**INFLUENCE OF TEMPERATURE ON THE BETA DRIFT OF TROPICAL CYCLONES**

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## 1. INTRODUCTION

The β-drift is an important component of tropical cyclone (TC) motion that arises from the interaction between the TC relative vorticity and the earth's vorticity, and causes the TC to drift poleward and westward. More generally, TCs tend to move towards the area where the wavenumber-1 (WN-1) component of the potential vorticity tendency (PVT) has a maximum, and this occurs mainly through the contributions of advection and diabatic heating processes (Wu and Wang 2000; Chan et al. 2002).

It is not known how the β-drift varies with temperature. Even though the impact of temperature changes on the tracks of TCs is a matter of current debate (Barros et al. 2014), changes in TC size have not been considered as a potential factor leading to track shift. While some studies propose changes in large-scale environmental flow as responsible for the shift in the tracks of TCs (e.g., Wu et al. (2005), Colbert et al. (2013), Chu et al.(2012)), others suggest that future shifts of the locations of TCs formation may have larger impacts (e.g., Wu and Wang (2004); Murakami and Wang (2010)). These results depend on the ocean basin and, even when considering the same basin, different studies lead to contrasting conclusions (e.g., Murakami and Wang (2010) and Colbert et al. (2013) for the North Atlantic basin).

Here, for the first time we explore the β-drift sensitivity to temperature, which may be informative of the response in a warming world.

## 2. METHODS

This study utilized the Advanced Research Weather Research and Forecasting model (ARW-WRF v3.5.1 Skamarock et al. (2005)).

A series of idealized experiments initialized with an identical axisymmetric vortex (Chan and Williams 1987; Rotunno and Emanuel 1987) and no background flow was conducted on an ocean-only spherical surface. In order to assess the sensitivity of TC β-drift to changes in temperature, the sea surface and atmospheric temperature profile were both changed (from -2ºC to +3ºC with respect to the control experiment).

Sets of experiments with different initial profile were also performed to explore the sensitivity of the β-drift to the initial wind profile.

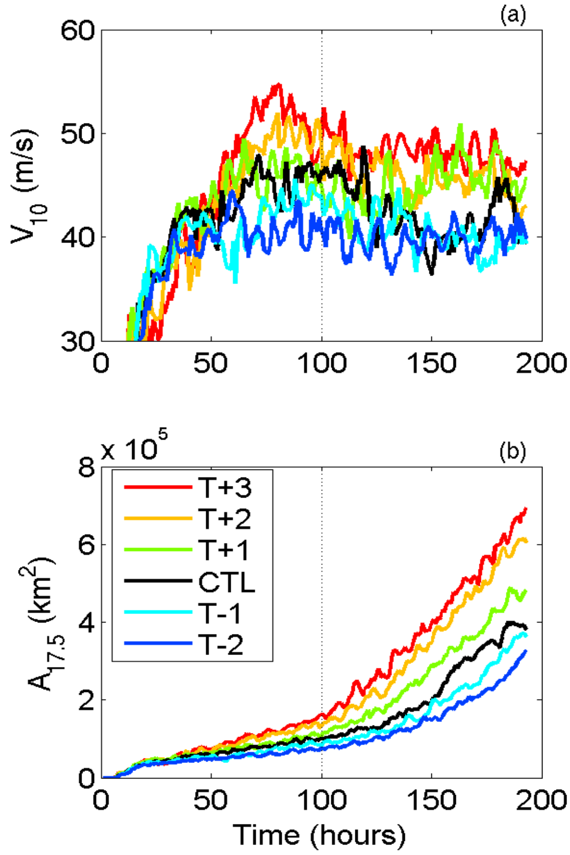


**Figure 1** Evolution of maximum 10-m wind speed (a) and area of gale-force wind (b) for the different experiments. The temperature is changed by -2°C (T-2), -1°C (T-1), +1°C (T+1), +2°C (T+2) and +3°C (T+3) relative to the control (CTL) experiment.

