Environmental influences on tropical cyclones

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A general discussion of the role that environmental processes play on tropical cyclone frequency, structure and behaviour is given. This includes surface, surrounding system and stratospheric environmental influences. Environmental influences are examined on time-scales from the climatological to the diurnal. They indicate that the time and space varying environmental conditions of the tropical atmosphere have a profound influence on cyclone frequency, structure and behaviour. The extent of this environmental role has, in general, yet to be fully appreciated.

Introduction

The more one studies tropical cyclones (TC) the more one becomes impressed at the primary influences of environmental or external forcing processes in TC formation, structure, structure change and motion.

Tropical cyclones typically do not evolve in climatologically fixed environments but rather in environments exhibiting various favourable and continually alternating deviations from background climatology. TC formation is often dependent upon the evolving disturbances' asymmetrical and varying wind conditions. Such varying environmental conditions establish conditions for the occurrence of impulsive wind surge action from selective directions. These wind surges cause temporary bursts in deep convection due to local increases in low-level convergence. These deep convective bursts are typically not the product of the general internal dynamics of the weather system itself but rather are caused by temporary alterations imposed from the system's environment. They often last for periods of only 12 to 18 hours. These wind surge related deep convective bursts may energise a fledgling weather system and then recede with time to reappear again 1 to 3 days later when another wind surge-convective burst occurs. This second convective burst is often associated with rapid TC inner-core intensification. Other similar appearing environmentally forced wind surges may not penetrate to near the system's highest mesoscale vorticity regions. In these cases their resulting convective surges will typically have only minimal influence on inner-core intensity change. TCs should not be thought of as going through their life cycle changes in protected and nonchanging mean tropical or other special environments.

The TC's lower boundary surface, its upper boundary in the lower stratosphere, the character of the large-scale tropospheric vertical wind shear in which it is embedded, its surrounding upper tropospheric trough and anticyclonic flow pattern arrangements, all these and other environmental factors play important roles in how a TC will evolve or not evolve and on the TC's structure and behaviour.

Although the role of the TC environment has been known and accepted in varying degrees by TC specialists for many years, the full extent of and the frequent dominant role of this environment has (in the author's view) yet to be fully realised. Acceptance of the fundamental role of the TC's surrounding environment has been slower in coming to the research than to the forecasting communities. TC researchers' attention has tended to be more focused on the evolving characteristics of the cyclone vortex itself in contrast to the cyclone's surrounding environment and its changes.

The crucial role that the environment plays in TC behaviour appears to have been more readily appreciated by the forecaster. A forecaster will usually use whatever will help him make the best forecast. He is also taxed with the problem of the
non-event—i.e., distinguishing systems that do not develop from those that do. Without much inner region TC data the forecaster has, of necessity, had to focus his attention on conditions existing in the cyclone’s environment. These environmental conditions unfortunately can vary a great deal from storm to storm and with time during the lifetime of the cyclone. They also vary by season and region. For instance the formation of Atlantic TCs within the trade winds presents a different type of environment from the type of monsoon trough TC formations that occur most frequently in the other storm basins.

Synthesised pictures of the TC’s surrounding environment as it relates to TC behaviour have thus not been so well elucidated and generally accepted by a majority of observationalists. This should not imply that environmental conditions are not of crucial importance, however. This lack of general observational synthesis by the observationalists is undoubtedly an important contributing factor to the TC modeller’s greater concentration on the inner vortex. The Primitive Equation (PE) modeller has been able to resolve and understand the TC’s inner regions better than he has been able to learn of and appreciate the varying and complicated influences occurring in the TC’s environment. This greater concentration on the TC inner structure and its own difficult and complicated physics by the research community had lead to a de-emphasised view of the importance of the TC’s environment.

This paper is written to bring more attention to the likely important roles which the TC’s vertical and surrounding environments play in TC formation, structure and behavioural changes.

Nature of TC environmental influences

The TC’s environmental or external forcing influences may be thought of as being of three basic types—the surface environment, the horizontal tropospheric environment and the upper-level or stratospheric environment (see Fig. 1).

Type 1 surface environmental influences on TC formation (Palmen 1948; Gray 1968) and TC intensity (Miller 1958, 1964; Malkus and Riehl 1960) resulting from sea surface temperature (SST) and surface energy fluxes have been well known and accepted for a number of years. Numerical modelling studies by Ooyama (1969) and Rosenthal (1971) have given detailed quantitative verifications of the important influences of SST and surface energy flux. Merrill (1988a) and Emanuel (1985) have recently presented more observational and theoretical evidence of SST requirements on TC intensity.

