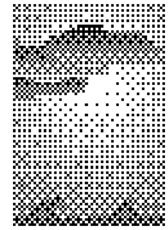
Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment



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ABSTRACT

The very limited instrumental record makes extensive analyses of the natural variability of global tropical cyclone activities difficult in most of the tropical cyclone basins. However, in the two regions where reasonably reliable records exist (the North Atlantic and the western North Pacific), substantial multidecadal variability (particularly for intense Atlantic hurricanes) is found, but there is no clear evidence of long-term trends. Efforts have been initiated to use geological and geomorphological records and analysis of oxygen isotope ratios in rainfall recorded in cave stalactites to establish a paleoclimate of tropical cyclones, but these have not yet produced definitive results. Recent thermodynamical estimation of the maximum potential intensities (MPI) of tropical cyclones shows good agreement with observations.

Although there are some uncertainties in these MPI approaches, such as their sensitivity to variations in parameters and failure to include some potentially important interactions such as ocean spray feedbacks, the response of upper-oceanic thermal structure, and eye and eyewall dynamics, they do appear to be an objective tool with which to predict present and future maxima of tropical cyclone intensity. Recent studies indicate the MPI of cyclones will remain the same or undergo a modest increase of up to 10%–20%. These predicted changes are small compared with the observed natural variations and fall within the uncertainty range in current studies. Furthermore, the known omissions (ocean spray, momentum restriction, and possibly also surface to 300-hPa lapse rate changes) could all operate to mitigate the predicted intensification.

A strong caveat must be placed on analysis of results from current GCM simulations of the "tropical-cyclone-like" vortices. Their realism, and hence prediction skill (and also that of "embedded" mesoscale models), is greatly limited by the coarse resolution of current GCMs and the failure to capture environmental factors that govern cyclone intensity. Little, therefore, can be said about the potential changes of the distribution of intensities as opposed to maximum achievable intensity. Current knowledge and available techniques are too rudimentary for quantitative indications of potential changes in tropical cyclone frequency.

The broad geographic regions of cyclogenesis and therefore also the regions affected by tropical cyclones are not expected to change significantly. It is emphasized that the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy. The very modest available evidence points to an expectation of little or no change in global frequency. Regional and local frequencies could change substantially in either direction, because of the dependence of cyclone genesis and track on other phenomena (e.g., ENSO) that are not yet predictable. Greatly improved skills from coupled global ocean–atmosphere models are required before improved predictions are possible.

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1. Introduction

a. Tropical cyclones

Tropical cyclones are perhaps the most devastating of natural disasters both because of the loss of human life they cause and the large economic losses they induce (Anthes 1982; Gray and Landsea 1992; Gray et al. 1993, 1994; Tonkin et al. 1997; Diaz and Pulwarty 1997). Vulnerability to tropical cyclones is becoming more pronounced because the fastest population growth is in tropical coastal regions. Understanding tropical cyclone genesis, development, and associated characteristic features has been a challenging subject in meteorology over the last several decades. In recent years, attempts to associate tropical cyclone trends with climate change resulting from greenhouse warming has led to additional attention being paid to tropical cyclone prediction (e.g., Emanuel 1987; Evans 1992; Lighthill et al. 1994). Exploring possible changes in tropical cyclone activity due to global warming is not only of theoretical but also of practical importance.

A tropical cyclone (TC) is the generic term for a nonfrontal synoptic-scale low pressure system originating over tropical or subtropical waters with organized convection and definite cyclonic surface wind circulation. Tropical cyclones with maximum sustained surface winds of less than 17 m s^{-1} are generally called "tropical depressions." Once a tropical cyclone achieves surface wind strengths of at least 17 m s^{-1} it is typically called a "tropical storm" or "tropical cyclone" and assigned a name. If the surface winds reach 33 m s^{-1}, the storm is called a "typhoon" (the northwest Pacific Ocean), a "hurricane" (the North Atlantic Ocean and the northeast Pacific Ocean), or a "severe tropical cyclone" (the southwest Pacific Ocean and southeast Indian Ocean) (Neumann 1993).

Tropical cyclones derive energy primarily from evaporation from the ocean and the associated condensation in convective clouds concentrated near their center (Holland 1993), as compared to midlatitude storms that primarily obtain energy from horizontal temperature gradients in the atmosphere. Additionally, tropical cyclones are characterized by a "warm core" (relatively warmer than the environment at the same pressure level) in the troposphere. The greatest temperature anomaly generally occurs in the upper troposphere around 250 hPa. It is this unique warm-core structure within a tropical cyclone that produces very strong winds near the surface and causes damage to coastal regions and islands through extreme wind, storm surge, and wave action.

Tropical cyclones occur predominantly over tropical oceans where observed meteorological data are scarce. In addition, the destructive nature of tropical cyclones makes their observations difficult and expensive. Reconnaissance aircraft, satellite observations, radar observations, rawindsonde observations, and conventional surface observations are used in monitoring tropical cyclone frequency and intensity. The best method of observing a tropical cyclone is by direct observations from reconnaissance aircraft, particularly for monitoring location and intensity. Satellite data, although extremely useful and widely used, are not a complete substitute for reconnaissance aircraft observations because of the difficulties involved in translating radiances into required parameters. The Dvorak technique (Dvorak 1984) in combination with spiral overlays and subjective interpretations is commonly applied to estimate the location and intensity of tropical cyclones from satellite imagery. However, there may be large errors if these estimates are made from the satellite observations alone, and calibration procedures based on aircraft reconnaissance have so far only occurred for the North Atlantic and western North Pacific. The uncertainties associated with the satellite imagery analysis are discussed in detail by Holland (1993). Unfortunately, the high cost of reconnaissance aircraft means that such observations are now routinely available only in the North Atlantic Ocean.

Each year approximately 80–90 tropical cyclones reaching tropical storm intensity occur around the globe (Gray 1979; Anthes 1982; Frank 1987; McBride 1995) with about two-thirds of these reaching hurricane intensity. The earlier statistics are updated to 1995 in Table 1. The globally averaged annual variation of cyclone occurrence is only about 10%. Regional variations are much larger, often around 30%, and no obvious correlations exist in variations between different regions (Raper 1993). For instance, in the Australian–southwest Pacific region, the average number of tropical cyclones observed during 1950–86 was 14.8, with an annual variation of 40% (Evans 1990). As pointed out by Holland (1981), the quality of the tropical cyclone databases can be highly variable. Different definitions, techniques, and observational approaches may produce errors and biases in these datasets that could have implications for the study of the natural variation of tropical cyclone activities and the detection of possible historical trends (e.g., Nicholls et al. 1998, manuscript submitted to *J. Climate*).

TABLE 1. Averaged annual total numbers of tropical cyclones (wind at least 17 m s^{-1}) and intense tropical cyclones (wind at least 33 m s^{-1}) and their standard deviations over all tropical cyclone basins (unit: number per year). Data are retrieved from National Climate Data Center GTECCA dataset for the period 1970–95.

		North Atlantic Basin	East North Pacific Basin	North Indian Basin	South-west Indian Basin	South-west Pacific Basin	West North Pacific Basin	Totals
Mean	TC	9.3	17.8	5.2	10.6	16.4	26.8	86.1
	Intense TC	5.0	10.3	2.0	4.8	7.5	16.4	45.9
Std	TC	2.6	4.7	2.2	3.2	4.6	3.9	7.9
	Intense TC	1.7	3.5	1.9	2.6	2.6	3.4	7.0

Note: Totals = global total numbers.

Gray (1968, 1975) produced a global map of genesis points for all tropical cyclones over the 20-yr period 1952–71. Preferred regions of tropical cyclone formation include the western Atlantic, eastern Pacific, western North Pacific, north Indian Ocean, south Indian Ocean, and Australian–southwest Pacific. Most of the cyclones (87%) formed between 20°N and 20°S. About two-thirds of all tropical cyclones form in the Northern Hemisphere, and the number of tropical cyclones occurring in the Eastern Hemisphere is about twice that in the Western Hemisphere. These differences are partially due to the absence of tropical cyclones in the South Atlantic and the eastern South Pacific during the 20-yr period study.

