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The effect of translation speed upon the intensity of tropical cyclones over the tropical ocean

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[1] During the past several decades operational forecasts of tropical cyclone (TC) tracks have improved steadily, but intensity forecast skills have experienced rather modest improvements. Here we use 40 years of TC track data to show that storm intensity correlates with translation speed, with hurricanes of category 5 moving on average 1 m s^{-1} faster than tropical storms. This correlation provides evidence that the translation speed of a storm can exert a significant control on the intensity of storms by modulating the strength of the negative effect of the storm-induced sea surface temperature (SST) reduction on the storm intensification (i.e., the SST feedback): Faster-moving storms tend to generate weaker sea surface cooling and have shorter exposure to the cooling, both of which tend to weaken the negative SST feedback. Consistently, there exists a minimum translation speed for intensification and its value grows with TC intensity, resulting in a minimum translation speed for the existence of a TC in each intensity category. Furthermore, a composite analysis of satellite-based SST measurements reveals that in the tropical region the average strength of the storm-induced sea surface cooling can be explained by the superposition of an effect due to the storm intensity and an effect associated with the translation speed, and implies that the variability of upper ocean stratification may not be an important factor in this region. Our results suggest that progress in the prediction of TC tracks, particularly in the translation speed of storms, should lead to improved storm intensity prediction.

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1. Introduction

[2] The track of a tropical cyclone (TC) is largely controlled by large-scale atmospheric flows [*George and Gray*, 1976], while its intensity (measured as the maximum surface wind speed) is determined by more local factors. This difference has resulted in a relatively modest improvement in the operational forecast of TC intensity in recent decades, whereas the prediction of TC movement has improved to a much greater extent [e.g., *DeMaria et al.*, 2005; *Cangialosi and Franklin*, 2011].

[3] A maximum potential storm intensity has been derived for a given atmospheric thermodynamical profile and sea surface temperature (SST) [*Emanuel*, 1988; *Holland*, 1997], but many internal and environmental processes can significantly limit the actual achievement of this maximum value [*Merrill*, 1988; *Emanuel*, 1999; *Emanuel et al.*, 2004]. One of the most important negative influences is the SST feedback associated with the surface water cooling induced by the storm passage [e.g., *Schade and Emanuel*, 1999; *Bender and Ginis*, 2000; *Ginis*, 2002; *Goni et al.*, 2009], which reduces heat fluxes from the ocean extracted by the storm and thereby inhibits the storm from intensifying.

[4] The amplitude of the TC-induced SST anomaly (SSTA) is affected by the translation speed of the storm: Slower-moving storms generate larger cooling as they input more momentum into the ocean that eventually leads to enhanced vertical mixing of surface warm water with deeper colder water [e.g., *Zedler*, 2009]. This, together with the fact that slower-moving TCs are exposed to their self-induced cooling over a longer period of time [*Lin et al.*, 2009], results in a strengthened negative SST feedback on slow-moving TCs, which in turn can efficiently limit the intensification of a TC.

[5] So far, the impact of TC translation speed on TC intensity has been investigated on a very limited number of case studies [*Wang and Wu*, 2004; *Lin et al.*, 2009]. Here we use a composite analysis of TC best track data and satellite-derived SST data to show that in the tropics the intensity of a TC correlates with its translation speed: Slower-moving TCs tend to induce larger cooling in the surface ocean, preventing the TC from intensifying.

2. Data and Methods

[6] The TC data used in this study are from the National Hurricane Center best track dataset [*McAdie et al.*, 2009] and the Joint Typhoon Warning Center best track dataset [*Chu et al.*, 2002] which provide the location and intensity of global TCs at 6-hr intervals. Only data for the period after 1970 were used because of the debate about accuracy of the data from the earlier period [*Landsea*, 2005]. The analysis is focused on the tropical ocean (equatorward of ~22° latitude), where the ocean's mixed layer is deep, where most of a storm's intensification takes place, and where no clear dependence of translation speed on latitude is present (Figure S1 in Text S1 in the auxiliary material).[1] By limiting our attention to this low-latitude band we can limit the impact of warm eddies, which are critical for maintaining cyclone intensification at higher latitudes where the climatological mixed layer is thinner. Totally more than 3090 storm