The role on TCs of environmental influences resulting from surrounding tropospheric (Type 2) and upper-level stratospheric influences (Type 3) have been much less documented and consequently less understood and less accepted. In contrast with Type 1 environmental influences which typically undergo little day to day change and can consequently often be held fixed in modelling simulations, environmental influences of Type 2 can undergo large day to day changes. And Type 3 environmental conditions can undergo large inter and intra-seasonal changes not usually observed to occur in the tropical lower boundary layer from Type 1 influences.

More attention needs to be paid to the likely important and at times dominant roles of Type 2 and Type 3 environmental influences. Sensitivity modelling of Type 2 and 3 environmental influences ought to be encouraged.

Environmental influences may be of global, regional, synoptic or mesoscale. They manifest themselves on a wide variety of time-scales from the multi-decadal or climatological down to the diurnal. These time-scales may be divided into scales representative of the

(1) Climatological time-scale
(2) Decadal time-scale
(3) Inter-seasonal time-scale
(4) Intra-seasonal time-scale
(5) Few days time-scale
(6) Diurnal time-scale

Tropical cyclone activity as related to environmental changes occurring on each of these time-scales will now be discussed.

Climatological time-scale

The author (1975, 1979) has previously discussed how well seasonal global TC frequency can be related to the Coriolis parameter (f) and to the five seasonally varying parameters of low-level rela-
tive vorticity, the magnitude of the inverse of the vertical shear of the horizontal wind ($S_v$) between the lower and upper troposphere ($1/\theta_v$), ocean thermal energy or sea temperature excess above 26°C to a depth of 60 m, the vertical gradient of equivalent potential temperature ($\theta_v$) between the surface and 500 mb, and to the magnitude of middle tropospheric relative humidity (RH).

The author has defined a seasonal TC genesis parameter that quantitatively relates the product of these 6 seasonal parameters to the frequency of global TC formation in each 5° latitude-longitude square for each of the year’s 4 successive seasonal periods. The rationale for how these physical parameters are expected to be associated with area and seasonal variations in TC frequency is given in these papers.

It was surprising how well these six seasonal parameters were directly related to seasonal TC frequency even though individual TC occurrence can be so desultory as to largely manifest itself on the smaller meso space-scale. Tropical cyclones are not temporary aberrations within the placid large-scale tropical environment. Their multi-frequency alterations with season and their global location-differences are consistent and direct products of the long-term background environments of the tropical oceans.

**Decadal time-scales**

Atlantic TC activity has, over the last century, exhibited surprising decadal variability. Decadal changes of TC activity in the (northwest) Pacific are also observed. Recent evidence has also indicated that the 11-year sunspot cycle has a detectable association with TC activity in east-wind stratospheric QBO seasons.

Decadal time changes in TC activity become more evident for low latitude and intense TCs. Differences are more detectable in the number of hurricane or typhoon days or in Hurricane (or Typhoon) Destruction Potential (HDP). This new parameter is defined in terms of the seasonal sum of the observed or estimated cyclone maximum wind ($V_{max}$) or

$$\sum (V_{max})^2$$

for each 6-hour period within a season in which a hurricane (or typhoon) is in existence. The author chooses to employ this HDP measure of TC activity because the wind and storm surge destruction of a TC is more dependent upon the square of the TC's maximum wind than the maximum wind itself. There are quite notable decadal variations in this parameter.

**Atlantic.** In terms of HDP the period of 1886-1917 in the Atlantic was on an annual average basis about 150 per cent more active than the period of 1917-1946. The 23-year period of 1947 through 1969 was very much more active than the last 18 hurricane seasons (1970-87) have been. Since 1970, Atlantic hurricane activity, by the standard of HDP, has been very low. Although the annual number of named storms and hurricanes per season has averaged only 16 and 27 per cent during the period 1947-1969 compared with the period 1970-1987, HDP has been more than

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Fig. 2 Seasonal variation in Hurricane Destruction Potential (HDP) defined as the sum of all hurricane maximum wind speeds squared for each 6-hourly observing period throughout the hurricane season. Units $10^4$kn$^2$.
twice as great (see Fig. 2). The average annual number of 6-hourly TC reports with maximum winds ≥ 100 knots was over 3½ times more frequent during 1947-69 as compared with 1970-87. As aircraft reconnaissance data have been available since 1947, comparisons of the period 1947-1969 with 1970-1987 are considered to be reliable.