Tropical cyclones are seasonal phenomena: most tropical ocean basins have a maximum frequency of cyclone formation during the late summer to early autumn period. This is associated with the period of maximum sea surface temperature (SST), although other factors, such as the seasonal variation of the monsoon trough location, are also important (Frank 1987; McBride 1995). In the Australian region, the tropical cyclone season typically extends from November to May with maximum cyclone activity in January and February (e.g., Holland 1984a,b; Holland et al. 1988; Evans 1990). The storm season in the North Atlantic becomes highly active during August–October, with a maximum frequency of occurrence in September (Neumann et al. 1985). The average tropical cyclone occurrence over the western North Pacific is about 26 per year, with a maximum cyclone activity in August and a highly seasonal variation. This total is more than in any other region (Xue and Neumann 1984), and this is also the only region where tropical cyclogenesis has been observed in all months of the year. The western North Pacific is particularly noted for the occurrence of very large and very intense tropical storms (Frank 1987; McBride 1995). Indeed, the 12 lowest central pressures in the global record have been observed for the tropical cyclones in the western North Pacific (Holland 1993).

The favorable locations for tropical cyclone genesis are in or just poleward of the intertropical convergence zone (ITCZ) or a monsoon trough (Gray 1968). The ITCZ is generally located near the monsoon shear line between low-level equatorial westerlies and easterly trades. The disturbances embedded in the easterly trade wind flow are also conducive to the formation of tropical cyclones (Frank 1987).

The physical parameters favorable for cyclogenesis have been summarized by Gray (1968, 1975, 1979, 1981). He found that the climatological frequency of tropical cyclone genesis is related to six environmental factors: (i) large values of low-level relative vorticity, (ii) Coriolis parameter (at least a few degrees poleward of the equator), (iii) weak vertical shear of the horizontal winds, (iv) high SSTs exceeding 26°C and a deep thermocline, (v) conditional instability through a deep atmospheric layer, and (vi) large values of relative humidity in the lower and middle troposphere.

Although the above six parameters are not sufficient conditions for cyclogenesis, Gray (1975, 1981) argued that tropical cyclone formation will be most frequent in the regions and seasons when the product of the six genesis parameters is a maximum. Gray defined the product of (i), (ii), and (iii) as the dynamic potential for cyclone development, and the product of (iv), (v), and (vi) may be taken as the thermodynamic potential. He derived the seasonal genesis parameter from these six parameters (Gray 1975).

b. Tropical cyclones and climate change

The Intergovernmental Panel on Climate Change (IPCC) "Impacts, Adaptation and Mitigation of Climate Change" report (Watson et al. 1996) stated that

> Reinsurers have noted a fourfold increase in disasters since the 1960s. This is not due merely to better recording, because the major disasters—which account for 90% of the losses and would always be recorded—have increased just as quickly. Much of the rise is due to socioeconomic factors, but many insurers feel that the frequency of extreme events also has increased. (p. 547)

It also stated that

> Insurers had at least one "billion dollar" storm event every year from 1987 to 1993. With such an unexpectedly high frequency, some local insurance companies collapsed, and the international reinsurance market went into shock. (p. 547)

This IPCC report went on to note that

> Traditionally, insurers have dealt with changes in risk in four ways: restricting coverage so that the balance of risk-sharing shifts toward the insured; transferring risk; physical risk management (before and after the event); or raising premiums. However, in view of the increasing costs of weather claims, insurers now are considering a more fundamental approach. . . . Lack of information about extreme events hampers such activity and makes insurers wary of committing their capital. (p. 548)

At the same time, the IPCC "Science of Climate Change" report (Houghton et al. 1996) stated that

> the-state-of-the-science [tropical cyclone simulations in greenhouse conditions] remains poor because (i) tropical cyclones cannot be adequately simulated in present GCMs; (ii) some aspects of ENSO are not well simulated in GCMs; (iii) other large-scale changes in the atmospheric general circulation which could affect tropical cyclones cannot yet be discounted; and (iv) natural variability of tropical storms is very large, so small trends are likely to be lost in the noise. (p. 334)

and

> In conclusion, it is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of tropical cyclones will change. (p. 334)

Research efforts focused on assessing the potential for changes in tropical cyclone activity in the greenhouse-warmed climate have progressed since those that were the basis of this IPCC assessment (themselves undertaken in 1994 and early 1995). This paper synthesizes the input from the members of a steering committee of the World Meteorological Organization Commission for Atmospheric Sciences and reflects recent experimental results in a summary of the new findings in this field.

This review should be read in the context of our current situation with regard to tropical cyclone predictions for a greenhouse-warmed world.

1) What do we know?

1) Tropical cyclones are currently devastatingly severe weather events.
2) Human vulnerability to TCs is increasing because of increasing populations on tropical coasts.
3) Tropical cyclone formation and intensity change are currently very difficult to predict.
4) Costs of TC impacts are increasing because of increasing costs of infrastructure and increasing "responsibility" claims on private and public funds.
5) The balance of evidence indicates that greenhouse gas emissions are producing climate change (Houghton et al. 1996).
6) Concern about possible future changes in tropical cyclone activity relates to changes in (i) frequency of occurrence, (ii) area of occurrence, (iii) mean intensity, (iv) maximum intensity, and (v) rain and wind structure.

2) What do we *not* know?

1) How to predict TCs today: genesis, maximum intensity.
2) How the environmental parameters that appear to be important for TC genesis will change.
3) How the large-scale circulation features that appear

to be linked to TC climatology, especially the quasi-biennial oscillation (QBO) and El Niño–Southern Oscillation (ENSO), will change.
4) How the upper-ocean thermal structure, which acts as the energy source for TC development, will change.

3) What tools are available to us now?

1) Coupled ocean–atmosphere general circulation models. (OAGCMs). These are providing useful information on the general characteristics of climate change, but they currently have coarse resolution (about 500 km), climate drift (or are energy corrected), and unproven skill for present-day TCs.
2) Atmospheric general circulation models (AGCMs) linked to mixed layer ocean submodels or employing SST predictions from OAGCMs have better resolution (about 100 km) but are still too coarse for mesoscale dynamics and share the latter two drawbacks of OAGCMs (as in 1).
3) Mesoscale models driven off-line from the output of OAGCMs or AGCMs have better resolution (about 20 km) but still share the other drawbacks (as for 1 and 2).
4) Empirical relationships such as Gray's genesis parameters or (much too?) simply SSTs alone suffer from drawbacks associated with empiricism.
5) "Upscaling" thermodynamic models, such as those of Emanuel (1991) and Holland (1997), are known not to capture all processes of importance.

This review is phrased in terms of doubled CO_2 climate conditions for simplicity and because the evaluations assessed predate any attempt to consider the additional impacts of sulfate, or other, aerosols on tropical cyclones. However, all the assessments are equally applicable to greenhouse conditions modified by either or both other greenhouse gases or atmospheric aerosols.

2. Natural variability in tropical cyclones and possible trends

Ascertaining tropical cyclone variability on interannual to interdecadal timescales is hampered by the relatively short period over which accurate records are available. For the North Atlantic Basin (including the North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea), aircraft reconnaissance has helped to provide a nearly complete record since the mid-1940s. The western North Pacific Basin (i.e., the Pacific north of the equator and west of the dateline, including the South China Sea) also has had extensive aircraft surveillance giving high quality records since the mid-1940s. For the remaining tropical cyclone areas (the north Indian, the southwest Indian, the Australian–southeast Indian, the Australian–South Pacific, and the northeast Pacific Oceans), there are only about 25–30 years of reliable measurements of annual activity derived from satellites. Thus, with the instrumental record so limited, it is difficult to make persuasive analyses of trends and of the physical mechanisms responsible for tropical cyclone variability.

However, even with these limitations, some information can be established about tropical cyclones in the past. The averages and standard deviations over these last couple of decades for each tropical cyclone area are well established (e.g., Neumann 1993). While the North Atlantic Basin averages 9–10 tropical cyclones reaching tropical storm strength (winds at least 17 m s^{-1}) of which 5–6 reach hurricane strength (winds at least 33 m s^{-1}), these compose only about 12% of the world total. The most active region, globally, is the western North Pacific with an annual average of 26 tropical storms and, of these, 16 typhoons (winds of at least 33 m s^{-1}), composing over 30% of the world total. Overall, the number of tropical cyclones reaching 17 m s^{-1} averages 84 globally, with a range of plus/minus one standard deviation from 76 to 92. Hurricane-force tropical cyclones average 45 each year with a range of plus/minus one standard deviation from 39 to 51.