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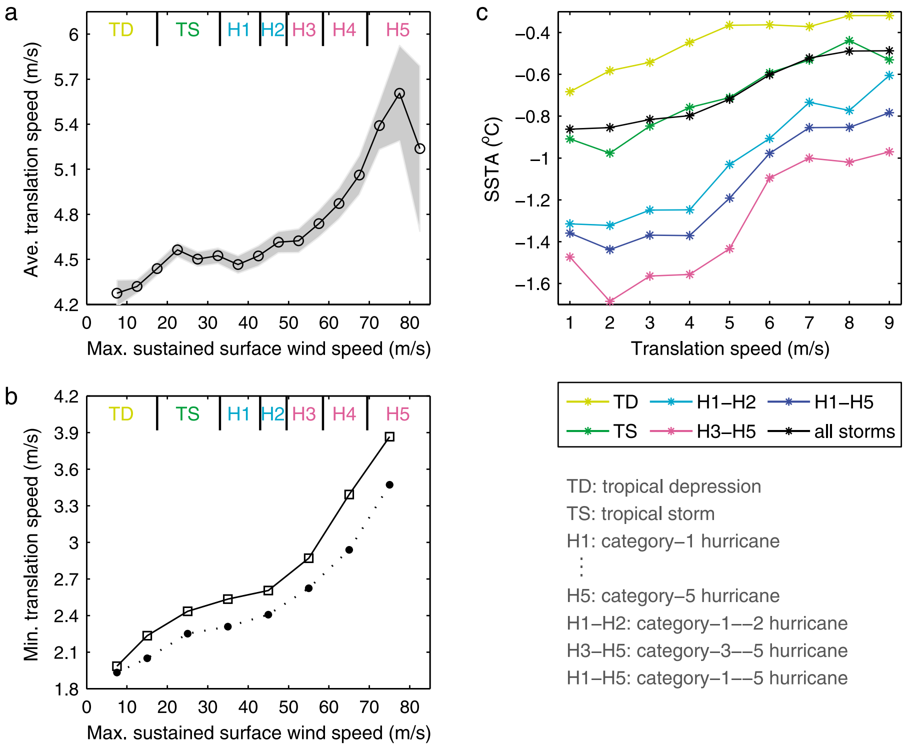

Figure 1. (a) Average translation speed (m s^{-1}) of all storms over the tropical ocean as a function of storm intensity (m s^{-1}). The shading indicates ± one standard error (SE) calculated by dividing the standard deviation by the square root of the number of tropical cyclones (a lower bound for the number of independent observations). (b) Dotted curve with closed circles: The 15th percentile of the distribution of translation speeds for all storms. Solid curve with squares: The 15th percentile of the distribution of translation speeds for intensifying storms. (c) Storm-induced surface cooling (°C) averaged within a 5° × 5° box as a function of the storm translation speed (m s^{-1}) for storms of different intensities. The sample size for the calculations in this figure as well as following figures is given in Tables S1–S8 in Text S1.

tracks (nearly 72 000 storm locations after removing those over land) are used in this work.

[7] The storm translation speed is calculated on the bulk of the data by dividing the sum of the respective distance the storm moves 6-hr prior to and 6-hr after reaching the current position by the total time interval (12 hr), using the positions reported in the TC best track data; for the starting and ending positions of the life time of a storm, translation speed is determined by forward and backward differencing the positions at 6-hr intervals, respectively. The intensification rate of a storm is computed by forward differencing the maximum 1-min sustained surface wind speed in time at a 6-hr interval. (Note that the derivative calculations may be improved with the use of a proper smoothing filter, such as the Savitzky-Golay filter used by *Malmstadt et al.* [2010].)

[8] To test the sensitivity of our results to the time interval covered by the data, the analysis reported here has been repeated using only data starting from 1975, 1980, 1985, 1990, 1995, and 2000. No significant differences were found. Accordingly, we use the longest available dataset to increase the statistical significance of the results.