This more inactive Atlantic hurricane period since 1970 is well associated with the extended period of West African drought since 1970. These periods are also well differentiated in the western tropical Atlantic and Caribbean Basin by the significantly higher values of summertime surface pressure and Caribbean Basin 200 mb zonal winds (see Table 1 and 2 and Fig. 3). These pressure and wind differences are a consequence of the summertime Atlantic subtropical ridge and ITCZ being shifted further equatorward during this latter period. This latitude shift has caused stronger 200 mb zonal winds over the lower Caribbean and Atlantic. These stronger upper tropospheric westerly winds have inhibited the formation of TCs originating from African disturbances. It is these African originated TCs which are of greatest intensity and have the longest storm tracks. This latitudinal shift of Atlantic wind patterns is in response to the basic global general circulation changes that have occurred over the last 18 years which has so affected West Africa and is detectable in other regions.

Table 1. August through October Mean Sea-Level Pressure Anomaly (SLPA) in mb for the Caribbean-Gulf of Mexico Region.

<table>
<thead>
<tr>
<th>Period</th>
<th>Difference 1970-86 minus 1950-69</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950-1969</td>
<td>+.27</td>
</tr>
<tr>
<td>1970-1987</td>
<td>+.36</td>
</tr>
</tbody>
</table>

Table 2. Lower Caribbean Mean 200 mb Zonal Wind Anomaly (ZWA) in m s⁻¹ for 1954-69 and 1970-80.

<table>
<thead>
<tr>
<th>Period</th>
<th>Difference 1970-86 minus 1954-69</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954-1969</td>
<td>−1.1</td>
</tr>
<tr>
<td>1970-1986</td>
<td>+2.3</td>
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NW Pacific. As in the Atlantic there has also been a decrease in TC activity in the NW Pacific between 1952-71 and 1972-86. Table 3 shows the differences between several indicators of NW Pacific TC activity equatorwards of 20° latitude. These multi-decadal changes are, like the Atlantic TC activity and the changes in West African drought condition since 1970, a result of basic decadal changes in the global general circulation.

![Fig. 3 Lower Caribbean Basin zonal wind profiles during the periods of 1954-69 (solid line) and the period 1970-87 (dashed line).](image)

**Table 3. Changes in Annual Average NW Pacific Tropical Cyclone Activity in 1952-71 vs. 1972-86.**

<table>
<thead>
<tr>
<th></th>
<th>1952-71</th>
<th>1972-86</th>
<th>% Annual Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Number of Typhoons</td>
<td>19.2</td>
<td>15.0</td>
<td>Higher 28%</td>
</tr>
<tr>
<td>Mean Number of Typhoon Days</td>
<td>318</td>
<td>215</td>
<td>Higher 48%</td>
</tr>
<tr>
<td>Annual Mean Typhoon Destruction Potential (HDP)</td>
<td>2987</td>
<td>1735</td>
<td>Higher 72%</td>
</tr>
<tr>
<td>No. of Typhoons With V&lt;sub&gt;max&lt;/sub&gt; ≥ 120 knots</td>
<td>118</td>
<td>57</td>
<td>Higher 207%</td>
</tr>
<tr>
<td>No. of Typhoons With V&lt;sub&gt;max&lt;/sub&gt; ≥ 150 knots</td>
<td>40</td>
<td>12</td>
<td>Higher 333%</td>
</tr>
</tbody>
</table>

**Sunspot activity and TC activity.** The surprising new observations of Labitzke and Van Loon (1987) and Van Loon and Labitzke (personal communication) on the association of sunspot activity with tropospheric and stratospheric circulation patterns when stratification is made by east vs west wind stratospheric QBO period is quite unexpected. Shapiro (personal communication) has already indicated a link between sunspot activity and Atlantic TC activity in east wind QBO situations.

A recent 40-year analysis by the author of Atlantic TC activity separated by QBO east and west wind situations shows that a weak direct
relationship ( 0.3 correlation) between HDP and sunspot activity in east wind QBO seasons. No relationship is found in QBO west wind seasons. A similar but opposite correlation is found between sunspot and TC activity in east wind QBO seasons in the NW Pacific. This topic obviously needs more investigation.