Among the basins with only relatively short reliable records, Nicholls (1992) identified a downward trend in the numbers of tropical cyclones occurring in the Australian region from 105°–165°E, primarily from the mid-1980s onward. However, it is likely that this change is primarily artificial, due to changes in tropical cyclone analysis procedures (Nicholls et al. 1998, manuscript submitted to *J. Climate*). As shown in Fig. 1a, if only more intense tropical cyclones are counted (i.e., those with a minimum pressure of less than 990 hPa) much of the downward trend in cyclone numbers is removed. In the remaining short-record basins, the northeast Pacific has experienced a notable upward trend, the north Indian a notable downward trend, and no appreciable long-term variation is observed in the southwest Indian and southwest Pacific (east of 165°E) based upon data from the late 1960s onward (adapted from Neumann 1993). However,

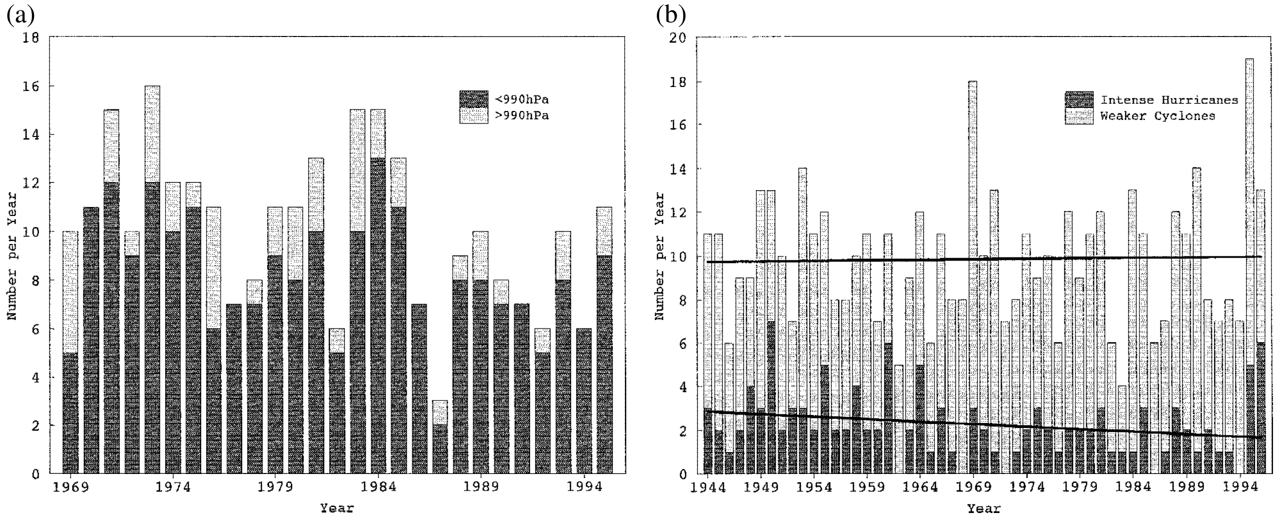

FIG. 1. (a) Time series of the number of tropical cyclones in the Australian region (105°–165°E) between 1969 and 1995. Dark bars indicate the number of cyclones with minimum pressure below 990 hPa. The gray bars indicate the numbers with minimum pressure between 1000 and 990 hPa [adapted from Nicholls et al. (1998, manuscript submitted to *J. Climate*)]. (b) Time series of Atlantic basin intense hurricanes (dark bars) and weaker cyclones (gray bars) for 1944–96. Intense hurricanes are those cyclones that attain sustained surface winds of at least 50 m s^{-1} at some point in their life cycle. Weaker cyclones include all other remaining tropical storms, subtropical storms, and hurricanes. The superimposed lines are the linear best fits for the intense hurricanes (lower line) and for the total number of cyclones (upper line) [from Landsea et al. (1996)].

whether these represent longer-term changes or reflect shorter-term (on the scale of tens of years) variability is completely unknown because of the lack of long, reliable records.

For the northwest Pacific basin, Chan and Shi (1996) found that both the numbers of typhoons and the total number of tropical storms have been increasing since about 1980. However, the increase was preceded by a nearly identical decrease from about 1960 to 1980. No analysis has been undertaken as yet of the numbers of intense typhoons (winds at least 50 m s^{-1}) because of an overestimation bias in the intensity of such storms in the 1960s and 1970s (Black 1993).

There has been an extensive analysis for the Atlantic basin in part because of the length of the reliable record for this basin (back to 1944) and for U.S. coastal landfalling hurricanes (back to 1899). In common with the northwest Pacific data, observations for this basin also have a bias in the measurement of strong hurricanes: from the 1940s through to the 1960s, the intensity of strong hurricanes is believed to have been overestimated by 2.5–5 m s^{-1} (Landsea 1993). This bias has been crudely removed to provide estimates of the true occurrence of intense (or major) hurricanes, those with winds of at least 50 m s^{-1}, which are designated as a category 3, 4, or 5 on the Saffir–Simpson hurricane intensity scale (Simpson 1974).

Examination of the record of the number of Atlantic tropical storms (including those designated as subtropical storms from 1968 onward) shows substantial year-to-year variability, but no significant trend (Landsea et al. 1996) (Fig. 1b). In contrast, intense hurricanes exhibited a pronounced downward trend from the 1940s through the 1990s, despite the near record-breaking years of 1995–96. In addition to these changes in frequency, there has been a decrease in the mean intensity of the Atlantic tropical cyclones, although there has been no significant change in the peak intensity reached by the strongest hurricane each year. Fluctuations in numbers of intense hurricanes are considerable in the 1940s through to the late 1960s; although there is a period of reduced activity in the 1970s through 1994, and a "spike" of activity in 1995 (Fig. 1b).

These trends for the entire Atlantic basin are mirrored by those from intense hurricanes striking the U.S. east coast, from the peninsula of Florida to New England (Landsea 1993). The quiet period of the 1970s to the early 1990s is similar to a quiescent regime in the first two decades of this century. Active conditions began in the late 1910s and continued into the 1960s. During two particularly active periods, the Florida peninsula and the upper Atlantic coast (from Georgia to New England) experienced seven intense hurricane landfalls in two periods each of seven years (1944–50 and 1954–60). Other time series for all U.S. hurricanes (Hebert et al. 1996) and for hurricanes affecting land areas around the Caribbean also show some quasiperiodicity.

It has been suggested that the Atlantic's hyperactive hurricane seasons of 1995 (19 tropical storms, 11 hurricanes, and 5 intense hurricanes) and 1996 (13 tropical cyclones, 9 hurricanes, and 6 intense hurricanes) may be heralding a return to an active regime similar to that seen between the 1940s and the 1960s (Landsea et al. 1996). Since the Atlantic hurricane activity observed during the 1970s and into the early 1990s was anomalously low compared with previous decades, a return to a more active regime is not surprising.

Data for typhoon activities around the island of Taiwan have been gathered since 1897 and can be used as an indication of interannual variabilities of the nonrecurved western North Pacific typhoons defined as tropical cyclones achieving wind speeds of 33 m s^{-1} and greater. Recent studies (Chang 1996) focus on the typhoons that have caused loss of lives and/or damage to properties on the island of Taiwan, regardless of whether they crossed the coast. In general, there are about 3–4 such typhoons per year, but there is a pronounced variation from as many as eight (1914) to as few as zero (1941, 1964). A slight decreasing trend is apparent, from 4 to 3 typhoons per year, but this may be a result of change in the definitions of such typhoons in 1962.

The global cyclone frequency taken from the National Climatic Data Center Global Tropical Cyclone Data Set indicates that the number of tropical cyclones may have increased since 1970. However, this increase has arisen entirely from the more poorly observed regions of the Southern Hemisphere and the eastern North Pacific and cannot be differentiated from changing observing practices and slow, multidecadal oscillations in cyclone numbers.

In the past few years, several attempts have been initiated aimed at trying to use geological records to quantify tropical cyclone activity back as far as the end of the last glacial episode, about 10 000 years ago. These methods, although still in their infancy, suggest that there may be potential for quantitative analysis of changing cyclone characteristics with climate. However, there is insufficient information available at present for quantitative estimation of trends and natural variability over geological timescales.

3. Tropical cyclone genesis and frequency and their potential to change in greenhouse conditions

The processes that are responsible for development of tropical cyclones are poorly understood, in large part because of the lack of good observations of the highly transient changes that occur. Even in current operational weather forecasts, prediction of tropical cyclone formation still lacks skill and such forecasting is reduced to "watchful waiting" (Holland 1993), relying on detecting the satellite signature, combined with knowledge of current environmental factors and the genesis climatology of tropical cyclones in the area. Understanding how tropical cyclone genesis may change in the greenhouse-warmed climate is certainly a significant challenge to current research.