## 3. RESULTS

Our analysis focuses on the mature stage of the TCs evolution when their intensity is in a quasi-steady state (after 100 hours). The intensity of the TCs increases with temperature (Figure 1). Regardless of the specific simulation, while the

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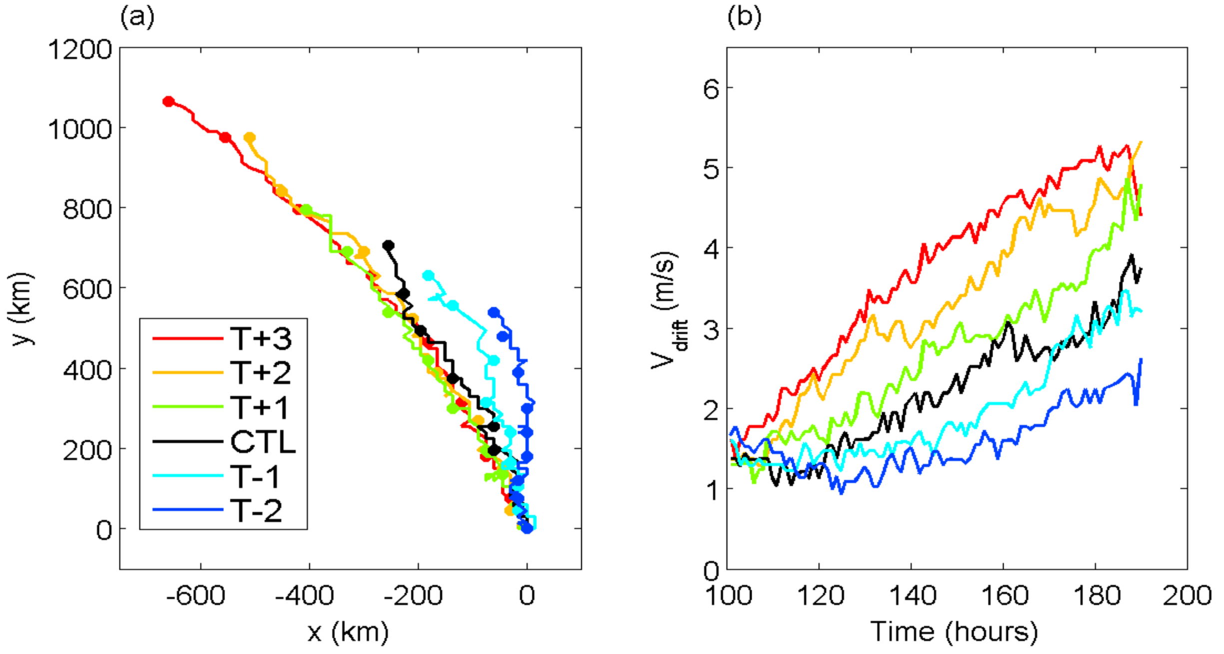


**Figure 2** (a) Tracks of the TCs after 100 hours of simulation with filled circles every 12 hours (b). Evolution of 24-h moving averaged β-drift speeds after 100 hours of simulation.

intensities saturate to a quasi-steady state, the TCs size (defined as the gale-force wind area) keeps increasing. The areal growth is faster with increasing temperatures. The final size of the TCs is also sensitive to the initial wind profile (not shown).

Initially, the TCs follow similar trajectories but in the mature stage there is a clear separation of β-drift speeds. The β-drift speed increases with increasing temperature (Figure 2). In the warmer experiments the TCs increasingly move westwards and further to travel a significantly larger distance than that travelled by the other TCs.

An analysis of the time-mean relationships of intensity, size, β-drift speed and mean relative angular momentum (MRAM) (Xiaofan Li 1992) with the change in temperature reveals that the intensity increases linearly with temperature, whereas size, MRAM and β-drift speed scale quadratically with temperature (not shown). Moreover, size and MRAM show linear hourly relationships with the β-drift speed (Figure 3a). When considering all sets of experiments (Figure 3b), we find that above a minimum critical MRAM of 5 x $10^6$ $m^2$ $s^{-1}$ all the TCs have β-drift speeds that increase linearly with MRAM ($R^2$ = 0.64, significant at 99% confidence level), regardless of the initial radial wind profile. The critical MRAM approximately corresponds to a critical minimum radius of gale-force winds of 250 km. None of the other factors such as maximum wind speed, minimum sea level pressure, nor latitude, exhibits a clear relation with the β-drift speed.

An analysis of the WN-1 component of the PVT reveals that the horizontal advection gives the dominant contribution to the motion and its maximum is significantly stronger in the warmer experiments. Even though the diabatic heating gives a smaller contribution, it fosters a westward deflection of the TCs, especially in the warmer experiments, because its maximum is located to the west of the TCs center (not shown).