At present we have no physical reasons why such a sunspot-TC association should be present in QBO east wind phase conditions. This sunspot relationship, although very weak, is nevertheless indicative of yet another external background influence on the TC.

Inter-seasonal time-scales

There are striking season to season variations in Atlantic TC activity which can be associated with the equatorial stratospheric QBO and the El Niño. Other weaker season to season TC activity relationships exist for seasonal variations in sea-level pressure anomaly, and upper tropospheric zonal winds. And there may be other parameter associations not yet found. NW Pacific typhoon activity also had detectable QBO and El Niño associations. Such relationships have, in general, yet to be carefully studied in the other ocean basins.

The QBO-TC association. There are nearly twice as many Atlantic hurricane days in seasons when stratospheric QBO winds are from a westerly as opposed to an easterly direction (Gray 1984). There are more intense and long lasting hurricanes in westerly phase QBO seasons. If seasonal hurricane activity is expressed in terms of HDP, it is possible to give quite skilful seasonal estimates of Atlantic HDP only from knowledge of the Balboa (9°N, 80°W) 50 mb September mean zonal wind. For the seasons of 1949-1986 the Balboa 50 mb zonal wind shows a positive correlation with Atlantic seasonal HDP at a level of 0.58. It is quite surprising that up to one-third of Atlantic season to season hurricane activity variance can be accounted for from just the measurement of stratospheric zonal wind speed from only one station and one month. There is no comparative tropospheric measurement which can explain this degree of Atlantic seasonal hurricane variance. The 50 mb wind data from other lower Caribbean stations give similar correlations. Slightly weaker relationships can also be observed from 70 mb low latitude wind data. It is the low latitude tropical systems coming off Africa that are most associated with the sign of the QBO wind phase. It is also surprising to note that 35 of 42 of the most intense hurricanes (as determined by maximum wind speed) in the Atlantic during the period of 1950-1987 occurred in QBO west wind phase as compared to the east wind QBO phase.

It is hypothesised that TC activity is inhibited in easterly phase QBO periods because of the extra lower stratospheric wind ventilation and resulting greater upper tropospheric to lower stratospheric vertical wind shear. As shown in Fig. 4 this ventilation and upper-level wind shear is much reduced in QBO west wind situations. Notice that in this 8-15° latitude belt, lower stratospheric zonal winds in the QBO west wind phase do not actually blow from the west but are weaker than normal from the east.

Fig. 4 Idealised portrayal of the vertical profile of zonal wind (u) and slope of inner-core deep convection in the tropical east wind QBO phase (left diagrams) vs the same conditions in the west wind QBO phase.

In the NW Pacific the QBO wind oscillation is not as strongly associated with typhoon activity. There is, however, a noticeable QBO-TC relationship at latitudes equatorwards of 15°. In contrast to the Atlantic, however, NW Pacific TC activity is more frequent in the QBO easterly wind phase. If the QBO is in its easterly phase, lower latitude NW Pacific TC activity will typically he higher than it was the year before. In westerly phase QBO seasons NW Pacific activity will typically be less than it was the year before. This back and forth year to year variation in NW Pacific TC activity has been observed in 24 of 34 years (70%) and 22 of 29 non-El Niño years (76%).

These QBO-TC relationships appear to result from upper-level vertical wind shearing influences associated with the penetration of cumulonimbus convection into the lower stratosphere within the TC's inner regional (0-2° radius). Convective penetration can frequently extend to levels as high as 80-60 mb. When lower stratospheric zonal winds are very much different from upper tropospheric zonal winds, TC upper-level vertical wind shear influences become too
strong and the tilt between the lower stratosphere and the upper troposphere becomes too large. This reduces the maintenance of the vertical structure of the TC's inner core and inhibits vertical wind shears and appears to also inhibit TC formation.

There are many rawinsonde, radar, and satellite measurements to indicate that the inner cores of tropical cyclones or their associated influences extend to levels well within the lower stratosphere. There are also the visual descriptions of many U-2 aircrews who have flown over the tops of hurricanes at lower stratospheric levels as to the vertical extent of cumulonimbus into the stratosphere within the cyclone's central regions.

