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Thermodynamic control on the climate of intense tropical cyclones

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How thermodynamic factors control the climate of intense tropical cyclones (TCs) is investigated by examining the relationship between the seasonally averaged maximum potential intensity (MPI, used as a representative index of the thermodynamic forcing) over an ocean basin where TCs form and the seasonal frequency of occurrence of intense TCs. It is found that only in the Atlantic does the MPI have a statistically significant relationship with the number of intense TCs, explaining about 40 per cent of the variance. In other ocean basins, there is either no correlation or the correlation is not statistically significant. In other words, only in the Atlantic are thermodynamic factors responsible, but still only to a certain extent, for the climate variations of intense TCs. In other ocean basins, it appears that the dynamic factors are much more dominant. Such a conclusion has important implications in considering whether global warming may influence the future climate of intense TCs for the following reason. Although it has been generally accepted that the thermodynamic energy available in the atmosphere is likely to increase under global warming, the results from this study suggest that such an increase does not necessarily imply a concomitant increase in the number of intense TCs, because how the dynamic factors will vary are still not clear. Until we can demonstrate that the dynamic factors will also become more favourable for TC intensification, it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario.

Keywords: tropical cyclones; climate change; global warming

1. Introduction

Emanuel (1988) proposed using a parameter called the maximum potential intensity (MPI) to estimate the maximum intensity that a tropical cyclone (TC) could reach based on the atmospheric and oceanic thermodynamic conditions in which the TC is embedded. The value of MPI depends upon three factors: sea-surface temperature (SST), the outflow temperature (T_o) and the net available convective available potential energy (CAPE) in the troposphere. Extending this concept to the entire TC season, a higher value of MPI summed over the ocean basin implies a more energetic atmosphere, at least thermodynamically, so that more TCs could reach higher intensities. In other words, a season with a higher value of MPI should have more intense TCs. If this is true, it is possible to estimate

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whether the frequency of occurrence of intense TCs is increasing in response to global warming by calculating the value of MPI from future model predictions. However, such usage of MPI neglects the contributions from dynamic factors such as vertical wind shear. Because MPI represents an integrated measure of the thermodynamic potential for the development of intense TCs, an examination of the relationship between the MPI and the frequency of occurrence of intense TCs can provide an indication of the extent to which such a frequency is controlled by thermodynamic versus dynamic factors, which is the objective of this paper.

The data and methodology are first described in §2. Correlations between the MPI and the number of intense TCs in each ocean basin are then presented in §3. The contributions of each of the terms in the MPI to the correlations are examined in §4. A summary and discussion of the results are given in §5.

2. Data and methodology

(*a*) *Data*

Since the studies by Emanuel (2005) and Webster *et al.* (2005), much discussion has been made on the veracity of the best-track datasets in the early years when satellite monitoring was either not available or not capable of providing high-quality images for a good estimation of TC intensity (e.g. Landsea *et al.* 2006). Subsequent studies have also pointed out related problems such as a different wind-pressure relationship in different periods (Emanuel 2007; Knaff & Zehr 2007) or performed sub-sampling to estimate the actual frequency of intense TCs (Chang & Guo 2007; Vecchi & Knutson 2008). Kamahori *et al.* (2006), Wu *et al.* (2006) and Nakazawa & Hoshino (2009) have also pointed out the differences in intensity estimates in the western North Pacific (WNP) among different warning centres after the termination of aircraft reconnaissance.

It is decided that the ‘official’ best-track datasets will be used for the present study instead of ‘modifying’ the best-track datasets based on the results from these subsequent studies for the following reasons. First, applying each correction will give a different set of data, and a consensus has yet to be reached as to which correction gives a dataset closer to the ‘truth’. Second, the best-track datasets have the longest data period so that the results could actually provide more insight into the differences between the pre-satellite and the current satellite eras. Third, at least for the WNP, Chan (2008) suggested that the Joint Typhoon Warning Center (JTWC, http://metocph.nmci.navy.mil/jtwc/best_tracks/) best-track dataset probably gives a more reasonable estimate of the number of intense TCs. Lastly, as will be seen from the results in §§3 and 4, such corrections will not change the general conclusions of the study.