The problem of predicting how tropical cyclone frequency might respond to greenhouse-induced climate change can be broken into two parts: predicting how the environmental capacity to sustain tropical cyclones may change and predicting how the frequency and strength of initiating disturbances may change. The thermodynamic analysis by Holland (1997) indicates that there could be an enhanced environment for tropical cyclone intensification. GCM predictions also indicate that the strength of very large-scale tropical circulations such as monsoons and the trade winds are expected to be increased, which could be expected to provide both an enhanced environment and more initiating disturbances. Balanced against this is the predicted increase of upper-tropospheric wind shear. Substantial uncertainties also exist in known regional factors correlated with cyclone frequency, such as Sahel rainfall (Landsea and Gray 1992) or ENSO (Nicholls 1984). Elementary applications of empirical relationships from the current climate to a future climate are fraught with danger and offer little useful insight.

Gray (1968, 1979) summarized the knowledge of large-scale conditions necessary for tropical cyclone genesis, but these are by no means sufficient. The Gray genesis parameter was applied to GCM results for climate change by Ryan et al. (1992). Their results were inconclusive and there remains doubt whether such parameters, which have been highly tuned to fit the current climate, are directly applicable to changed climate conditions. For example, a widespread misconception is that were the area enclosed by the 26°C SST isotherm to increase, so too would the area experiencing tropical cyclogenesis. Application of a thermody-

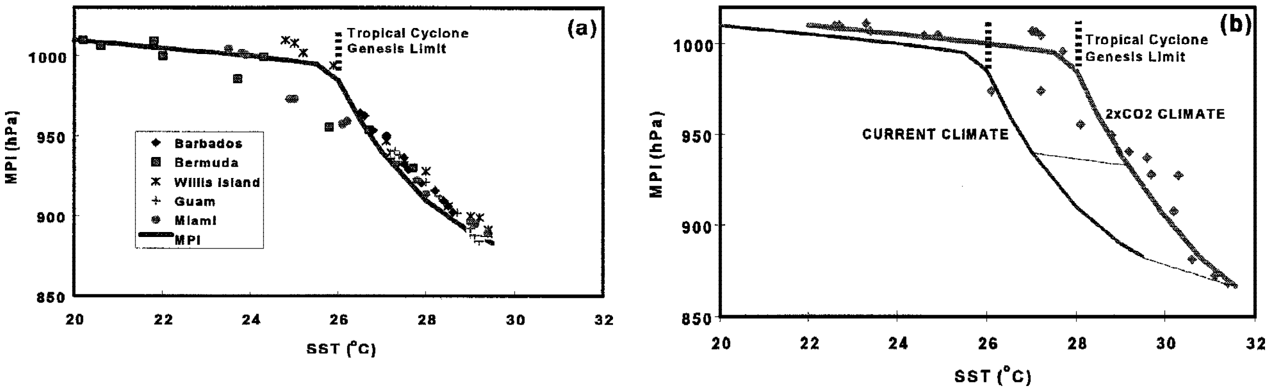

FIG. 2. Plots of MPI of tropical cyclones against sea surface temperatures. (a) MPI estimated from monthly mean atmospheric temperature soundings and ocean temperatures at several tropical cyclone sites (indicated by different symbols) and compared with an empirical curve for North Atlantic modified from DeMaria and Kaplan (1994) as discussed in Holland (1997). (b) MPI estimated from greenhouse conditions constructed by adding the MECCA model simulated atmospheric and oceanic temperature changes near the tropical cyclone sites in (a) to the observed monthly mean temperature soundings at these sites. Rhomboidal symbols indicate these estimations at the different sites (not distinguished) and the solid thick line is the best fit curve to these points. Thin dashed lines indicate the sense of MPI change and thick vertical dash lines show the changing cyclogenesis limit.

namic technique (Holland 1997) to climate change scenarios in Figs. 2a and 2b clearly indicates that cyclone development in a warmer climate occurs at higher oceanic temperatures, particularly for intense tropical cyclones. This arises from upper-atmospheric warming that compensates to some extent for the increased energy potential from the warmer oceans. This conclusion is supported by the known importance of dynamical processes, such as development of a broad region of upward ascent, which are, themselves, governed by unchanging parameters such as the earth's rotation. The finding also concurs with the modeling studies of Bengtsson et al. (1996). The net result, therefore, is that current knowledge indicates that the broad geographic regions affected by tropical cyclones are not expected to change significantly. In particular, there is no reason to believe that the region of cyclogenesis will expand with the 26°C isotherm.

It is conceivable, however, that changes in the large-scale circulation of the atmosphere could increase or decrease the rate of movement of tropical cyclones out of their genesis regions and into higher latitudes. It is also possible that the extratropical transition of tropical cyclones may change in character.

*a. Relationships between tropical cyclones and large-scale circulation*s

Gray (1984a,b) related tropical cyclone activity in the western Atlantic and western North Pacific to the phase of the stratospheric QBO. He found that when QBO winds are from a westerly direction, there are nearly twice as many hurricane days in the western Atlantic as compared to when the QBO is in an easterly phase. In westerly phase QBO seasons, there seem to be more intense and longer lasting Atlantic hurricanes. In the western North Pacific, this relationship is not as strong as in the western Atlantic. In contrast to the Atlantic, in the western North Pacific tropical cyclone activity is more frequent in an easterly phase of the stratospheric QBO.

In recent years, the ENSO influences on tropical cyclone activity have been investigated (e.g., Nicholls 1984, 1992; Gray 1984a,b; Revell and Goulter 1986; Dong 1988; Evans and Allan 1992). El Niño events have been shown to be related to the seasonal frequency and interannual variations of tropical cyclone occurrence. Nicholls (1984), Chan (1985), and Dong and Holland (1994) have clearly shown strong relationships between the ENSO and longitudinal shifts in the regions of cyclone development.

During an ENSO warm event in the eastern Pacific, the SSTs over the western Pacific are relatively cooler and atmospheric pressure over Australia is higher than normal. This leads to a reduced number of cyclones in the Australian region (Nicholls 1984; Evans and Allan 1992), while the center of tropical cyclone activity moves farther east and north (toward the equator), and the frequency of cyclone formation east of 170°E actually increases (Revell and Goulter 1986; Evans and Allan 1992). In cold ENSO events (La Niña) these trends are reversed. Nicholls (1992) has shown that the number of tropical cyclones around

Australia (105°–165°E) has decreased rather dramatically since the mid-1980s. Some of this reduction may be associated with there being more El Niño events since that time (i.e., 1982–83, 1986–87, 1991–92).

The relationship between the ENSO events and tropical cyclone activity in the northwest Pacific has also been studied (e.g., Chan 1985; Dong 1988; Lander 1994). Consistent with results for the Australian–southwest Pacific basin, there are reduced numbers of tropical cyclone genesis west of 160°E, but increased cyclogenesis events in a region east of 160°E and south of 20°N during El Niño events (Chan 1985; Lander 1994). The opposite occurs during cold ENSO events. There is also a tendency for the tropical cyclones to form closer to the equator during El Niño events.

In the North Atlantic region, the ENSO influence on tropical cyclone activity is quite different (Gray 1984a; Shapiro 1987; McBride 1995). During El Niño events (ENSO warm phase), tropospheric vertical shear is increased by the stronger upper-tropospheric westerly winds. This inhibits tropical cyclone genesis and intensification. In contrast, seasonal frequency of tropical cyclone occurrence is slightly enhanced in non–El Niño years. Unfortunately, since current climate models do not adequately simulate ENSO events, no definite statements can be made about the likely impacts of changing climate on these coupled phenomena.

Recently, Landsea and Gray (1992) have detected a strong empirical relationship between North Atlantic hurricanes and various observable parameters of the climate system, such as the extent of summer rain in the Sahel. As yet unpublished work by Holland and collaborators also indicates that cyclone frequency in the Australian region may be related to establishment of suitable thermodynamic preconditions. Holland (1995) has also hypothesised that large-scale circulation patterns in the western North Pacific are associated with and conducive to extended periods of repeated cyclogenesis. None of these results have yet been applied directly to cyclone development and climate change.