New satellite IR analyses (Zehr 1988) of cloud top temperatures are showing that the central regions (0–2° radius) of TCs often have mesoscale regions where cloud top temperatures are as cold as −75° and −85°C—levels near or above the tropopause. It is likely that individual convective cells (presently not resolved by these GMS IR satellite images) extend to considerably higher levels. Stereographic satellite and sky laboratory visual cloud height measurements (Black 1977) support this assessment. Although somewhat weaker than at 30 or 50 mb, the QBO zonal wind signal is also well detectable down to levels of 70 mb (18.6 km) and 80 mb (17.9 km). The author is preparing another paper which more fully documents the evidence for the vertical penetration of TC inner-core convection into the lower stratosphere and the likely physical implications of this for the QBO-TC association. There are also other TC influences not directly observable in cloud heights (such as gravity or other types of vertical wave action) which extend upwards to 30 mb or higher and which are associated with variations in TC frequency, especially in the Atlantic.

The author attributes the opposite Atlantic and NW Pacific QBO-TC association to the differences in upper tropospheric zonal wind regimes in the two oceans as portrayed in Fig. 5. Hurricane formation in the Atlantic is typically inhibited by too strong values of upper-tropospheric (~ 150 mb) westerly wind. This creates too large values of tropospheric vertical wind shear. Hurricane formation occurs when upper-tropospheric zonal winds are weaker than normal from the west or stronger than normal from the east as indicated by the dashed line of the left diagram in Fig. 5. It is at these times that the vertical wind shear from point 2 (70 mb) in the west wind QBO phase to point 1 (200 mb) is smallest. Hurricane formation and stronger intensity hurricanes are more favoured in these weaker upper-level vertical shear cases. In the QBO east wind phase, however, the 70 mb zonal wind (point 3) causes much larger vertical wind shear between points 3 and 1. Conditions are less conducive to TC development and TC intensity change.

The situation is reversed in the NW Pacific. Here 200 mb zonal winds are typically stronger from the east during the most active TC months. In this case the vertical wind shear between 150 mb (point 1) and 70 mb (point 2) is larger in west wind phase QBO situations than in east wind QBO situations (points 3 to 1). It might then be expected that the stratospheric QBO might act differently in the NW Pacific than in the Atlantic.

Regardless of this physical explanation these QBO-TC relationships are, nevertheless, strongly indicative of the likely role of the stratosphere in TC dynamics. They obviously need more analyses in these and in the other TC basins.

El Niño-TC association. El Niño influences on Atlantic hurricane activity have been observationally documented (Gray 1984) and are now well accepted. In terms of seasonal number of hurricane days, the Atlantic has on average only about 40 per cent as many hurricane days in seasons when moderate and strong El Niño events are occurring in comparison with other seasons. These seasonal reductions in Atlantic hurricane activity in El Niño years are well related to the anomalous increases in upper-tropospheric zonal winds over the lower Caribbean Sea and eastern tropical Atlantic which almost always occur during El Niño years in comparison with other years. Numerical modelling and other
observational analyses on the influence of positive eastern and central Pacific tropical SSTs verify that such enhancement of upper tropospheric zonal winds are to be expected 40 to 80° to the east of such SST warming events.

It is known that El Niños cause South Pacific TC activity to occur further eastward than normal and also to bring about a general suppression of TC activity in the Coral Sea and north Australia region.

El Niño-TC associations have also been noted in the NW Pacific. This has been previously reported on by Chan (1985) who showed that there are biennial and 3 to 4 year peaks in NW Pacific TC activity. Chan noted that TC activity was typically suppressed in periods of El Niño weakening or just following the El Niño event. This often manifests itself in a reduction of NW Pacific TC activity in the spring and summer following the El Niño event. Dong (personal communication) has also verified this.

We observe that these alterations in TC activity are associated with alterations of the 150 mb zonal winds in the 5 to 15° latitude belt of the NW Pacific as indicated in Fig. 6. Upper tropospheric zonal winds are stronger from the east in the periods when SE Pacific tropical SSTs are warmest or are warming up with time vs the periods when SE Pacific SSTs are cooler than normal or cooling with time. Lower latitude NW Pacific TC activity in these warmer SST periods is about 150 per cent greater than in cool SST periods.

**Global circulation-TC and regional associations.** There is, of course, a number of other global circulation and regional circulation changes not related to the QBO and El Niño which can cause substantial variations in season to season TC activity.