[9] The daily SST data derived from the Tropical Rain Measuring Mission (TRMM) Microwave Imager (TMI; December 1997–December 2009) are used to study the SSTA induced by the TC passage, generally following the method by *Hart et al.* [2007]. This product is suitable for this purpose since TMI relies on microwave measurements and can see through the clouds, though the adverse effect of heavy rains still limits the availability of data during the TC passage (e.g., Figure S2 in Text S1). The data were first preprocessed to remove the climatological seasonal cycle and long-term linear trend for each grid. Then for each TC location, the temporal evolution of the SST averaged over a TC-centered 5° × 5° box was obtained before, during and after the TC passage; the total number of the constructed boxes is greater than 22 000 over the period when the TMI SST data are available. The obtained box-averaged SST for each TC location and time was used to get the composites of the SST evolution in terms of TC intensity, and the SSTAs in the post-storm period were defined with respect to the one-month average pre-storm conditions at the same location. Then the *storm-induced surface cooling* (shown in Figures 1c and 3a) was defined as the maximum negative SSTA, usually appearing on the day after the storm passage. The SSTA during the day of the storm passage was also analyzed to explore the feedback of the SST reduction onto the storm development: We refer to it as the SSTA *experienced* by the TC, shown in Figure 2. As discussed in auxiliary material, the results are robust to the size of the box used for the calculation (see Figure S4 in Text S1).

[10] In addition, a simple mixed layer slab model developed by *Pollard et al.* [1973] is used to study the relationship between the SST response and the wind stress associated with a TC: Conservation of momentum and energy imply mixed layer deepening and cooling in response to wind stress at the surface, provided the shear kinetic energy overcomes

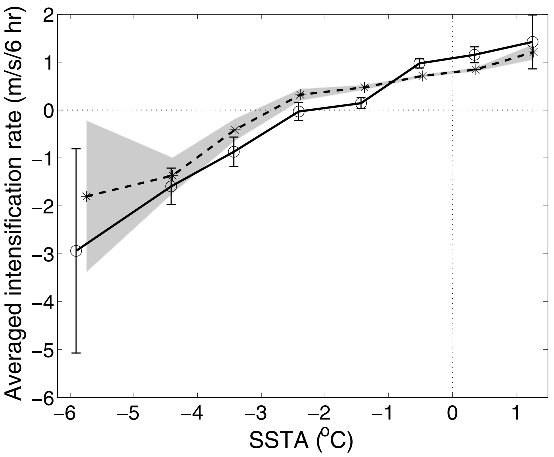

Figure 2. Averaged storm intensification rate (m s^{-1} per 6 hours) as a function of the SST anomaly (°C) the storm experiences. Dashed line is for all storms with shading showing the SE. Solid line is for storms of hurricane intensity with the vertical bars showing the SE.

the barrier in gravitational potential energy associated with the stratification at the base of the mixed layer. Details on the model are given in auxiliary material.

3. Results

[11] Using the translation speed calculated at each of the positions along more than 3090 TC tracks sampled at 6-hr intervals, we computed the mean translation speed for each TC intensity category. We find that, on average, as the TC intensity increases so does the translation speed (Figure 1a; note that the opposite is not necessarily true as we discuss later). The relationship is most prominent for storms of intensity greater than 50 m s^{-1}. For example, category-5 hurricanes (measured on the Saffir-Simpson scale) on average move approximately 0.9 ± 0.2 m s^{-1} faster than category-2 hurricanes.

[12] The correlation between TC intensity and translation speed is consistent with the hypothesis that the SST feedback acts as a filter which preferentially allows faster-moving TCs to reach higher intensities, as suggested by the concept of "affordable minimum translation speed" proposed by *Lin et al.* [2009]. The hypothesis is further supported by the analysis of the distribution of translation speeds for TCs experiencing intensification (i.e., TCs whose instantaneous maximum wind speed increases in the following 6 hours): The lower range of the distribution (see Figure 1b for its 15th percentile shown as a function of TC intensity, and Figure S3 in Text S1 for other percentiles) shifts to faster speeds as TC intensity increases. In other words, only TCs that are moving relatively fast can intensify and the lower translation speed limit for intensification depends on intensity itself; correspondingly, we see an increase in the lower translation speed limit for TCs to exist as the TC intensity increases. For example, for a category-4 hurricane to intensify into category 5 its speed must typically be greater than 3.4 m s^{-1} (as indicated by the 15th percentile of the translation speed distribution of intensifying category-4 hurricanes in Figure 1b). Consistent with this, category-5 hurricanes with translation speeds lower than 3.5 m s^{-1} occur very rarely (cf. the 15th percentile of the distribution of all category-5 hurricanes), and typically, they only intensify if their translation speed is greater than 3.9 m s^{-1} (cf. the 15th percentile of the distribution of intensifying category-5 hurricanes). While *Lin et al.* [2009] emphasized the importance of the upper ocean thermal structure in setting the minimum translation speed for intensification, here we point out that for the tropical band, equatorward of ~22°, the climatological relationship between translation speed and intensity emerges above the noise induced by variability in the upper ocean heat content.

