, 42]). However, CAM5’s shallow ([43]) and deep convection schemes ([44]) were replaced by UNICON ([45, 46]) with a revised treatment of convective detrainment processes ([47]). Reference [31] demonstrated that the global mean climate and ENSO simulated by SAM0/SEM0 are similar to those simulated by CAM5/CESM1. However, SAM0/SEM0 substantially improves the simulation of MJO, the diurnal cycle of precipitation, and TG.

The methods we utilized for defining ENSO, MJO, and TG are similar to those presented in [31]. El Niño, neutral ENSO, and La Niña events are defined as years in which the standardized detrended monthly SST anomalies averaged over the NINO34 region (170°W–120°W, 5°S–5°N) during the months of November to January are greater than 1, between −1 and 1, and smaller than −1, respectively. To define MJO phases for individual days, we conducted multivariate empirical orthogonal function analysis using 20–100 day bandpass filtered, OLR and zonal winds at levels of 850 and 200 hPa averaged over the range of 15°S–15°N. The first two normalized principal components were squared and added to define the daily MJO index ([48]). The days with an MJO index smaller than 1 were defined as ‘neutral MJO’ and the other days were grouped into eight MJO phases (P1, P2, ..., P7, and P8) based on the two principal components. Following the procedure presented in [31], TG was identified utilizing 6 hourly instantaneous outputs if the relative vorticity at 850 hPa, denoted ξ850, was greater than 12.5 × 10⁻³ s⁻¹, the warm-core strength, denoted ξ850 − ξ500 was greater than 12.5 × 10⁻³ s⁻¹, and the two conditions were satisfied at least for two consecutive days. The first time step at which these conditions were simultaneously satisfied was defined as the TC onset time. The climatology of TC genesis obtained from our detection method is shown and discussed in [31] (see figures 18 and 19 of [31]). We tested another TC detection method suggested by [49], which is an extension of [39], and the results were similar to the ones shown in our paper (not shown). In addition, we repeated the analysis by defining individual phases of ENSO and MJO using the standardized anomalies of −0.5 and 0.5 instead of −1 and 1, and the results were similar (not shown). Due to the short available periods and infrequent occurrence of TCs, the observed TG anomalies associated with the combined variations of ENSO and MJO averaged over the 5° latitude × 5° longitude grid boxes were too noisy to be interpreted. To address this issue, following the methods presented in [30] and [22], we computed spatially smoothed TGs by partitioning individual TG events into nearby grid boxes using a two-dimensional Gaussian distribution with a standard deviation of 5° in both the x and y directions to serve as a normalized probability density function for individual TG events. After defining the ENSO years and MJO days in different phases, the spatially smoothed TGs defined for each 5° latitude × 5° longitude grid box were composited onto the phases of ENSO (figure 1) and MJO (figure 2), as well as the combined phases of ENSO and
MJO over the globe (figure 3) and in several specific regions (figure 4). We compared the composite results from CESM1 and SEM0 to observed data.

3. Results

Figure 1 presents the composite TG anomalies during the El Niño and La Niña years obtained from CESM1, SEM0, and observations. During the El Niño years, the observed TG increases in the central and eastern northern-hemispheric tropical Pacific and the central southern-hemispheric tropical Pacific oceans, where SST (OLR) anomalies are positive (negative), but decreases in the western Pacific and eastern Indian oceans, where SST (OLR) anomalies are negative (positive) (figure 1(b)). TG also decreases over the far eastern Pacific ocean near the coast of Central America.
and most of the tropical North Atlantic ocean, although the anomalies in SST and OLR are less pronounced. These results are consistent with previous observational studies ([2, 3, 51, 52]). In La Niña years, the aforementioned anomalies are reversed (figure 1(e)). Qualitatively, both CESM1 and SEM0 reproduced the observed anomalies of SST, OLR, and TG in association with ENSO. However, CESM1 generally underestimates the magnitude of observed TG anomalies associated with ENSO. Both models underestimate the observed TG anomalies over the North Atlantic ocean, where the climatological TGs simulated by CESM1 and SEM0 are lower than the observed values ([31]). Compared to the observations, the simulated positive SST and negative OLR anomalies during El Niño years extend too far westward into the western equatorial Pacific and accordingly, the simulated positive TG anomalies also extend too far westward. Similar features can be seen for La Niña years. The pattern correlation ($r$) between the observed and CESM1-simulated SST anomalies in the tropical region ($30^\circ$S–$30^\circ$N) is 0.84 (0.86) during the El Niño (La Niña) years. SEM0 produces similar $r$ values of 0.87 (0.88), indicating that both models have similar performance in terms of simulating the observed ENSO. However, both models produce substantially lower pattern correlations for TG anomalies (0.15 (0.25) for CESM1 and 0.23 (0.30) for SEM0), although SEM0 performs slightly better than CESM1.