An interesting, and potentially useful, statistic on tropical cyclone frequency is that the global frequency is highly stable from year to year: variations are typically around 10%. This compares markedly with local regional variations that are typically 100% of the long-term mean (e.g., Fig. 1) and can be more than 200%. It is concluded that current knowledge and available techniques are too rudimentary for quantitative indications of potential changes in tropical cyclone frequency. However, the available evidence strongly points to an expectation of little or no change in global frequency. Regional frequency could change substantially in either direction.

b. GCM studies of numbers of tropical cyclones

GCMs have been used by a number of groups to try to infer changes in tropical cyclone activity by analyzing the resolvable-scale vortices that develop. These studies are subject to a number of caveats and produce conflicting results: Haarsma et al. (1992) found an increase in frequency of tropical cyclones, Bengtsson et al. (1996) found large decreases, and Broccoli and Manabe (1990) found that increases or decreases could be obtained by reasonable variations in the model physics. A commentary on these simulations is provided below.

The possible changes in tropical cyclone activity associated with greenhouse-induced climate change have been investigated using GCM results directly (e.g., Broccoli and Manabe 1990; Haarsma et al. 1993; Bengtsson et al. 1995, 1996). Broccoli and Manabe (1990) used the Geophysical Fluid Dynamics Laboratory GCM to study the response of tropical cyclones to increases in atmospheric CO_2. Two versions of the model, R15 (4.5° lat × 7.5° long) and R30 (2.25° lat × 3.75° long), were utilized. The cloud treatments adopted were with fixed cloud and variable cloud amounts. In the experiments with fixed cloud, the number and duration of tropical storms increased in a doubled CO_2 climate for the R15 integration. However, a significant reduction of the number and duration was indicated in the experiments with variable cloud. The response of the simulated number of storms to a doubling of CO_2 is apparently insensitive to the model resolution but crucially dependent on the parameterization of clouds (Broccoli and Manabe 1992).

Haarsma et al. (1993) undertook similar experiments for present-day and doubled CO_2 concentrations. Their model resolution was R30 (2.25° lat × 3.75° long) with variable cloud amount. Evans (1992) argued that it is important to examine the physical mechanisms involved in the generation of the model "storm" and test the degree to which the model vortices have physical similarities with real tropical cyclones. The simulated tropical disturbances for the present climate analyzed by Haarsma et al. (1993) have a much larger horizontal extent and weaker intensity than those observed, but some physical features of tropical cyclones, such as low-level convergence, upper-tropospheric outflow, and a warm core, were produced by this GCM. In the doubled CO_2 conditions, the number of simulated tropical storms increases by about 50%.

Bengtsson et al. (1995, 1996) investigated the influence of greenhouse warming on tropical storm climatology, using a high-resolution GCM at T106 resolution (triangular truncation at wavenumber 106, equivalent to 1.1° lat–long). Their studies suggest a substantial reduction in the number of storms, particularly in the Southern Hemisphere. They attribute this reduction to a warming in the upper troposphere, enhanced vertical wind shear, and other large-scale changes in the tropical circulation such as reduced low-level relative vorticity. In comparison to the results for the control experiment, there are no changes in the geographical distribution of the GCM-simulated storms. The seasonal variability of the storm distribution is said to be in agreement with that of the present climate. However, application of their model results may be limited by their model's sensitivity to its resolution and perhaps also by incompatibilities in the experiment. In the ECHAM3 (T106) doubled CO_2 experiment (Bengtsson et al. 1996), the fixed global SSTs were taken from ECHAM3 (T21) doubled CO_2 experiment of Cubasch et al. (1992) in which an enhanced tropical hydrological cycle by a strengthened ITCZ was simulated with a fully coupled ocean model and the SSTs were warmed between 0.5° and 1.5°C. Surprisingly, with such high global SSTs and noting the results from the underpinning experiment, Bengtsson et al. (1996) reported a weakened tropical hydrological cycle in their high-resolution experiment. This weakening in tropical circulation appeared to be one of the primary reasons for the decrease in the model's tropical cyclone activity. It appears that this model's tropical climate is very sensitive to its horizontal resolution. It is possible that the changes of SSTs in the doubled CO_2 climate, if simulated by the high-resolution AGCM coupled with the same OGCM as Cubasch et al. (1992), may be different from the ones used in Bengtsson et al. (1996) and thus might give a different prediction of the changes in tropical cyclone activities in the greenhouse-warmed climate.

An alternative approach to prediction of the potential changes in tropical cyclone activity is to apply Gray's (1968, 1975) seasonal genesis parameter to GCM fields (e.g., Ryan et al. 1992). A recognized weakness of this is that the Gray genesis parameter was derived based on the present climate, but it does not account for how well the parameter would govern tropical cyclogenesis in a different climate (Tonkin et al. 1997). Watterson et al. (1995) used Gray's seasonal genesis parameters as an objective criterion to derive a model's climatology of tropical cyclone genesis from a GCM with 3.2° lat × 5.6° long resolution. First they applied the genesis parameters to the European Centre for Medium-Range Weather Forecasts climatology and compared the results with the observed cyclogenesis. Although their results confirmed the success of these genesis parameters as a diagnostic tool for locating the genesis regions of tropical cyclones, they found that these parameters overestimated the number of tropical cyclones in the Southern Hemisphere. Results from the GCM climatology also show the sensitivity of the model tropical cyclogenesis to the SST variations and that Gray's seasonal genesis parameters have deficiencies in diagnosing both climatological and interannual tropical cyclone frequency.

Recently, Walsh and Watterson (1997) studied the tropical-cyclone-like vortices in a limited area model focused on the Australian continent and nested into a GCM. This limited-area model has a horizontal resolution of 125 km and has successfully simulated some of the physical features of tropical cyclones such as the warm core, low-level wind maxima in the modeled tropical-cyclone-like vortices detected using objective genesis parameters. Compared with observed cyclogenesis over these regions, this study showed that although Gray's seasonal genesis parameters have some skill in predicting model cyclogenesis for current climate conditions, it is not a definitive measure and a reformulation of such parameters may be warranted. Walsh and Watterson (1997) identified two main limitations of climate models that constrain the model capability for simulating small and convective-driven systems such as tropical cyclones: coarse horizontal and vertical resolutions and inadequate representation of moist convective processes.

4. Tropical cyclone intensities and their potential to change in greenhouse conditions

The sensitivity of tropical cyclone intensity to SST change has been investigated using a variety of numerical modeling techniques (e.g., Baik et al. 1990; Drury and Evans 1993; Evans 1993; Bengtsson et al. 1994). With an axisymmetric tropical cyclone model, Baik et al. (1990) performed extensive sensitivity experiments. They found that when only the SST was varied, the intensity of the model-simulated storm increased with warmer SST and decreased with cooler SST. Considering the impacts of moist convective instability on tropical cyclone intensity, Drury and Evans (1993) explored the sensitivity of a simulated storm to increased SST and demonstrated that there seems to be the potential for more intense, wetter tropical cyclones in a moister and warmer world. In their experiments, the atmosphere with warmer SST was adjusted such that the convective available potential energy (CAPE) of the lower-tropospheric air was unchanged. They found that the changes in simulated cyclone intensity are significantly less than those in the experiment in which only SST was varied. It should be mentioned that previous studies of the sensitivity of maximum potential intensity (e.g., Emanuel 1986) also held CAPE fixed while SST was varied.

Historical data covering five tropical ocean basins for the 20-yr period 1967–86 were examined by Evans (1993) to identify the relative importance of SST in the tropical cyclone intensification process. The results indicate that while SST does influence tropical cyclone development and provides an upper bound on tropical storm intensity, it is not the overriding factor in determining the maximum intensity attained by a storm. Based on empirical evidence, McBride (1981) found that SST does not seem to be the primary variable in determining whether incipient storms develop, although a warm ocean surface is needed for tropical cyclone formation and development.

Evans et al. (1994) utilized a limited area model to study potential changes in tropical cyclone intensity to varying SSTs. They performed several experiments for two well-observed tropical cyclones occurring simultaneously in the northern Australian region. The sensitivity studies reveal that if the underlying SST is warmed, the minimum central pressure will decrease and the associated rainfall will increase. In other words, tropical cyclones could become stronger than in the current climate with warmer SSTs, if other environmental conditions are held constant.

a. Thermodynamic model studies of tropical cyclone intensity

The maximum intensity that can be reached by tropical cyclones is ultimately limited by the available energy in the atmosphere and ocean. It has been well established (e.g., Byers 1944; Riehl 1954; Malkus and Riehl 1960) that the atmosphere alone cannot provide sufficient energy for the development of a very intense tropical cyclone. The warm tropical oceans support intense cyclone development by a feedback process in which falling surface pressures in the cyclone core release additional energy from the ocean surface. Adverse atmospheric conditions, together with internal cyclone dynamics and local oceanic cooling by mixing and upwelling, often prevent tropical cyclones from achieving this theoretical limit (Holland 1997).