The main datasets used in this study are therefore (i) the HURDAT dataset of the US National Hurricane Center for the Atlantic and eastern North Pacific TCs (http://www.nhc.noaa.gov/pastall.shtml) and (ii) the best-track datasets from JTWC for all the other basins. For the Atlantic, the WNP and the eastern North Pacific (ENP), the data period is between 1960 and 2007. For the South Indian Ocean (coast of Africa to 105° E) and the South Pacific (east of 155° E), the data period is between 1981 and 2007. This relatively short period is chosen

Table 1. Domain and TC season for each ocean basin used in averaging the values of MPI and in calculating NCat45.

ocean basin	domain	months
Atlantic	10–20° N, 20–60° W	Jul–Oct
WNP	10–27.5° N, 120–160° E	Jul–Nov
ENP	10–20° N, 140–105° W	Jun–Oct
South Indian Ocean	10–20° S, 50–105° E	Nov–Apr
South Pacific	10–20° S, 155° E–160° W	Dec–Mar

because Trewin (2008) and Harper *et al.* (2008) have shown that in the Australian region, TC intensities prior to the 1980s are likely to be underestimated. With even less data in the South Indian Ocean and the South Pacific east of Australia, it is logical to expect that the data would be of even a poorer quality before 1980. The North Indian Ocean and the Australian region (105–155° E, south of equator) are not studied because of the small number of intense TCs in these two regions.

To provide more 'confidence' in the validity of the results and to compare with the results from the best-track datasets, a second TC dataset is used, which is the 'homogeneous' dataset produced by Kossin *et al.* (2007), who performed detailed analyses of the satellite images from 1979 to 2006.

The atmospheric and ocean datasets from the US National Centers for Environmental Prediction (NCEP) reanalyses (Kalnay *et al.* 1996) are used to compute the value of MPI. This dataset rather than the ERA40 from the European Centre for Medium-range Weather Forecasts is used because the latter dataset ends in 2001.

(*b*) *Methodology*

Several metrics have been used as a measure of the frequency of occurrence of intense TCs within a season. These include the accumulated cyclone energy (ACE; Bell *et al.* 2000), the power dissipation index (PDI; Emanuel 2005) and the number of TCs with maximum intensity in Category 4 or 5 (NCat45) on the Saffir–Simpson scale (Saffir 2003). Another simpler measure could be to average the maximum intensity for all TCs. Because both the ACE and PDI involve the lifetime of TCs, a slightly weaker TC lasting for a long time, or many more such weak TCs, may contribute as much as a short-lived intense TC. Averaging the maximum intensity of all TCs could also reduce the contribution of intense TCs. Therefore, the metric of NCat45 is used to represent how active the season is in terms of generating intense TCs.

Calculation of the MPI is done using the FORTRAN program downloaded from the website ftp://texmex.mit.edu/pub/emanuel/TCMAX/. The daily NCEP reanalyses are used to compute the MPI at each grid point. The values of the MPI are then averaged over the entire ocean basin (see table 1 for the domain of each basin) and then over the TC season, which is different for each basin, as shown in table 1.