The author has previously discussed (1986) how Atlantic TC activity is (beside QBO and El Niño associations) also dependent upon variations in seasonal low latitude Caribbean basin 200 mb wind in non-El Niño years and seasonal sea-level pressure anomaly (SLPA). Shapiro (1982a,b) earlier noted SLPA features associated with seasonal Atlantic hurricane variability. Nicholls (1979) has related Australian region seasonal TC activity to the Darwin surface pressure. Other similar types of seasonal parameter and TC activity relationships have been reported and it is likely that other relationships may be uncovered in the future. These seasonal global and regional environmental circulation anomalies which lead to variations in season to season TC activity should be noted. They are yet another piece of evidence for the substantial role which the environment plays in TC activity.

**Intra-seasonal time-scales**

Global TC activity clusters in time. One can often observe 10 to 20 cyclones about the globe within an active 2 to 3-week period. These active periods are typically separated by 2 and 3-week periods when there is little TC activity. The author has previously discussed this typical TC clustering in time separately for the northern and southern hemispheres (Gray 1979) and for the whole globe combined (WMO 1986).

Figure 7 portrays global information for a recent seven-year period of active and inactive periods of named TC formation. The number of named storms whose initial detection date fell within the various shaded (active) and unshaded (inactive) periods is shown by the number within each time period. Even though the months of April to June have a concentration of inactive periods, the back and forth oscillation of these 2 to 3-week periods of active and inactive storm intervals is evident in all years. Note how typical 15 to 25-day active periods of named storm formation alternate with 15 to 25-day periods of general TC inactivity. Although quite variable in length, active and inactive periods each average roughly 20 days or so in duration. About 7 or 8 named storms form during a typical active period while only 1 or 2 cyclones form during the usual inactive periods.
Similar time clustering of weaker tropical weather systems such as cloud clusters is much less evident. Cloud cluster systems exist at nearly any time and can occur in large-scale environmental situations not conducive to cyclone genesis. It appears that active cyclone periods are a product of favourable large-scale general circulation changes in the tropical atmosphere which occur on timescales of about 1.5 to 25 days or so. Unfavourable TC periods exist for similar periods.

These oscillation periods of named storm activity appear to have a degree of correspondence with the 40 to 50-day oscillation which has been detected in tropical surface pressure, upper-level zonal winds, and outgoing longwave radiation (OLR). This 40 to 50-day tropical oscillation, first detected by Madden and Julian (1971, 1972), needs to be better sorted out with respect to TCs. The author has previously noted (unpublished) a 62 to 38 per cent modulation in NW Pacific typhoon activity which appears to be associated with an approximately 40 to 60-day oscillation of 200 mb minus 850 mb vertical wind shear as determined by the Truk (7°N, 152°E) rawinsonde during a 10-year period during the 1970s. Periods were equally divided into successive high and low values of 200 mb minus 850 mb zonal wind shear. Other researchers have also recently detected TC activity variations on this timescale.

Shapiro (1987) has recently discussed intra-seasonal regional circulation pattern differences that can be related with intra-seasonal differences in Atlantic TC activity. It is likely that most intra-seasonal TC activity variations can be associated with certain characteristic regional or global circulation pattern alterations. Intra-seasonal TC variations are usually not well related to intra-seasonal variations in SST, lapse-rates and rainfall, however. It is the intra-seasonal circulation pattern differences that are most responsible for such intra-seasonal TC variations.

**Few days time-scale**

It is the larger-scale synoptic environment in which the tropical disturbance or TC exists that has the most influence on how the TC will evolve, how it will move and how large and intense it will become. These background environment changes occur on timescales of a few days.

There is no question that the TC's surrounding large-scale deep tropospheric flow patterns primarily determine TC movement. The characteristics of the broader-scale lower-level flow patterns (Merrill 1984) in which the TC forms or into which it moves largely determine the areal extent of the TC's cyclonic circulation. Although not yet well understood, it is also observed that the characteristics of the TC's surrounding upper tropospheric flow patterns have a strong and at times a dominant influence on the TC's inner-core intensity change as has been discussed by Sadler (1978), Holland and Merrill (1984), Merrill (1988a,b), Chen and Gray (1984) and many other observational researchers and forecasters.