[13] The strength of the SST feedback depends on the amplitude of the cooling, which is controlled primarily by the wind-induced mixing of surface waters with colder waters from below during the TC passage [e.g., *Price*, 1981] and on the amount of time a TC is exposed to the cold anomaly (that is, the residence time of the TC at a given location) [*Lin et al.*, 2009]. The potential sensitivity of TC intensity to the amplitude of the SSTA is large. Even a small increase in the amplitude of the SSTA can result in a large decrease of the heat extracted from the ocean by the TC [*Cione and Uhlhorn*, 2003]. To quantify this effect, we binned the intensification rate according to the SSTA experienced by the TC. We then computed the average intensification rate

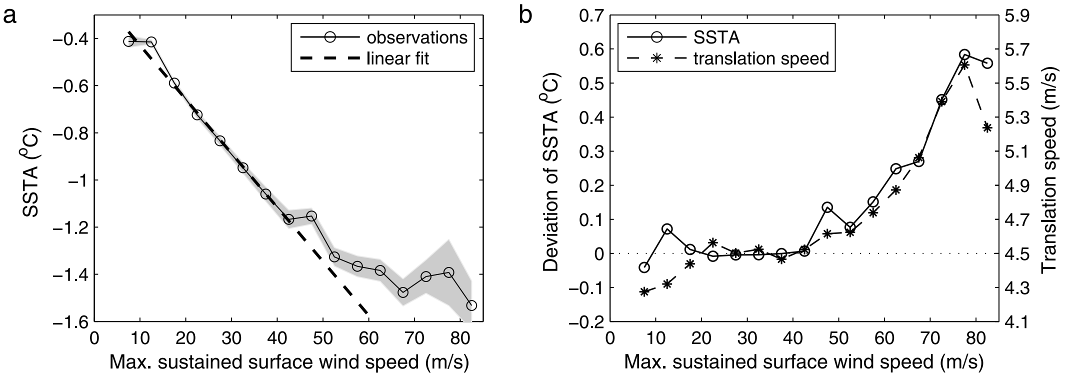

Figure 3. (a) Storm-induced surface cooling (°C; solid line) averaged within a 5° × 5° box as a function of storm intensity (m s^{-1}). Shading shows the SE of the averaged SST cooling. Dashed line shows a linear fit of the surface cooling based on the six points with maximum wind speed (v_s in m s^{-1}) between 15 and 45 m s^{-1}: $\mathrm{SSTA_{ref}} = -0.023v_s - 0.199$ with units of °C. (b) Deviations of the storm-induced SST anomaly (°C; solid line) from the linear fit $\mathrm{SSTA_{ref}}$ in Figure 3a and storm translation speed (m s^{-1}; dashed line and same as in Figure 1a) as a function of storm intensity.

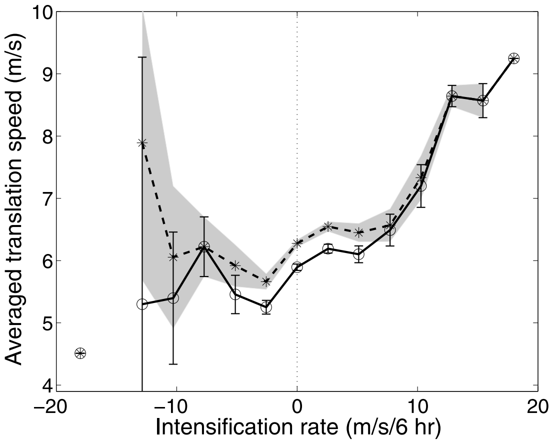

Figure 4. Averaged storm translation speed (m s^{-1}) as a function of storm intensification rate (m s^{-1} per 6 hours) in the North Atlantic tropical open ocean. Dashed line is obtained using all data with shading for the SE. Solid line is obtained using only data with translation speed below 10 m s^{-1} with vertical bars for the SE.

for each bin and plotted it as a function of the SSTA (Figure 2). The monotonic relationship between the intensification rate and the amplitude of the SSTA shows that cooling limits TC intensity.