Table 2. Correlations between the annual NCat45 obtained from the best-track dataset in each of the ocean basins with MPI. The data period for each ocean basin is also shown. The correlations using the Kossin *et al.* (2007) dataset for the Atlantic and WNP are also shown. Values in bold indicate significance at 95 per cent or higher.

ocean basin	period	correlation (best track)	correlation (Kossin *et al.* 2007)
Atlantic	1960–2007	**0.45**	
	1970–2007	**0.59**	
	1980–2007	**0.63**	
	1979–2006	**0.61**	**0.61**
WNP	1960–2007	−0.01	
	1970–2007	−0.06	
	1980–2007	−0.08	
	1981–2006	−0.13	−0.36
ENP	1960–2007	**0.29**	
	1970–2007	**0.35**	
	1980–2007	0.34	
South Indian Ocean	1981–2007	0.35	
South Pacific	1981–2007	0.03	

3. Correlation between MPI and number of intense TCs

The seasonal MPI for each ocean basin is calculated and correlated with the annual NCat45. For the Atlantic, the correlation for the entire period 1960–2007 is 0.45, which is significant at the 99 per cent level (table 2). If the period begins in 1970, the correlation increases to 0.59 and further to 0.63 if the period starts in 1980, all of which are significant at the 99 per cent level. These results suggest that the MPI does have a relationship with the annual number of NCat45 in the Atlantic, and the relatively lower correlation if earlier data are included appears to be a result of the lower quality data in the pre-satellite and early-satellite eras, an issue that has been discussed in §2.

For the ENP, the correlation coefficients are 0.29 and 0.35, respectively, for both the 1960–2007 and the 1970–2007 periods, both of which are significant at the 95 per cent level (table 2). However, the correlation coefficient for the two most recent decades (1980–2007) is not statistically significant.

None of the correlations are significant at the 95 per cent level for all the other ocean basins (table 2). In particular, the correlation is close to zero for the WNP and the South Pacific.

Because of the possible uncertainties in the data, correlations are calculated again using the Kossin *et al.* (2007) dataset, with the results also shown in table 2 for easy comparison. The correlation for the Atlantic is the same as that from the best-track dataset. For the WNP, although the correlation is higher, it is still negative and insignificant at the 95 per cent level. Thus, the differing results between the Atlantic and the other ocean basins cannot be attributed to data uncertainties.

To investigate in greater detail about the temporal variations of these correlations, 21-year running correlations are examined for the three Northern Hemisphere ocean basins (as the period in the Southern Hemisphere is too short). The choice of a 21-year window is to remove variations on annual or decadal timescales that could be contributed by shorter-term events such as El Niño and to focus on multi-decadal variations, which have been found in both the Atlantic (Bell & Chelliah 2006) and the WNP (Chan 2008).

For the Atlantic (figure 1*a*), the correlation between MPI and NCat45 begins to become statistically significant at 95 per cent (critical value = 0.43) when the period begins around 1978 (i.e. the data point corresponding to 1998) and then continues to increase. This is consistent with the idea that the data become more reliable from the late-1970s. The results are similar for the ENP (figure 1*c*), with the correlations becoming statistically significant when the period starts at around 1978 except that the values of the correlation coefficients are smaller. However, this only lasts for a few years and the correlations drop again if the period starts around 1980. Nevertheless, these results suggest that perhaps the MPI may still bear a relationship with NCat45 in the ENP.

The results for the WNP are completely different (figure 1*b*). The correlation coefficients are positive prior to the mid-1980s, but become negative afterwards, although none of the values is statistically significant except for the latest period 1987–2007 (the last point in figure 1*b*).

The obvious question is why the MPI has a strong correlation with NCat45 mainly in the Atlantic and only for a brief period in the ENP, but none in the other ocean basins. This will be addressed in the following section.

4. Correlations with individual components of MPI

As indicated in §1, MPI consists of three factors. It is, therefore, useful to study the correlations between each of these factors and NCat45. For the Atlantic, the 21-year running correlations for CAPE are almost exactly as those for MPI, whereas those for SST are slightly lower, being 95 per cent statistically significant after 1984 (data point for 2004; figure 1*a*). The variations of the correlations for T_o are similar but negative, reaching the 95 per cent significant level after 1979. These results suggest that in the Atlantic, an increase in SST and especially CAPE, and/or a decrease in the outflow temperature, may lead to more frequent occurrence of intense TCs. In other words, it appears that in the Atlantic, the climate of intense TCs is at least to a large extent controlled by thermodynamic factors. However, it should be pointed out that although the thermodynamic factors have significant and physically explainable correlations with NCat45, it is also possible that the linkage can have an extra dimension in that some studies have shown a decrease in vertical wind shear associated with warm SST during the positive phase of the Atlantic Multi-decadal Oscillation (AMO; Goldenberg *et al.* 2001; Bell & Chelliah 2006; Kossin *et al.* 2007). That is, the thermodynamic and dynamic forcings can work together to produce the observed NCat45 values.