While the internal dynamics of tropical cyclones and the manner in which they interact with their environment are extremely complex and not well understood, the maximum potential intensity (MPI) has been estimated in recent years by a consideration of the energetics (e.g., Kleinschmidt 1951; Emanuel 1986, 1991; Holland 1997). Although these techniques involve a number of simplifying assumptions and caveats, Tonkin (1996) has shown that the techniques of both Emanuel (1991) and Holland (1997) exhibit considerable skill when evaluated using monthly mean and daily soundings from a large number of stations in the western Pacific and North Atlantic Oceans. Figure 3 (for the Australian–southwest Pacific region) shows that these two techniques provide an MPI bound on the climatological record, recognizing that the short cyclone record will not include all possible combinations of extreme cases. Furthermore, Fig. 4 indicates that there is substantial potential skill in forecasting the maximum intensity of individual cyclones using observations of ambient atmospheric and oceanic conditions.

Application of the Holland (1997) technique to current and future climate conditions is illustrated in Fig. 2. MPI estimates made from monthly mean atmospheric temperature soundings and oceanic temperatures (SST) at several tropical radiosonde sites in the Northern and Southern Hemispheres were first compared with tropical cyclone observations. Because the atmospheric conditions are closely tied to the surface temperatures of tropical oceans, a plot of SST versus MPI provides a convenient display of the results (Fig. 2a). The theoretical estimates agree closely with the observed curve of worst-case tropical cyclones for warm oceans and accurately reproduce the well-known requirement of SST >26°C for cyclone development (Gray 1968). The scatter of MPI near 26°C is partially due to the method and partially reflects real changes of MPI–SST relationships between ocean basins (e.g., Evans 1993). At cooler SSTs, the observations are composed of cyclones that developed over warmer tropical oceans and are decaying as they move poleward. The sensitivity of the model's estimations to a variety of parameters employed in such approaches is discussed in detail by Holland (1997).

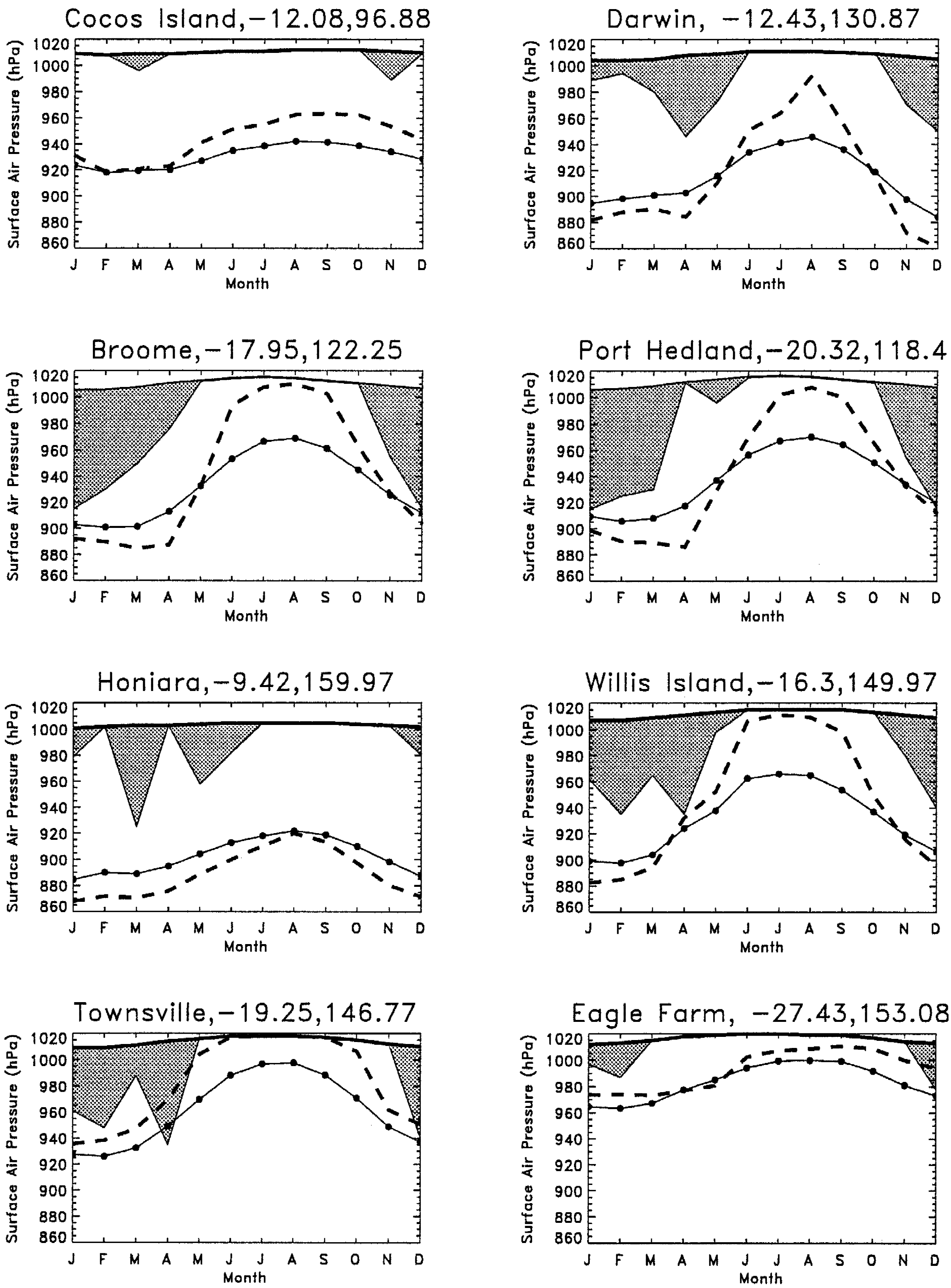

FIG. 3. Seasonal march of MPI predicted by applying the techniques of Holland (1997) and Emanuel (1991) to a number of monthly mean radiosonde soundings in the Australian–southwest Pacific region, together with the observed extreme cyclone intensities (shaded region). The solid line is the ambient surface pressure; the line with dots is the MPI from Emanuel model; the dashed line is the MPI from Holland model [adapted from Tonkin (1996)].

Taking the climate model forecasts of monthly mean atmospheric and oceanic temperature changes at Willis Island and Guam radiosonde sites from those MECCA (Model Evaluation Consortium for Climate Assessment) GCMs that have adequately good simulations of observed climate and adding these to the observed temperatures used in Fig. 2a results in Fig. 2b. The minimum SST at which tropical cyclones develop increases by 2°–3°C. This is similar to that modeled by GCMs for the ocean changes in a warmed climate. Thus, the geographical region of cyclogenesis will remain roughly unchanged. A small increase of cyclone intensity is predicted, consistent with the more comprehensive examination by Li (1996). This increase of MPI is reasonably independent of the choice of parameter values used in the thermodynamic technique, provided that no unforeseen changes occur in these parameter values with climate change.

The thermodynamic approaches provide an objective estimate of the lowest central pressure that can be achieved. This provides a conservative parameter for indicating current and potential future changes in cyclone intensity, and is in accord with the archiving practices of most major cyclone centers. There are direct relationships between central pressure and maximum winds (e.g., Holland 1993, chap. 9), but a number of factors, including asymmetries from the cyclone motion and local wind transients, result in a significant scatter. We note that the maximum winds vary as roughly the square root of the central pressure, so that percentages in expected wind changes will be slightly less than the percentage changes predicted for central pressure.

There is considerable sensitivity to choice of, or variations in, some parameters used in these thermodynamic models. For example, Holland (1997) assumes a value of 90% for the relative humidity under the eyewall. This value is consistent with existing information on the conditions in this region, and it produces satisfactory predictions for current climate (Tonkin 1996). However, its use grossly oversimplifies the complex interactions between wind, ocean, and spray occurring in the maximum wind region. Several studies have shown that the presence of spray considerably modifies the near-surface atmospheric layer for winds above 20 m s^{-1} (Pudov and Petrichenko 1988; Fairall et al. 1994), but virtually nothing is understood of the effects at very high wind speeds.

