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The Impact of Scaling Behavior on Tropical Cyclone Intensities

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Theory suggests tropical cyclone maximum potential intensity increases with increasing ocean temperature. However, most tropical cyclones fail to achieve this maximum intensity. Instead, empirical studies suggest that tropical cyclone intensities are uniformly distributed between this maximum potential intensity and an intensity that marks the transition between tropical storm and hurricane scaling regimes. Here it is shown that this transition shifts significantly on interannual to interdecadal time scales in both the North Atlantic and Western North Pacific basins. The intensity at which this transition occurs effectively determines the fraction of tropical cyclones entering the hurricane scaling regime, and as such, strongly impacts the fraction of tropical cyclones that become intense. The increase in the fraction of intense tropical cyclones in recent decades results primarily from a shift in this scaling transition toward weaker winds rather than an increase in the maximum potential intensity directly attributable to rising sea surface temperatures. This scaling transition is shown to be sensitive to sea surface temperature (SST) anomalies in the tropical cyclone main development regions relative to tropical mean SST anomalies, in contrast to the maximum potential intensity which scales with the SST itself.

1. Introduction

Recent studies have found an apparent increase in the proportion and number of tropical cyclones (TCs) that become intense [*Webster et al.*, 2005] along with links of this increase to positive sea surface temperature anomalies [*Emanuel*, 2005; *Hoyos et al.*, 2006] and possibly global warming [*Trenberth*, 2005]. However, the sensitivity of TCs to changes in sea surface temperature (SST) remains controversial [*Landsea et al.*, 2006; *Shapiro and Goldenberg*, 1998], as modeling and theoretical studies suggest only small changes to TC intensities given the observed 0.5°C SST warming that has occurred since the 1970's [*Emanuel*, 1988; *Knutson et al.*, 2001]). Further, satellite reanalysis suggests no increase in the fraction of intense TCs outside the North Atlantic basin [*Kossin et al.*, 2006]. Trends in TC intensity are difficult to discern, as statistics are inherently noisy due to fluctuating storm numbers and life spans. As the theory underlying TC intensities specifically predicts only the maximum potential intensity, it is necessary to control for these other factors if the response of the TC intensity to changes in SST is to be understood.

Examining TC maximum intensity distributions provides one route toward quantifying changes in TC behavior. Insofar as steady-state thermodynamic theory provides an upper bound for storm intensity (the so-called maximum potential intensity (MPI) [*Emanuel*, 1988; *Holland*, 1997], the complementary cumulative distribution function (CDF) of tropical cyclone maximum winds is bounded [*Emanuel*, 2000]. *Emanuel* [2000] found that the CDF of observed maximum wind speeds for hurricanes, normalized by the MPI, decreases linearly from some lower intensity bound to zero as the storm maximum intensity approaches the MPI. Curiously, while the normalization by the MPI is theoretically robust, the lower intensity bound is based upon the empirical observation that tropical storm-strength TCs scale differently than hurricane-strength TCs. Whether this lower bound is robust to changes in the large-scale environment has not been explored. However, the importance of this lower bound cannot be overestimated; it effectively controls the fraction of TCs that enter the hurricane scaling regime. As such, it is as important to determining the fraction of intense TCs as the MPI itself.

2. Tropical cyclone scaling behavior

We examine TC winds for the period 1950-2005 in two tropical cyclone basins; the North Atlantic (NATL) based upon Tropical Prediction Center best track reanalysis, and the western North Pacific (WNPAC) based upon Joint Typhoon Warning Center (JTWC) best track data. While potential deficiencies of the JTWC WNPAC best track data have been discussed by *Wu et al.* [2006], the continuity, consistency, and length of the record make it the best available data source for this study. However, it is possible that cessation of aircraft probing of TCs in the WNPAC in 1987, along with deficiencies due to changing application of Dvorak techniques may contaminate any trends in the fraction of intense TCs in that basin [*Landsea et al.*, 2006]. If such deficiencies are present, they should be apparent on an *a posteriori* basis, either as unprecedented statistical behavior compared to the remainder of the 1950-2005 period, unexplainable jumps in statistical quantities at the 1987 threshold, or the breaking of relationships between statistical quantities and environmental factors (e.g. SST) established prior to that point in time. The analysis below is robust to the use of corrected best track tropical cyclone intensities of *Emanuel* [2005] .