The results for the ENP are similar to those for the Atlantic although the values of the correlation coefficient are smaller (figure 1*c*). However, for the WNP, the results are completely different, with the correlation coefficients for T_o being

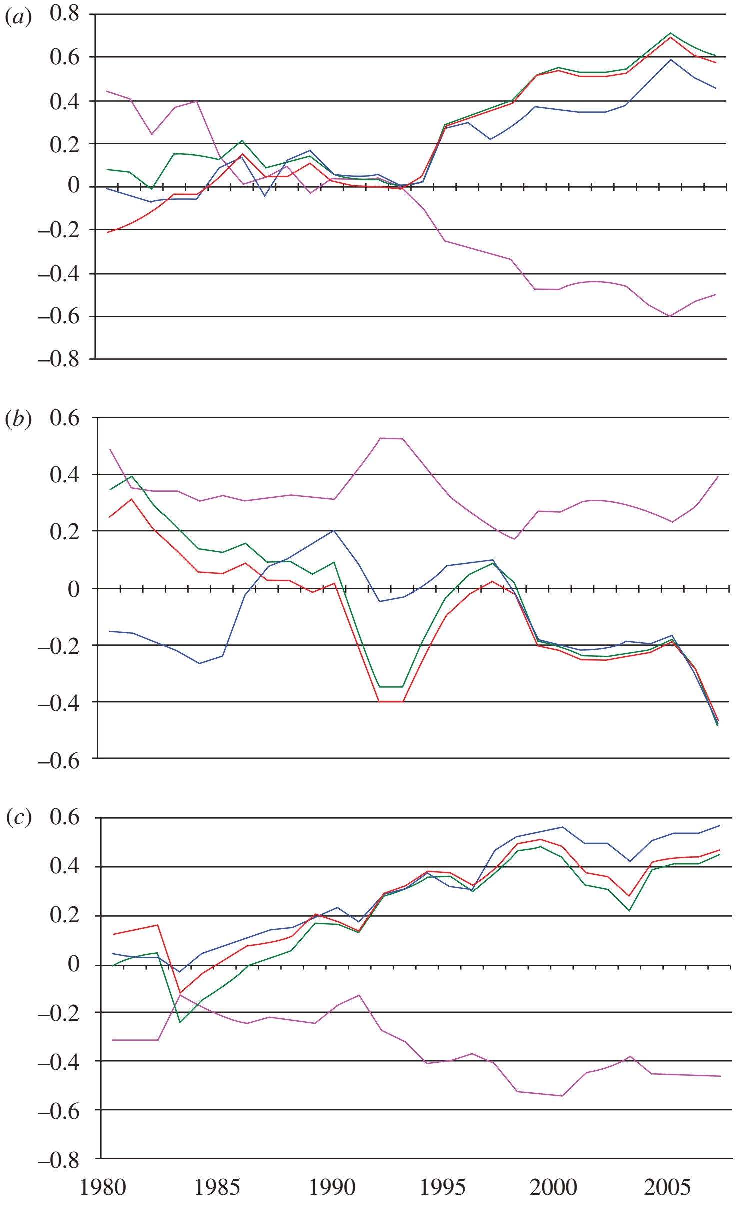

Figure 1. Twenty-one-year correlations between NCat45 and MPI and its components (CAPE, T_o and SST) in (*a*) Atlantic, (*b*) WNP and (*c*) ENP. Critical value for 95 per cent significance is 0.43. The red line stands for MPI, green for CAPE, pink for T_o and blue for SST.

positive and only significant for a brief period (1972–1994), and those for CAPE very similar to those for MPI though statistically not significant, and those for SST hovering around zero (figure 1*b*).