Recently, J. Lighthill (1996, personal communication) proposed a mechanism relating spray to the thermodynamics of tropical cyclones, based upon the work of Fairall et al. (1994), who undertook a fluid-dynamical analysis of extensive observations made at sea in winds as high as 25–30 m s^{-1}. These observations found a substantial layer of "a third fluid" (ocean spray) between the atmosphere and the ocean and measured wind temperatures were substantially less than the SST. The existence of such a temperature shortfall would affect the saturated water-vapor concentration and therefore the maximum latent-heat content of the air around the tropical cyclone eyewall base. Moreover, an extrapolation by Fairall et al. (1994) to 40 m s^{-1} wind speed suggests that the mass density of spray might rise to only 0.008 kg m^{-3} (less than 1% of the air density) and yet that vapor transfer from spray to air could exceed direct transfer from the ocean surface by an order of magnitude. It is, therefore, proposed that there is a need for a modest correction to established views of tropical cyclone thermodynamics. Specifically, if much of the vapor transfer to surface winds came from spray droplets, then cooling from the corresponding latent heat transfer might not be fully compensated by sensible-heat transfer from the ocean surface, so that air temperature (as observed) would reach an equilibrium value below that of the ocean surface. The consequence would be that the average temperature of saturated air around the base of the eyewall would be less than the SST. From the thermodynamic viewpoint, the importance of such a correction to the temperature of saturated air around the base of the eyewall stems from the associated very substantial reduction in latent heat intake per unit mass of air, consequent on the very steep dependence of saturated water-vapor concentration on temperature. This type of mechanism has not yet been incorporated in the current MPI models.

Since a primary mechanism for tropical cyclone intensity is the balance between input of mechanical energy from buoyancy forces acting on saturated air rising in the eyewall (approximately, along a moist-air adiabat) and dissipation of wind energy in the turbulent boundary layer at the ocean surface, then ocean spray may provide a self-limiting process. The energy input per unit mass of air must be reduced if air at the base of the eyewall has a water-vapor concentration well below that associated with the SST, whereas dissipation in the turbulent boundary layer is unlikely to be greatly modified by the presence of spray at a mass density less than 1% of air density.

Current research is focused on discovering whether the relationships indicated above are likely to develop further as wind speeds rise from the highest value analyzed by Fairall et al. (40 m s^{-1}) toward those typical

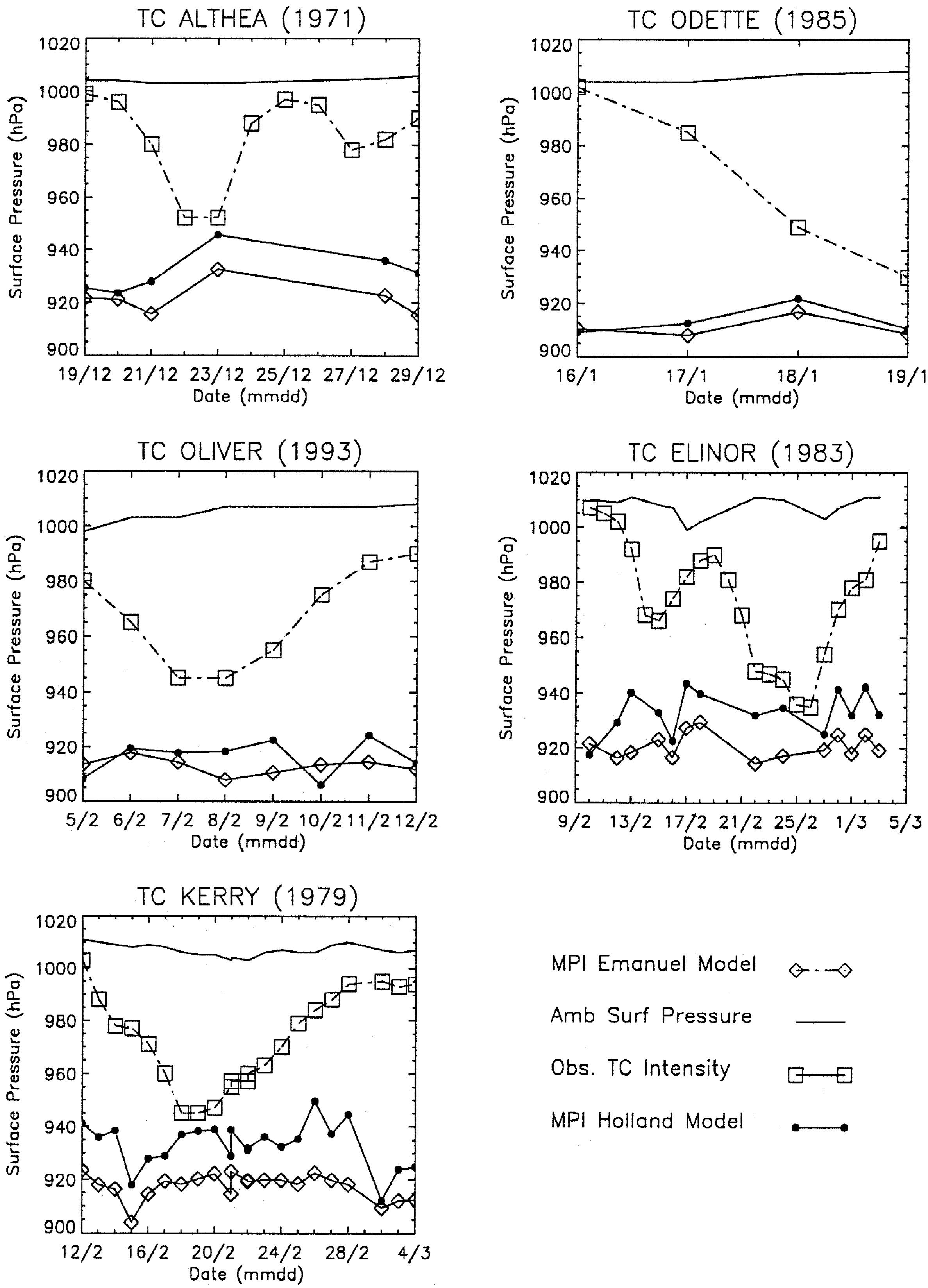

FIG. 4. Prediction of individual tropical cyclone maximum intensity by applying the techniques of Holland (1997) and Emanuel (1991) to Willis Island soundings applied to tropical cyclones in the eastern Australian region and within approximately 500 km of the island. The data are plotted as a time series of maximum intensity predictions compared to the actual cyclone intensity change [adapted from Tonkin (1996)].

of intense tropical cyclones (50–60 m s^{-1}). Initial efforts to achieve more comprehensive statistical modelling of droplet trajectories suggest that spray distribution may be critically dependent on a certain velocity ratio. It is when vertical gust components have a standard deviation far greater than the terminal velocities of most droplets that it is anticipated that a substantial thickening of the spray zone will occur and hence an enhancement of the effects of ocean spray on tropical cyclone thermodynamics. This may be a significant restraining mechanism on any increase in the maximum intensity of tropical cyclones in response to increasing SST because the deep ocean spray zone of intense tropical cyclones could constrain further thermodynamic development.

Some recent studies by Gray (1996) show that momentum considerations are a fundamental component that must also be taken into account in combination with lapse rates in upscaling models of MPI. As a tropical cyclone's maximum winds increase, its low-level frictional dissipation goes up with the square or slightly higher power of the wind. Eyewall cloud buoyancy, although always large in the weak stages of the cyclone, rises at a much slower rate than does friction. At high tropical cyclone intensities, eyewall buoyancy is still only marginally (or not at all) enough to support the larger increase in the need for eyewall cloud vertical motion to balance friction. A point is reached where the buoyancy-driven eyewall cloud vertical motion is unable to increase sufficiently to match the exponential rise in tropical cyclone momentum requirements. The frictional momentum dissipation was considered in the MPI approach of Emanuel (1995) and his recent study (Emanuel 1997) further shows that the MPI estimated by the thermodynamic approach can be rederived from energetic considerations, and Holland (1997) showed the energetic consistency in his MPI estimation. Nevertheless, we still lack a clear understanding of how the tropical cyclone inner-core dynamics and thermodynamics limit its intensification.

b. Global climate model (GCM) studies of tropical cyclone intensity

Haarsma et al. (1992) found an increase in the number of more intense tropical disturbances and in the intensity of the most intense storms in a warmer GCM climate. The increase of the maximum simulated wind speed is about 20%. They also suggested that the GCM severely restricts the maximum possible intensity of the simulated tropical storms because of its coarse spatial resolution. Bengtsson et al. (1995, 1996) found that although the number of modeled storms is significantly reduced in their T106 GCM simulation, there seems to be no reduction in their overall strength.