From this best track data, CDFs are calculated by finding the maximum wind for each individual TC, and calculating the total fraction of TC events for which the maximum wind speed exceeds a specified value. All events with maximum wind speeds 20 ms^{-1} or greater are included.

Figure 1 shows the CDF of TC maximum winds is well approximated by two distinct linear scaling regimes in both the NATL and WNPAC basins. A tropical storm scaling regime extends from 20 ms^{-1} to roughly 40 ms^{-1} in each basin, and indicates that TC maximum winds in this range are uniformly distributed, i.e., TCs attaining maximum winds in this range exhibit no preference as to the value of that maximum. Following a break in scaling marked by a change in slope, a hurricane scaling regime extends from 40 ms^{-1}. Since the probability distribution function is proportional to minus the slope of the CDF, this indicates an equal, but lower likelihood that hurricanes will achieve a given intensity up to but not beyond an empirical MPI marked by the intercept of the linear fit with the abscissa. Note that the transition between these two scaling regimes lies near the boundary of Category 1 (> 33 ms^{-1}) and Category 2 (43 to 53 ms^{-1}) storms on the Saffir-Simpson scale in all basins, i.e., well within what have traditionally been classified as hurricane strength storms.

These two linear regimes of TC scaling have been previously recognized relative to a derived storm dependent MPI [*Emanuel*, 2000]. However, the distinct linear regimes exist in both hurricane basins without reference to any storm-dependent quantities. Note that the fraction of TCs entering the hurricane scaling regime varies between the two basins, as only 30% of TCs in the NATL enter the hurricane scaling regime compared to 50%

of TCs in the WNPAC. For this reason, it is useful to consider this scaling break as a gatekeeper that determines the fraction of TCs entering into the hurricane scaling regime. Shifts in the wind speed at which this break occurs will materially impact the proportion of TCs that become intense.

3. Scaling changes

Sole control of TC intensity by a thermodynamically determined MPI would be marked by a change in the slope of the CDF in the hurricane scaling regime, without any change in the wind value at which the break between the linear scaling regimes occurs. This does not appear to be the case in either the NATL or WNPAC basins. Instead, Figure 2 shows that interdecadal changes in the CDFs in both basins are dominated by shifts in the break between the tropical storm and hurricane scaling regimes. Specifically, during the period 1958-1965 the scaling break occurred at between 25-30 ms^{-1} in both basins, with more than 80% of TCs entering the hurricane scaling regime and a consequent increase in fraction of TCs that became intense (maximum wind > 60 ms^{-1}) relative to the respective climatological CDFs of Figure 1. Conversely, during the periods 1966-1973 (NATL) and 1974-1981 (WNPAC), fewer than 30% of TCs entered the hurricane scaling regime in the respective basins, and an individual TC was roughly half as likely to become intense as it was during the period 1958-1965. The most recent period 1998-2005 has shown a reversion toward the behavior of the 1958-1965 period, with an increased fraction of TCs entering the hurricane scaling regime and a marked upswing in the fraction of TCs that become intense compared with the 1966-1973 (NATL) / 1974-1981 (WNPAC) periods. Curiously, the tropical storm scaling regime in both basins appears robust, as the best linear fit to this regime varies by a statistically insignificant amount between all time periods in both basins. In addition, the empirical MPI is robust, varying by less than 5 ms^{-1} compared the 20 ms^{-1} variation in the wind speed at which the break between the TC and hurricane scaling regimes occurs.

Notably, the behavior of the TC maximum intensity CDF over 1998-2005 in both basins falls within the range of TC scaling behavior compared to earlier periods. Moreover, Figure 2 suggests that if anomalies in TC intensity estimation have occurred in the WNPAC, they are the result of an interesting convergence of choices at the best track level, choices that left the tropical storm scaling regime unchanged while preserving the linear character of the hurricane scaling regime.

The marked interdecadal variability in this scaling behavior suggests that straightforward interpretation of the response of TC intensity to increasing SSTs in terms of an increase in MPI is fundamentally flawed, as the structure of the CDFs changes markedly on these time scales, while the empirical MPI remains roughly fixed. Changes in CDF scaling behavior appear to dominate any changes in the MPI, regardless of whether one is interested in an average TC intensity or the fraction of TCs that become intense.