The correlation between SST and NCat45 for the WNP is very different from the result of Emanuel (2005) that showed a strong correlation between SST and PDI. Because PDI is strongly biased towards intense TCs, its value is highly correlated with NCat45 (Chan 2006). The difference between these two results therefore needs to be discussed. First, the data used are different for the earlier years. Emanuel (2005) significantly scaled down the winds prior to 1973 because he argued that the wind-pressure relationship in the earlier years tends to overestimate the maximum intensity. As a result, the PDI values between 1960 and 1972 are substantially lower than the original values. However, whether such an adjustment is valid is still debatable especially with the study by Knaff & Zehr (2007), who proposed a more comprehensive approach to derive a wind-pressure relationship. Chan (2008) has shown that the atmospheric and oceanographic conditions during the period 1960–1970 with high, unadjusted NCat45 values are very similar to those in the other high-NCat45 period during the 1980s to 1990s, which further suggests that the adjustment may not be appropriate. Second, the time series in Emanuel (2005) terminates at around 2000. After this time, the values of PDI in the WNP have been on the decrease, whereas SST continues to increase (see Chan 2006). A 10-year filtered time series of PDI and SST for the period 1965–2004 gives a correlation of only approximately 0.4, whereas that for the period 1965–1993 is approximately 0.86 (not shown). This variation in correlation is, to a certain extent, reflected in that between NCat45 and SST shown in figure 1*b*. If PDI or NCat45 is indeed physically linked to SST, such variation in the correlation coefficients should not occur. For example, the correlation coefficients for the Atlantic shown in figure 1*a* have a rather constant value beginning in the late-1970s when the data became more ‘trustworthy’. Thus, the result in Emanuel (2005) is likely to be not physical and probably due to the choice of the length of the time series and an arbitrary adjustment in the maximum winds.

Why are the correlations between NCat45 in the WNP and SST as well as CAPE negative? This has actually been explained by Chan & Liu (2004) and Chan (2007) that the negative correlation between the frequency of occurrence of intense TCs in the WNP and SST is not because SST does not provide more enthalpy to the atmosphere. Rather, the negative correlation does not imply causality, but merely reflects the fact that the frequency of occurrence of intense TCs in the WNP is strongly influenced by the El Niño/Southern Oscillation (ENSO) such that a warm ENSO event generally corresponds to a higher frequency (Camargo & Sobel 2005). This is because in a warm ENSO event, the SST in the WNP is below normal so that the correlation with the frequency becomes negative. A similar explanation can be given for CAPE, which is highly correlated with SST (not shown). Thus, the negative correlation or the lack of correlation between NCat45 and MPI is to be expected. Most of the TCs in the WNP form and develop within the monsoon trough (Gray 1979), where the SST is often above 29°C (figure 2). Hence, the amount of thermodynamic energy for development is always more than adequate. In other words, the necessary conditions are generally satisfied. A slight increase in SST due to global warming therefore does not have any influence on the potential for TCs to become intense. The determinants are the dynamic factors such as relative vorticity and vertical wind shear in the environment (Chan 2007), which can therefore be considered as sufficient conditions. In other words, in the WNP, the climate of intense TCs is unlikely to be controlled by thermodynamic factors. As a result, no trend can be found in the number of intense TCs (Chan 2007).