[14] Both the amplitude of the cold SSTA and its effect on the TC are directly related to a TC's translation speed. Slow-moving TCs have relatively more time to input momentum into the upper ocean, which results in a larger vertical shear at the base of the mixed layer. Shear-induced mixing is then more effective at deepening the mixed layer and producing colder SSTAs [*Zedler*, 2009]. This effect is shown quantitatively in Figure 1c in which the amplitude of the TC-induced SSTAs is plotted as a function of translation speed for TCs of different intensity. For a fixed intensity, slower-moving TCs generate colder SSTAs. Meanwhile, slow-moving TCs are exposed to their self-induced cold SSTAs for a longer period of time and are thus more susceptible to the negative SST feedback. Both effects tend to make the SST feedback more effective for TCs with lower translation speeds.

[15] To separate the effect of translation speed from the effect of TC intensity on the amplitude of the TC-induced SST cooling, we use the simple mixed layer model described in section 2 and auxiliary material. The model, which ignores the effect of translation speed, predicts a linear relation between TC intensity and SSTA for TCs of intensity above a small minimum threshold (Figure S4 in Text S1). By contrast, the observed SSTA, which is affected by both TC intensity *and* translation speed, is linearly related to the TC intensity only for TCs of intensity below 50 m s^{-1} (Figure 3a). Above this intensity, the observations show a pronounced leveling-off of the SST reduction with increasing TC intensity. Figure 3b shows that the observed deviation of the SSTA from the linear trend can be explained by the increase in translation speed that accompanies the increased intensity. Indeed, Figure 3b shows a remarkable correlation between the reduced SSTA and the increased translation speed: An increase of 25% in the average translation speed ($\sim$1 m s^{-1}) for category-5 hurricanes with respect to that of tropical storms (Figure 1a) corresponds to a reduction in surface cooling of nearly 30% compared to the linear relationship that applies to less intense storms ($\sim$0.5°C averaged over an area of 3×10^5 km^2; Figure 3b).

[16] A recent study [*Lloyd and Vecchi*, 2011] has also noted the leveling-off of SST cooling with increasing TC intensity, but attributed it to the preferential presence of anomalously weak upper-ocean stratification below the most intense TCs, a circumstance that has been shown to occur in some case studies [e.g., *Shay et al.*, 2000]. Our analysis, however, points to an alternative explanation: The increasing strength of the negative SST feedback associated with the higher TC intensity can be offset by an increase in the translation speed, allowing for continued intensification. This increase in translation speed with intensity accounts for the observed positive correlation between the average translation speed and TC intensity, and is responsible for the leveling-off of the cold SSTAs. However, we must emphasize that our conclusions do not necessarily apply to higher latitudes where the mechanism described in the explanation of *Lloyd and Vecchi* [2011] probably dominates. At higher latitudes, shallower climatological mixed layers require the presence of warm eddies for TCs to overcome the negative SST feedback and continue to intensify.

[17] To further support our claim, we related the translation speed to the intensification rate calculated at 6-hr intervals. The result for the tropical Atlantic, reported in Figure 4, shows that TCs experiencing strong intensification tend to move fast, whereas those decaying or undergoing weak intensification tend to move more slowly; similar results hold for other basins (not shown). Not all the TCs that move fast necessarily intensify, as other factors also come into play to generate variability around the average behavior. In particular, the few TCs with a very large translation speed (above 10 m s^{-1} for the tropical Atlantic) are not the ones that experience the strongest intensification (Figure S5 in Text S1). We believe this can be related to three facts: (1) A very large translation speed tends to destroy the TC's symmetric structure and the associated convective convergence [*Peng et al.*, 1999], both of which are needed for intensification. (2) The bias of the cold wake away from the TC track is greater for TCs that move faster (Figure S6 in Text S1). The strong bias leads to an asymmetry in the heat fluxes extracted from the ocean by the TC, which further strengthens the asymmetry in the convective convergence and thus is also unfavorable for the development of the TC. (3) TCs with very large translation speeds over the tropical ocean likely experience a large vertical shear when a faster than normal trade-wind steering flow is overlain by upper tropospheric westerlies of normal speed. Strong vertical shear tends to disrupt the vertical coherence of the convective structure and limits its intensification. Despite these caveats, the bulk of the climatological data is consistent with the idea that as TCs become more intense they must move faster if they are to overcome the increasing strength of the negative SST feedback that accompanies more intense TCs.