4. A Global Bifurcation in the Main Development Region

Changes in the average TC intensity are dominated by changes to the intensity of storms originating in the main development region (MDR) in these two basins. Let us consider in detail storms that originate in the NATL MDR, which here is defined as 20°-60° W, 6°-16° N. Figure 3a shows the time evolution of average intensity for TCs originating within the NATL MDR, estimated by simply integrating the CDF, where the CDFs are constructed by accumulating storm statistics over running 3 year periods. Curiously, the average TC intensity over the period appears to flip back and forth between two states, one with intensity greater than 45 ms^{-1} and another with intensity less than 40 ms^{-1}. The apparent bimodality emerges more clearly in the histogram of these intensities (Figure 3b). The separation between the two peaks in intensity suggests jumps in either the scaling behavior or the MPI.

Consistent with this bimodal behavior, the CDF for intense years, i.e., years where the average TC intensity for storms that originate in the MDR exceeds the median, differs substantially from the CDF for mild years (Figure 3c). TCs that develop in the MDR during intense years exhibit approximate linear scaling from 20 ms^{-1} to the empirical MPI (roughly 75 ms^{-1}). In contrast, TCs that develop in the MDR during mild years have well defined linear tropical storm and hurricane scaling regimes, with the transition between the two scaling regimes occurring at roughly 35 ms^{-1}.

The marked difference in scaling as well as average intensity between intense and mild years suggests the presence of a global bifurcation of MDR basin TC dynamics, at least in the NATL basin. During intense years, basically all TCs enter the hurricane scaling regime, with the result that hurricanes of all intensities are roughly twice as likely as during mild years. This markedly different behavior occurs without a significant change to the empirical MPI, which is consistent with the relatively weak sensitivity of MPI to changes in underlying SSTs [*Emanuel*, 1988].

Behavior reminiscent of this is found in the WNPAC MDR, but interpretation is more complicated given the much higher level of interannual variability associated with El

Niño [*Camargo and Sobel*, 2005]. This interannual variability, coupled with the fact that the WNPAC appears to prefer a hurricane-only scaling regime, obscures any bimodal behavior. However, the qualitative behavior of the CDFs, such as shown in Figure 2, strongly resembles that observed in the NATL.

5. Trends

An important question is what underlies the interdecadal variation in TC intensity in the NATL and WNPAC apparent in Figures 2 and 3. Following *Emanuel* (2005), the SST in the main development region (MDR) is certainly a candidate. For the purposes here, the NATL MDR is defined as 20°-60° W, 6°-16° N, while the WNPAC MDR is 130°-180° E, 5°-15° N, and we consider August-September SSTs in each basin. The SSTs are taken from the HADSST2 data set for 1950-2005 [*Rayner et al.*, 2006]. To minimize the impact of interannual variability, statistics are accumulated over a 7 year period, and for completeness the CDFs include TCs that develop inside and outside the MDR. In the NATL, Figure 4b shows the marked interdecadal swing in intensity from Figure 3a remains (Figure 4b), with TC intensities anomalously large during the 1950's to the mid-1960's, around 1980, and from 1995. In the WNPAC, Figure 4c shows that intensities were large in the 1950's to mid 1960's, declined to roughly 1975, and have increased since that point in time to the present. Significantly, average TC intensities in both basins were as large during the 1950's and 1960's as during the period 1998-2005. Viewed in the light of Figure 4, the period 1975-2004 examined by *Webster et al.* [2005] is fortuitous; it captures the minimum of TC intensities during the 1970's and the subsequent increase in TC intensities. However, the post-1975 upward intensity trend over this period does not appear to mark a fundamental shift in TC intensity behavior; this behavior is still within the upper bound set during the 1950's in both the NATL and WNPAC basins.

Curiously, Figure 4a shows that the SST in the respective MDRs was mostly flat over the period 1950-1975, inconsistent with the large decrease in TC intensity in both basins over this period. While TC intensities have generally increased with MDR SST in both basins post-1975, the failure of MDR SST to explain intensity behavior prior to 1975 suggests MDR SST by itself is not sufficient to explain TC intensities. Quantitatively, the correlation between the SST in the respective MDRs and each basin's average TC intensity is insignificant given the number of degrees of freedom here.