Figure 2 presents the composite anomalies of TG at different MJO phases in all ENSO phases. Similar to ENSO, MJO has a significant impact on the variations of regional TG around the world. Similar to the results presented in [12], the signs of TG anomalies systematically change depending on MJO phases in all active TC regions. Most TG anomalies are congruent with OLR anomalies, indicating that TCs occur more frequently when latent heat is released by strong mean upward motion ([10]). One notable exception is the simultaneous decreases in OLR and TG over the western North Pacific ocean centered at ($15^\circ$N, $165^\circ$E) during MJO phases seven and eight (figure 2(k)), implying that some factors other than large-scale upward motion also control TG. Enhanced vertical wind shear may contribute to suppressing TG in this region ([53, 54]). CESM1 has trouble simulating the observed MJO, as indicated by the very low spatial correlations ($r = 0.26–0.37$) between observed and simulated OLR anomalies compared to SEM0 ($r = 0.76–0.92$). Consequently, the simulated TG anomalies from CESM1 are less realistic ($r = 0.09–0.54$, root mean squared error (rmse) $= 8.9–10.9 \times 10^{-2}$) than those from SEM0 ($r = 0.64–0.87$, rmse $= 5.0–7.6 \times 10^{-2}$) and weaker than the observations. Similar to the ENSO composite, the simulated TG anomalies associated with MJO over

**Figure 3.** Annual composite of TG anomalies during the (first row) El-Niño and MJO phases one and two, (second row) El-Niño and MJO phases five and six, (third row) La-Niña and MJO phases one and two, and (fourth row) La-Niña and MJO phases five and six obtained from (left column) CESM1, (center column) observations, and (right column) SEM0. Black lines represent the composite anomalies of OLR with a contour interval of 3 W m$^{-2}$ ($\pm 2.5$ W m$^{-2}$ lines are also shown). Only statistically significant OLR anomalies above a 95% confidence level based on a two-sided students t-test are shown. The pattern correlations and rmse values of OLR and TG anomalies in the tropical region ($30^\circ$N–$30^\circ$S) between the simulations and observations are shown in the upper-left and upper-right corners of the simulation maps, respectively. The number of samples used for the composite is shown at the title of individual plots.
the North Atlantic ocean for both models are weaker than the observations.

Figure 3 presents the composite anomalies of TG and OLR in association with the combined variations of ENSO and MJO. The observations reveal that the combined impacts of ENSO and MJO on TG are complicated, which is expected because the ENSO-related anomalies of TG and OLR (Figure 1) are comparable in magnitude to the MJO-related anomalies (Figure 2), but different in terms of spatial structure. The positive TG anomalies over the South China Sea in the far western North Pacific ocean during La Niña years (Figure 1(e)) are further strengthened during MJO phases five and six (Figure 3(k)), but are reversed during MJO phases one and two (Figure 3(h)). The well-defined positive TG anomalies over the eastern North Pacific and western Atlantic oceans during MJO phases one and two, which are presented in Figure 2(b), are modulated by ENSO (Figures 3(b) and (h)). Regardless, most TG anomalies continue to be congruent with OLR anomalies. In general, as indicated by the higher correlation values and lower rmse values, SEM0 reproduces the observed anomalies of TG and OLR in association with the combined variations of ENSO and MJO more accurately than CESM1. We speculate that some of the discrepancies between the observations and simulations are a result of the short available period and associated noise in the observational analysis: the number of samples used for the observed composites is only 265–359 d for each combined phase.

Figure 4 presents the composite TG anomalies at different phases of ENSO and MJO averaged over several regions in which TCs are generated frequently (see Figure 2(a)). Similar to the previous figures, one can see that the impacts of ENSO and MJO on TG exhibit strong regional dependencies. Over the NAT/NIO/SIO, the observed TG is the largest during La Niña years and smallest during El Niño years, while the opposite is true over the ENP. TCs over the SP (WNP) occur least (most) frequently during neutral ENSO. SEM0 well reproduces the observed dependencies of regional TG on different ENSO phases, at least qualitatively. However, over the WNP, the maximum and minimum TG values are simulated during the El Niño and La Niña years, respectively, instead of during the neutral ENSO. This is due in part to too westward extension of the simulated SST and OLR anomalies in the western tropical Pacific ocean, as mentioned.
previously (see figure 1). SEM0 also reproduces the MJO-related inter-phase variations of the observed TG in each region with reasonable accuracy. Overall, CESM1 performs worse than SEM0.