Influences on TC structure change resulting from upper-level shearing patterns occurring when TCs move poleward into strong baroclinic currents are well known. This often results in the upper portions of the TC being detached from its lower circulation. This is entirely a result of the influence of the TC's environment.

There are many other characteristics of the TC's structure and its alteration that are due to environmental forcings of various types. It is in the TC's formation processes that environmental influences appear to be especially dominant.

**TC formation.** Tropical disturbances that develop into named TCs usually have distinctively different surrounding environmental flow fields from those tropical disturbances that do not become named storms.

Tropical cyclone formation will likely not be well understood until we more fully document and understand the differences in physical processes occurring between the environmental flow features of those tropical disturbances that develop into named cyclones in contrast with the environmental flow features of those prominent tropical disturbances that do not develop. Apparently successful numerical modelling of TC formation is unlikely to be well accepted as the way the formation process occurs in nature until similar numerical modelling of the non-formation process with realistic time varying environmental data sets is also accomplished for comparative purposes.

Holland (1987) appeared to state the case well when he recently wrote:

'There is, in particular, an inclination to assume that because one set of mechanisms
produce a hurricane-like vortex that other processes are unimportant. For example, each of the axisymmetric analytic and numerical models described by Ooyama (1969), Challa and Pfeffer (1980), and Emanuel (1986) contains quite explicit physics from the others, yet each also produces "realistic" tropical cyclone structures. Further observational studies have noted consistent environmental interactions associated with tropical cyclone formation and structure changes, yet most numerical models develop tropical cyclones without including such environmental interactions.

It is the interaction of the fledgling tropical disturbance with its transient surrounding environment and with the lower stratosphere that appears to have been the most neglected component in the numerical modelling studies of TC formation.

The most consistent differences we have found in two decades of project observational research on the topic of TC formation shows that:

(1) developing systems must have very weak tropospheric vertical wind shear in the places where they form (Gray 1968), and

(2) the large-scale low-level tropospheric winds at radii of 3 to 6° around developing systems are, on average, significantly higher for developing than for the non-developing systems. (Many project papers have verified this—see for example Gray 1968; McBride and Zehr 1981; Lee 1986.)

But these two solid observational factors, although almost always necessary as background features for distinguishing between the typical formation and the typical non-formation case, do not always make this distinction in the individual case. Other relevant processes also appear to be involved such as the presence or lack of surrounding disturbance asymmetrical low-level wind surge action as discussed by Love (1985a,b) for the synoptic scale. This surge action is itself dependent upon the time varying character of the large-scale environment.

This large-scale surrounding wind surge action often leads to strong asymmetrical mesoscale inflow into the fledgling disturbance which is sometimes able to penetrate to near the disturbance's centre (see Fig. 8). This can initiate deep convection near the centre or within mesoscale regions of the disturbance where the relative vorticity is the highest (often many times larger than the earth's rotating). Our project's new observations using low-level investigative reconnaissance flights into NW Pacific early-stage forming and non-forming disturbances (Middlebrooke 1988; Lunney 1988) are indicating that TC formation usually requires that this type of mesoscale inner disturbance wind surge penetration take place.

Figures 9 and 10 give examples of the type of low-level environmental induced wind surge forcing that often occurs and which leads to the formation of the small-scale wind surge we so often observe in the early stage tropical disturbance transformation to named storm status. Named storm formation usually requires that these low-level wind enhancements of environmental origin be able to cause rapid radial wind inflow to near the tropical disturbance's region of maximum vorticity. This often results in a 12 to 18-hour blow-up and concentration of inner disturbance deep convection and the initiation of an unstable growth process. It appears that this type of wind surge penetration and inner disturbance convective blow-up typically does not take place if environmental conditions surrounding the disturbance are not conducive to such asymmetric surge generation. Prominent non-developing disturbances tend to lack such wind surge penetration to their areas of highest vorticity.

Without the inclusion of the special favourable asymmetrical influences of the surrounding disturbance environment (often manifesting themselves in low-level wind surge action) it is not, in general, possible to realistically explain early-stage tropical disturbance growth on the time-
Fig. 9 The 850 mb flow pattern and isotachs on 30 October-2 November, 000 UTC for the early stages of genesis of pre-typhoon Vera as given by the European Centre for Medium Range Weather Forecasts (ECMWF) analysis. The shaded areas are the regions with a wind speed > 10 m s⁻¹. The centres of the pre-typhoon vortex are shown by the large dots. The maximum intensity at this time is 25 knots or less (from Lee 1986).