An alternative candidate is the deviation of the SST in the MDR from the Northern Hemisphere tropical mean SST (0° - 15° N), i.e. the relative MDR SST anomaly. In contrast to the MDR SST in isolation, Figure 4b,c shows that this relative SST anomaly varies in a manner quite similar to the average TC intensity in both the NATL and WNPAC. The fraction of variance explained is in excess of $r^2 = 0.5$ in the NATL and $r^2 = 0.3$ in the WNPAC over the period 1950-2005. This suggests that when SSTs in the MDR are high relative to the tropical mean SST in a given basin, TC intensity responds quite strongly. This behavior is consistent with the tendency for regions of anomalously warm SSTs to cannibalize moist convection in the tropics, most apparent in the global-scale reorganization of convective behavior that occurs during El Niño events.

The apparent link between the MDR relative SST and TC intensity suggests relative MDR SST anomalies act as a 'switch' for TC intensity, with years of intense TCs occurring when the anomalous relative MDR SST is positive and mild TCs when the anomalous relative MDR is negative. The relationship is clearer in the NATL, perhaps again due to the smaller level of interannual variability associated with El Niño in that basin.

6. Discussion

The results here show that recent TC intensity changes in the NATL and WNPAC are the result of changes in scaling behavior and are not primarily a response to increased MPI. Those changes appear to be associated with SST anomalies in the main development regions relative to the tropics as a whole, not the main development region SST anomalies themselves.

There are several troubling aspects to this empirical observation. First, there is no guarantee that the scaling behavior in either MDR is robust. There is no compelling theoretical explanation why a linear hurricane scaling regime that extends from 20 ms^{-1} to the MPI as shown in Figures 2 and 3c even exists, let alone why it should mark the upper limit of TC transition probability from tropical storm-strength systems to hurricane strength systems.

Secondly, the scaling behavior for TCs originating in the MDRs suggests extrapolation of past sensitivities to underlying environmental factors such as SSTs is itself a dangerous proposition. Past sensitivity appears to be associated with an underlying bifurcation and associated changes in scaling behavior, particularly in the NATL (Figure 3), and it is unclear whether future increases in relative SST anomalies will result in similar changes in average TC intensity.

Finally, the apparent sensitivity of TC intensity to relative MDR SST anomalies is itself troublesome. How these relative SST anomalies will change under global warming scenarios is unclear, as modeling relative SST anomalies is a much more difficult task than modeling SST anomalies for the tropics as a whole. As such, it is unclear whether the coincident increase in MDR SST anomalies and relative MDR SST anomalies since the mid-1970's shown in Figure 4 will continue. Given this state of affairs, projections of changes in TC intensity due to future global warming must be approached cautiously.

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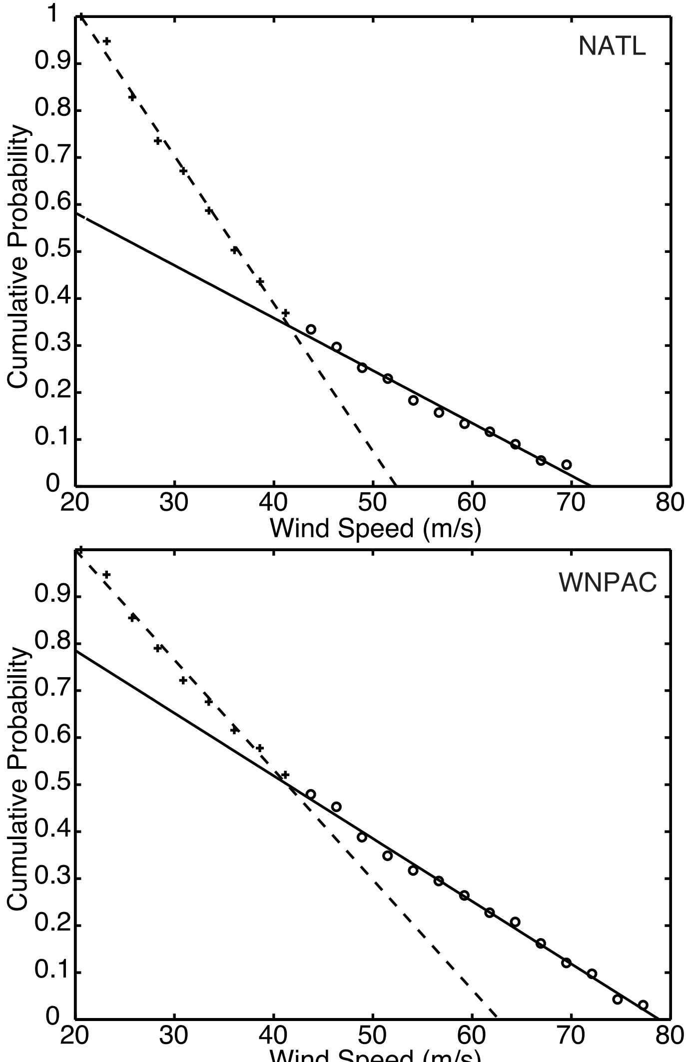
Fig. 1. Complementary cumulative distribution function of tropical cyclone maximum winds for the North Atlantic (NATL) and western North Pacific (WNPAC) basins. Pluses indicate points used in the tropical storm scaling regime linear fit and circles points used in the hurricane scale regime linear fit. All linear fits are significant with $r^2 > 0.99$.