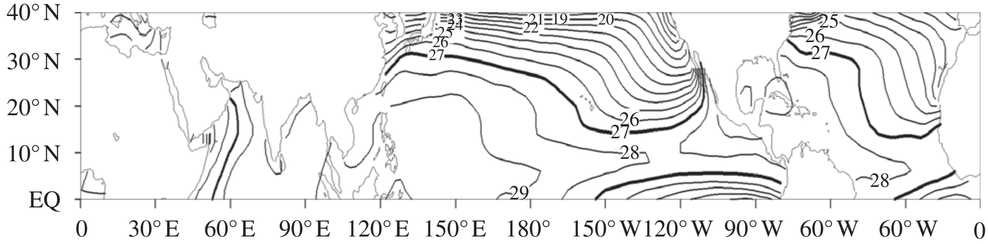

Figure 2. SST climatology for the Northern Hemisphere averaged for July–October.

The reason why the Atlantic is different appears to lie in the fact that most TCs in this ocean basin form from easterly waves coming off the west coast of Africa. Whether they continue to intensify when they reach the western Atlantic depends critically on the amount of thermodynamic energy available for convective development. An increase in SST and CAPE will therefore help provide more energy to the TCs. In addition, during the warm phase of the AMO when the SST is also warmer, the African easterly jet is generally more unstable and the vertical wind shear also decreases (e.g. Bell & Chelliah 2006). Thus, the dynamic factors must also be favourable, as evident from the fact that the MPI can only explain about 36 per cent of the variance of the annual NCat45.

For the ENP, the SST is around 28°C (see figure 2). An increase in SST could therefore enhance the amount of convection and the subsequent development of intense TCs.

The appreciable contribution of thermodynamic factors in the Atlantic to NCat45 may be a reason why some model predictions of future TC activity suggest that Atlantic is the only basin in which the frequency of TC occurrence is likely to have a modest increase under global warming (Chauvin *et al.* 2006; Oouchi *et al.* 2006). However, other models either indicate no significant change (e.g. Bengtsson *et al.* 2007; Emanuel *et al.* 2008) or even a slight decrease (e.g. McDonald *et al.* 2005; Gualdi *et al.* 2008; Knutson *et al.* 2008). Such differences in the modelling projections further highlight not only the uncertainties in the model projections, but also the fact that given the same thermodynamic forcing, other dynamic factors such as vertical wind shear (e.g. Vecchi & Soden 2007) may negate the effects due to an increase in SST.

5. Summary

It has been shown in this paper that thermodynamic control on the frequency of annual occurrence of intense TCs is only significant in the Atlantic, with about 40 per cent of the variance being explainable by thermodynamic factors during the last 30 years. For other ocean basins, the thermodynamic factors do not seem to have any appreciable contribution towards the variability of the annual occurrence of intense TCs. As discussed above, the major reason for such a difference lies in the difference in formation mechanism of TCs in the different ocean basins. In the Atlantic, thermodynamic factors are important in providing the necessary energy for TC development, while this necessary condition is generally satisfied in other ocean basins. As a result, the determinant for these other basins becomes the dynamic factors such as vertical wind shear, which of course is also important in the Atlantic.

This conclusion has an important implication on how global warming affects the frequency of occurrence of intense TCs. Although it is generally accepted that under global warming, the thermodynamic energy available in the atmosphere is likely to increase, such an increase does not necessarily imply a concomitant increase in the number of intense TCs, because how the dynamic factors will vary is still not clear. In other words, until we can demonstrate that the dynamic factors will also become more favourable for TC intensification, it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario. Even in the Atlantic where a significant correlation between the thermodynamic factors and the frequency of intense TCs exists, it is not clear whether global warming will produce a net increase in such a frequency because model projections suggest an increase in vertical wind shear associated with an increase in SST (Veechi & Soden 2007). Further, how global warming might change the regional atmospheric and ocean conditions (e.g. changing the frequency of occurrence of El Niño events) in such a way as to modify the formation location of TCs, their movement and their lifetimes is not known. More research on these issues must be undertaken before a more definitive conclusion can be made on how global warming might contribute to variations in the frequency of occurrence of intense TCs.

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