## 4. DISCUSSION AND CONCLUSION

An increase in the environmental temperature leads to the development of more intense and larger TCs. While intensity saturates after the initial intensification, the size of the TCs continues to increase during the whole simulation time. The intensity saturation and linear temperature dependence agree with the maximum potential intensity theory of (Emanuel 1986).

The key result of our study is that the β-drift becomes larger with increasing temperature. A stronger outer flow (beyond 300 km from the center of the TC) leads to a greater β-drift because of the enhanced horizontal advection (Fiorino and Elsberry 1989). In our experiments, both the size and the MRAM display good correlations with the β-drift speed, in agreement with previous numerical studies (Xiaofan Li 1992; Wang and Holland 1996a,b). In particular, when the MRAM (or size) exceeds a critical value, the linear increase in the β-drift speed is independent of the initial wind profile shape. This critical MRAM corresponds to a critical minimum radius of gale-force winds of 250 km, which is in good agreement with the previous finding that the winds beyond 300 km play a fundamental role in determining the β-drift speed.

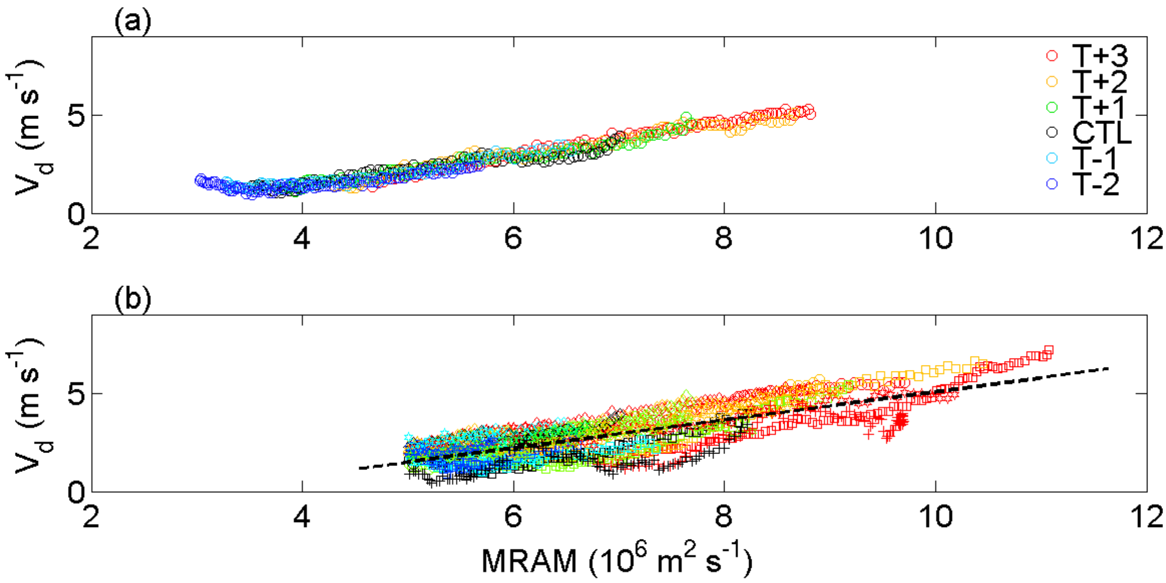


**Figure 3** Relation between 24-h moving averaged β-drift speed and MRAM after 100 hours of simulation for one set of experiments with identical initial wind profile (a) and all sets of experiments with different initial profiles when TCs exceed 5 x $10^6$ $m^2$ $s^{-1}$ (b).

Our results suggest that, when the outer winds exceed the gale-force threshold, the β-drift speed increases linearly with the TC size, regardless of other factors.

The analysis of the PVT reveals that its azimuthal WN-1 component is dominated by the horizontal advection term and, in agreement with Wu and Wang (2000) and Chan et al. (2002), it is located towards the direction of motion of the TCs. The horizontal advection term mainly includes the environmental steering flow and the ventilation flow. Since there is no environmental flow, the horizontal advection is primarily related to the size of the TCs. This confirms the importance of size in determining the β-drift of TCs. The diabatic heating term mainly contributes to the westward deflection of the TCs in the warmer experiments.

Whereas recent studies on the shift of TC tracks in a warming climate focus exclusively on the role of changes in the environmental steering flows and genesis locations, our study reveals that variations of the environmental temperature could lead to large changes in the magnitude of the β-drift. This study hints that in warmer environment the TC climatology may be shifted westwards and polewards independent of the basin.

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