Fig. 2. Tropical cyclone maximum intensity CDF in the NATL and WNPAC basin for the periods indicated in each respective panel. Solid lines indicate least squares fits for the hurricane scaling regime, and the dashed line is the respective tropical storm scaling regime from Figure 1.

Fig. 3. (a) Average tropical cyclone intensity for storms originating in the NATL main development region. (b) Histogram of the intensities in panel (a). (c) CDFs for storms during intense (heavy solid) and mild (intermediate solid) years for TCs originating in the NATL MDR. Also shown for comparison is the CDF for tropical cyclones originating outside the MDR (dotted), which exhibits exponential scaling.

Fig. 4. (a) SST anomalies for the NATL and WNPAC main development regions, along with the tropical mean SST anomaly. (b) TC intensity anomaly for the NATL along with the NATL relative MDR SST anomaly. (c) As in (b), but for the WNPAC.

Figure 1



NATL
Cumulative Probability
Wind Speed (m/s)
WNPAC
Cumulative Probability
Wind Speed (m/s)

Figure 2

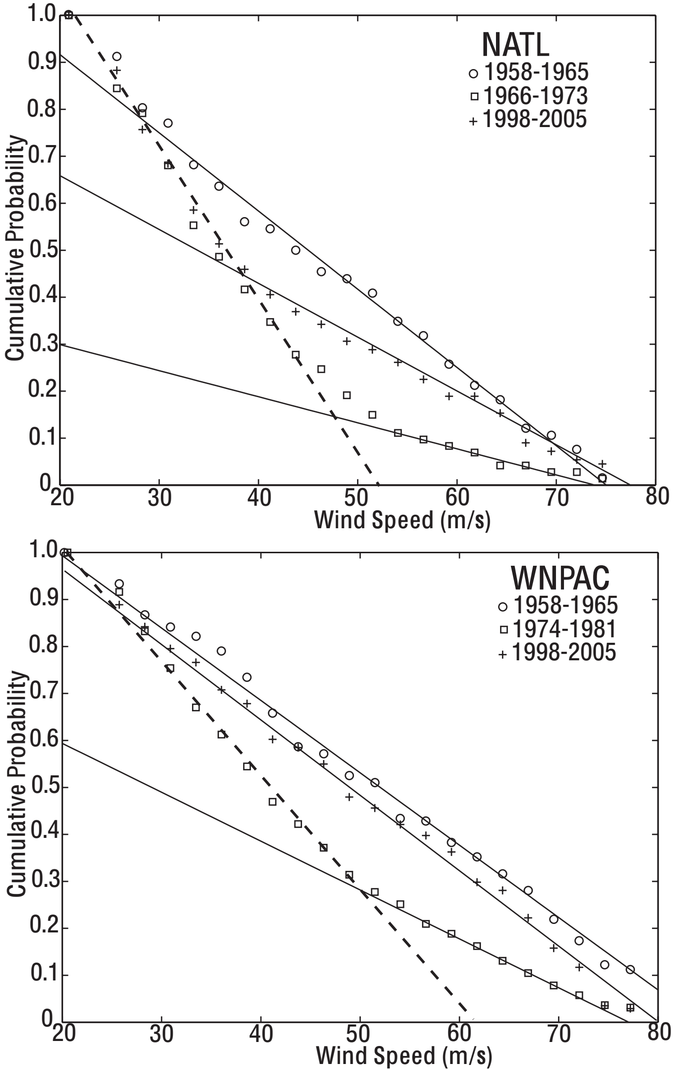
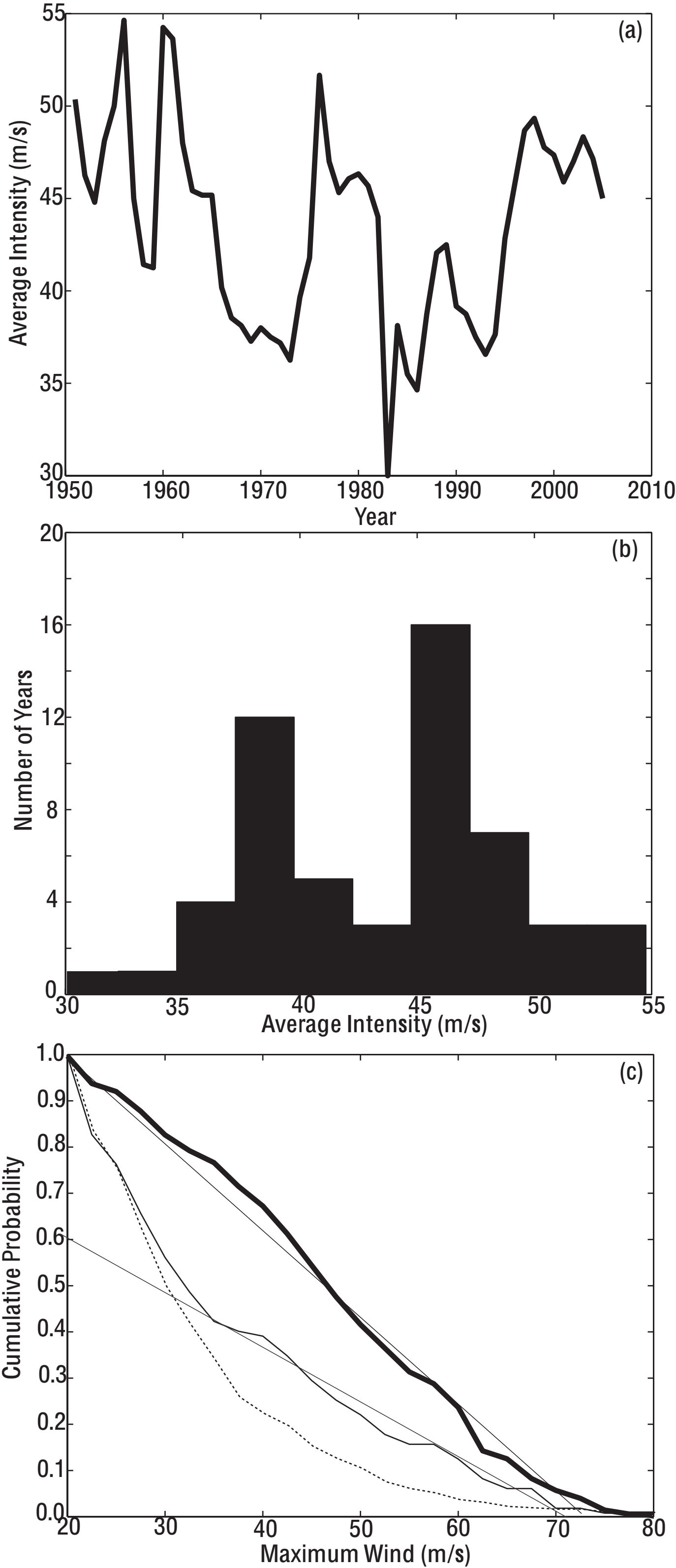
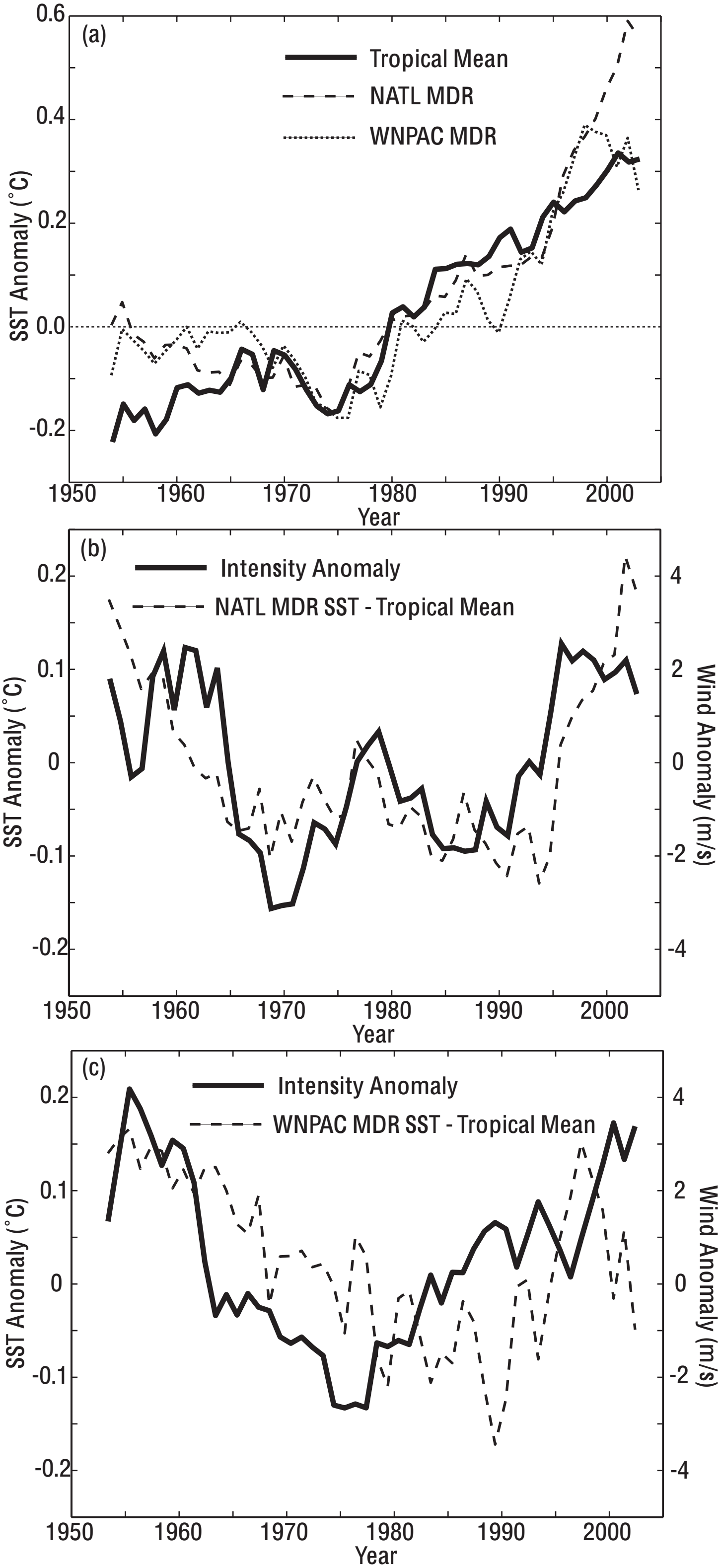