(a) 140°E 160°E

October 30, 1979 (10 kts)

(b) 140°E 160°E

October 31, 1979 (10 kts)

(c) 140°E 160°E

November 1, 1979 (15 kts)

(d) 140°E 160°E

November 2, 1979 (25 kts)

scale to which it occurs in nature. Most numerical models that have simulated early-stage TC development on a realistic time-scale appear to have done so by employing heating schemes that give unrealistically high values of condensation and vertical motion as compared with early stage composite rawinsonde analysis (Lee 1986).

Numerical models have yet to simulate these types of horizontal transient environmental forcings. This type of surge action cannot be treated by symmetric models.

There is little doubt that the environmental influences that are operating on a time-scale of one to a few days are the most dominant factors in understanding TC formation, structure, structure change and motion. This does not, however, negate the significant role also played at times by environmental influences on other time-scales.
Diurnal influences

As discussed by Gray and Jacobsen (1977), Foltz and Gray (1979) and McBride and Gray (1980a,b) there are very large differences in the diurnal variations in tropical region deep convection and in compensating clear region subsidence. Deep convection and clear region subsidence both have morning maximums which are, on average, twice as large as evening minimums.

New area integrated IR cloudiness measurements of TCs by Zehr (1987) have shown how remarkably consistent is the TC's diurnal cycle of deep convection as measured by 3-hourly geostationary meteorological satellites (GMS) measurements. Figure 11 is a typical case. A similar cycle is observed in nearly all of our other many TC cases. Note the consistent diurnal cycle in deep convection (or areas of IR cloudiness colder than $-65^\circ C$) with a near sunrise maximum and an early evening minimum. This diurnal cycle in TC deep convection is found in both the inner and outer regions of the TC and in all TC intensity classes. It is only found in the very cold clouds ($<-65^\circ C$). We attribute this large diurnal cycle in TC deep convection to day vs night differences in tropospheric net radiational cooling. The enhanced night-time radiational cooling in the clear and partly cloudy areas around the TC causes enhanced mass subsidence and brings about a simultaneous mass compensating increase in full cumulonimbus convection.

Although this diurnal cycle in deep convection does not significantly influence the TC's tangential wind field, this is yet another illustration of environmental or external forcing (i.e. in this case radiation) on the TC. Is it not surprising that the deepest convection of the TC would have such a large and systematic diurnal modulation? Surely the internal dynamics of the TC itself with their lack of observable diurnal differences in tangential wind cannot be thought of as being responsible for such a systematic deep convective diurnal cycle.

Fig. 11 Area of IR observed cloudiness colder than $-65^\circ C$ (165 mb level) within 96$^\circ$ radius for NW Pacific Typhoon Forrest in September 1983. Dotted vertical lines are at 24-hr intervals and correspond to 00Z or about 10am local time. The numbers in the upper right show the maximum wind speeds at each 00UTC time in knots.
Suggestion to TC modellers

The author would like to encourage new 3-D numerical modelling sensitivity studies of a number of the environmental influences here discussed. I would particularly like to encourage sensitivity modelling of:

1. The influence on TC formation and intensity change of asymmetrical wind surge action which causes strong and limited periods of inward radial mass penetration to near the vortex centre.

2. The role of large-scale horizontal wind blowthrough or ventilation across the TC at different levels in relation to its evolving structure and intensity. This involves the role of tropospheric vertical wind shear.

3. The above discussed TC vs QBO associations calls for new PE modelling efforts of the likely greater than previously expected influence of the lower stratosphere on TC formation and intensity.

4. The role of favourable positioning of upper-tropospheric troughs and anticyclones around the TC to TC intensity change.

5. The influence of different arrangements of large-scale lower tropospheric flow patterns to TC outer circulation size.

These are only a few of the more pressing sensitivity modelling studies that would likely be beneficial to our increased knowledge of the many ways environmental processes can influence TCs.

Summary

It is time that we TC researchers develop a better appreciation of the likely important role of the background environment on tropical cyclones. We have, in general, given a disproportionate emphasis to the TC vortex itself at the expense of the TC’s environment. If we do not develop a better appreciation of the various environmental processes affecting the tropical cyclone it is likely that we will not be able to greatly improve our understanding and predicting of these violent and mysterious whirlwinds.

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