The impact of ENSO (MJO) on regional TG varies in a complex way depending on the phase of MJO (ENSO). For example, over the ENP and NIO, La Niña enhances TG during the MJO phases five and six, but suppresses TG during the MJO phases three and four. Over the NAT, MJO phases one and two enhance TG during La Niña years, but suppress TG during El Niño years. The maximum (minimum) TG values over the WNP are observed during neutral ENSO and MJO phases five and six (La Niña and MJO phases three and four), while the maximum (minimum) TG values over the SIO are observed during La Niña and MJO phases three and four (El Niño and MJO phases seven and eight). To quantify how well the models reproduced the observed dependencies of regional TG on the combined variations of ENSO and MJO, we computed the correlation coefficients and rmse values between the observed and simulated TG values over all of the combined phases of ENSO and MJO in each region (i.e. three ENSO phases multiplied by nine MJO phases, including the neutral MJO phase, results in a total of 27 combined phases). The results are presented in the plots in figure 4. From CESM1 to SEM0, the inter-phase correlation with the observations increases from 0.27 (0.61, 0.25, 0.29, 0.47, and −0.02) to 0.76 (0.76, 0.54, 0.46, 0.77, and 0.68) over the WNP (ENP, NAT, NIO, SIO, and SP). Over the WNP, NAT, and SP, the correlation increases by more than two times. Except over the NIO, the rmse values decrease from CESM1 to SEM0 in all regions. Overall, SEM0 has much better performance than CESM1 in terms of reproducing the observed dependency of TG on the combined variations of ENSO and MJO.

4. Summary and conclusions

Most GCMs have trouble simulating observed ENSO, MJO, and TCs. In our previous studies, it was shown that compared to CESM1, SEM0 with its recently developed UNICON convection scheme substantially improves the simulation of MJO, the diurnal cycle of precipitation, and TCs without degrading the mean climate and ENSO ([31, 46]). By extending these studies, we examined the impacts of ENSO and MJO on TG based on a set of long-term coupled simulations in the pre-industrial period driven by the forcing data from CMIP6 and compared the results to observations.

Similar to previous studies, we found that both ENSO and MJO have substantial impacts on the observed TG over the globe and that the impact of ENSO (MJO) on regional TG varies in a complex manner depending on the phase of MJO (ENSO). Most TC anomalies are congruent with the anomalies of OLR. Both CESM1 and SEM0 underestimate the observed TG anomalies over the North Atlantic ocean, mainly because the simulated climatological TG is substantially lower than the observations in this region. Additionally, compared to the TG anomalies associated with MJO, SEM0 and CESM1 showed relatively poor performance for reproducing the observed TG anomalies associated with ENSO, which can be attributed to short observational periods and excessive westward extension of the simulated SST and OLR anomalies in the western equatorial Pacific associated with ENSO. Despite these issues, SEM0 reproduces the observed impacts of ENSO and MJO on TG in various regions around the world more accurately than CESM1. The inter-phase correlations between the observed and SEM0-simulated TG over the combined phases of ENSO and MJO are 0.76 and 0.54 over the western North Pacific and North Atlantic oceans, respectively, which are much greater than the corresponding values of CESM1 (0.27 and 0.25). These improvements from CESM1 to SEM0 are likely a result of the improved simulation of interactions between the TG process and controlling environmental variables, as well as the improved simulations of controlling environmental variables. Additional studies are planned to analyze the sources of these improvements at the process level, which will contribute to understanding the TG processes observed in nature. The coupled simulations forced by the present-day climate forcings may reduce the excessive cold tongue biases existing in our pre-industrial coupled simulations ([55, 56]) and so better reproduce the observed ENSO-TG relationship. Since the TC simulation with a GCM may be sensitive to the horizontal resolution, we plan to run and analyze higher resolution simulations (e.g. 0.5°). In conclusion, SEM0 can serve as a useful tool for studying the interactions between ENSO, MJO, and TCs, as well as their evolution in a changing climate and methods for improving short-term TC forecasting.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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