NATL
1958-1965
1966-1973
1998-2005
Cumulative Probability
Wind Speed (m/s)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
30
40
50
60
70
80
WNPAC
1958-1965
1974-1981
1998-2005
Cumulative Probability
Wind Speed (m/s)

Figure 3



(a)
Average Intensity (m/s)
55
50
45
40
35
30
1950
1960
1970
1980
1990
2000
2010
Year
(b)
Number of Years
20
16
12
8
4
0
30
35
40
45
50
55
Average Intensity (m/s)
(c)
Cumulative Probability
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
20
30
40
50
60
70
80
Maximum Wind (m/s)

Figure 4



(a)
Tropical Mean
NATL MDR
WNPAC MDR
SST Anomaly (˚C)
0.6
0.4
0.2
0.0
-0.2
1950
1960
1970
1980
1990
2000
Year
(b)
Intensity Anomaly
NATL MDR SST - Tropical Mean
SST Anomaly (˚C)
Wind Anomaly (m/s)
0.2
0.1
0
-0.1
-0.2
4
2
0
-2
-4
1950
1960
1970
1980
1990
2000
Year
(c)
Intensity Anomaly
WNPAC MDR SST - Tropical Mean
SST Anomaly (˚C)
Wind Anomaly (m/s)
0.2
0.1
0
-0.1
-0.2
4
2
0
-2
-4
1950
1960
1970
1980
1990
2000
Year