4. Conclusions and Discussions

[18] This work has shown that over the tropical ocean mean translation speed (averaged over each TC intensity category) positively correlates with TC intensity (the correlation coefficient is 0.90). Composite analysis of satellite-derived SSTs

reveals that the mechanism behind this positive correlation is that translation speed can exert a strong control on the amplitude of the TC-induced sea surface cooling and determine the exposure time of the TC to the cooling: A slower-moving TC produces larger negative SSTAs and is exposed to the cooling for a longer period of time, and thus is subject to a strengthened negative SST feedback and has less chance reaching higher intensity. Consistently, a minimum translation speed exists for intensification and its value grows with TC intensity, resulting in a minimum translation speed for the existence of a TC in each intensity category.

[19] Recently a considerable effort has been put in assimilating subsurface ocean temperature data in operational TC forecast model, with an average reduction in intensity error of only about 1% [e.g., *Mainelli et al.*, 2008; *Goni et al.*, 2009]. The rational behind this effort is that the presence of warm eddies and a deeper than normal mixed layer have been linked to a particularly weak SST cooling under the eye of the TC [e.g., *Shay et al.*, 2000; *Wu et al.*, 2007], reducing the negative SST feedback on TC intensity. Our results however might explain why the average forecast improvement has been quite modest: We find that in the tropics the average TC-induced SST cooling is largely controlled by the intensity and translation speed of TCs. In this area the average upper ocean stratification under the tracks of most intense TCs is not anomalously weak, while the mean translation speed for most intense TCs is larger than that for all TCs: Hurricanes of category 5 have average translation speed of 5.44 ± 1.87 m s^{-1} (mean ± standard deviation (SD)) whereas the mean translation speed of tropical storms is 4.51 ± 2.25 m s^{-1} (mean ± SD). The situation is likely different in the extratropical region, where the shallower climatological mixed layer is responsible for a severe inhibition of TC intensification and thus most intense TCs probably form preferentially over weaker than normal upper ocean stratification.

[20] In the above discussion, we have considered the large-scale air flow as the main driver of TC movement. However, theoretical and numerical work [e.g., *Fiorino and Elsberry*, 1989] has shown that the interaction of a TC with the beta effect can also induce variations in translation speed, which is known as the beta-gyre effect. To rule out the possibility that the observed relation between translation speed and TC intensity can be explained by the beta-gyre effect, we point out that those studies indicate that the beta-gyre-effect-induced TC movement depends on the outer wind speed (i.e., the strength) rather than the maximum wind speed (i.e., the intensity), which is located in the inner region of the TC. Furthermore, the self-induced movement associated with the beta-gyre effect is directed in a northwest to north-northwest direction in the Northern Hemisphere. Thus if the beta-gyre effect is responsible for the observed relation between translation speed and intensity, this relation should be especially prominent for the meridional component of the speed. As shown in Figure S7 in Text S1, however, this relation is dominated by the zonal component of the speed. This result supports the idea that TC translation speed is mainly determined by the large-scale environmental flow [*George and Gray*, 1976].

[21] The relationship between translation speed, intensification rate and TC intensity reported in this study suggests that improvements in operational forecasts of TC intensity could benefit from the improvements in the prediction of TC movement, provided that the effects of TC translation speed on sea surface cooling are appropriately represented in hurricane forecast models. Clearly, because of the large spread of the distribution of intensification rates and TC intensities for a fixed translation speed (e.g., see Figure S5 in Text S1) and the corresponding small percentage variance of instantaneous TC intensity explained by translation speed, a relatively large uncertainty in the prediction of TC intensity would remain. In practice, many other factors such as wind shear [*DeMaria*, 1996], upper-ocean structure [*Shay et al.*, 2000; *Wu et al.*, 2007] and internal dynamics like eyewall replacement [*Houze et al.*, 2007], which also exert significant influences on the development of the TC, must also be taken into consideration to obtain a precise forecast of the TC intensity.

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