Li (1996) has applied the Emanuel and Holland approaches to the climate models used in the MECCA present-day and greenhouse intercomparison (Howe and Henderson-Sellers 1997). He shows that the individual models produce widely varying values of MPI for current climatic conditions, largely due to the poor thermodynamic structure of the model atmosphere and the poorly predicted SSTs. Li (1996) does find increased intensity of cyclones using both the Holland and Emanuel thermodynamic models, although the increases in MPI found in his analysis are inside the uncertainty range derived from individual model predictions. This introduces considerable uncertainties for direct application to climate change predictions and calls into question the results of "downscaling" by means of embedding mesoscale models into global climate models (e.g., Walsh and Watterson 1997).

The coarse- and large-scale vortices generated by GCMs do not capture the detailed core-region physical and dynamical processes that are known to be important to tropical cyclone intensification, including oceanic coupling, and they do not have the capacity to fully develop intense cyclones by the thermodynamic processes that feed back between the ocean and the cyclone. Their usefulness as prediction tools depends upon the degree to which the cyclone intensity is governed by external environmental factors, which is not well known.

As pointed out by Gray, tropical cyclone potential intensity (MPI) appears to depend on the existence of background conditionally unstable lapse rates from the surface to 300 hPa, or, equivalently, θ_e decreases from the surface to 300 hPa, which is the usual level of strongest tropical cyclone eyewall cloud updrafts. Buoyancy decreases above this level. For example, the northwest Pacific has the highest background value of conditional instability from the surface to 300 hPa, and the most intense tropical cyclones occur in this region. Other regions with lower values of this quantity have weaker or no cyclones. The question to be addressed is how this surface to 300 hPa lapse rate will change as global warming occurs. In recent years, a number of studies has been done to investigate the moist stability and CAPE in the tropical atmosphere (e.g., Rennó and Ingersoll 1996; Robe and Emanuel 1996). Rennó and Ingersoll (1996) argue that a necessary consequence of CO_2-induced warming is larger CAPE, because the mean temperatures at which radiation is absorbed and emitted become more different. However, cloud feedbacks may reduce this effect.

Most global models indicate large mid- to upper-tropospheric warming (3°–6°C) in their doubled CO_2 simulations over the tropical oceans. They also show only small 1°–2°C surface warming in the tropical cyclone ocean basins. Since surface moisture increases occur with the surface warming, little or no background environmental surface to 300 hPa θ_e gradient change is expected with global warming. Indeed, results from Bengtsson et al. (1996) did not show any large change in the atmospheric moist stability in their doubled CO_2 simulation. From this point of view, more intense tropical cyclones should not be expected in a greenhouse-warmed climate.

By analyzing six MECCA model results, Li (1996) shows large increases of atmospheric dry static stability ($\partial\theta/\partial p$) in all MECCA models with larger warming in the high troposphere than at the surface (Fig. 5). As noted by Holland (1997), this is quite different from the destabilization that occurs when SST increases each year in current climate (Fig. 5a). Li also finds that the atmospheric moist static instability ($\partial\theta_e/\partial p$) (calculated as the difference of θ_e between models' surface and 200 hPa) exhibits only slight changes following greenhouse warming in the MECCA models. Further analysis from five of the MECCA models shows that the instability of the low-level atmosphere is increased in the greenhouse-warmed climate but the stability is increased in the middle and upper troposphere. Calculations of CAPE from these models show the major increases to be limited to the low levels. This is quite different from seasonal changes in current climate (Fig. 5b) where the instability increases through a deep layer. How the atmospheric thermodynamic structure will change in the future climate and any implication this may have for changes in tropical cyclone intensities needs to be addressed in future evaluations.

c. Distribution of tropical cyclone intensities

No information is available from current research on changes in the distribution of cyclone intensities. A net skewing of the intensity distribution up or down could have a greater effect than changes in the worst possible case. Landsea and Gray (1992) have found climatic indicators for the gross distribution of hurricane intensities for the North Atlantic. Recent work by Holland and collaborators has also found that there may be environmental signatures in the Australian–southwest Pacific region. However, such techniques have not yet been applied successfully to climate simulations. DeMaria and Kaplan (1993, 1994) found that the difference between current intensity and an empirically defined MPI provided a good predictor of whether hurricanes in the North Atlantic would continue intensifying. This implies that a higher MPI will lead to a greater frequency of intense cyclones in general, but this is not supported by the results in Fig. 4, which indicate that there are substantial local and temporal variations of MPI that affect individual tropical cyclones. It is concluded that there is insufficient evidence with which to predict changes in tropical cyclone intensity distribution.

5. Tropical cyclones in a greenhouse-warmed world

The impacts on society by tropical cyclones have been marked by a substantial decrease in deaths in the

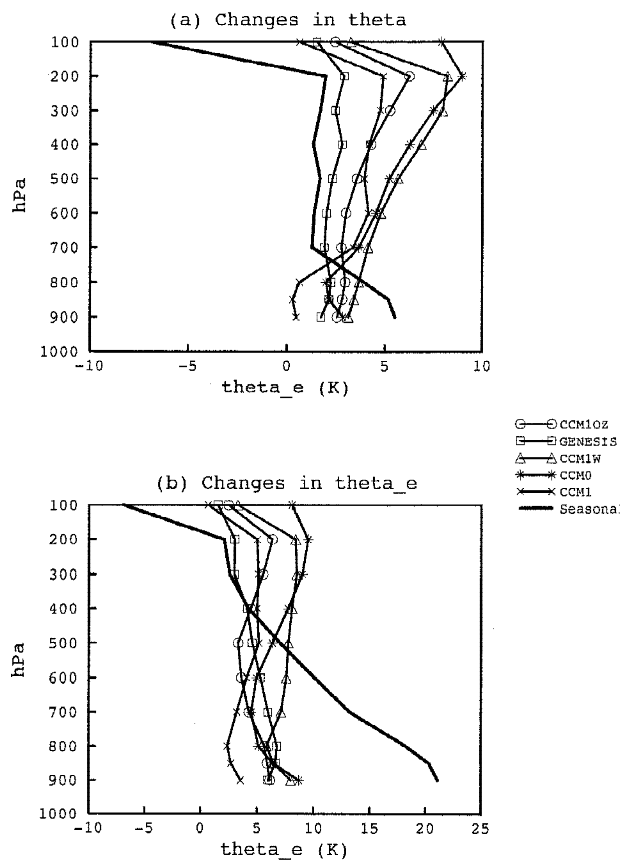

FIG. 5. Simulated changes (enhanced greenhouse minus control simulation) in potential temperature (a) and equivalent potential temperature (b) over the GCM grid point near Willis Island (16.3°S, 149.97°E) in August for five MECCA models with observed seasonal changes (February minus August) at the same location.

developed nations, but a rapid increase of economic damage and disruption of burgeoning coastal communities over the past few decades. The insurance industry in particular has experienced a rapid increase in losses from tropical cyclone disasters during the last decade. This has been caused, to a large extent, by increasing coastal populations, by increasing insured values in coastal areas, and, perhaps, by a rising sensitivity of modern societies to disruptions of infrastructure. However, the insurance industry is worried about the possibility of increasing frequencies and/or intensities of tropical cyclones in addition to the higher exposures in coastal areas. Until scientific predictions provide conclusive proof that these fears are unwarranted, the industry has to prepare itself for extreme catastrophic losses by means of appropriate reserves and restrictive underwriting.

Some progress has been made toward understanding the possible impacts on tropical cyclones of greenhouse warming. Detailed empirical and theoretical studies have greatly improved our understanding of what is not known and, therefore, which topics offer the greatest likelihood of improved prediction skill. These include

- increased realism in coupled ocean–atmosphere global climate models;
- improved observations of air–sea interactions and other aspects of tropical cyclone genesis and evolution; and
- further and more complete paleoclimatological analyses relating past climate changes to changes in tropical cyclone activity.

Since the production of the 1996 IPCC reports, our knowledge has advanced to permit the following summary.

- There are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses.
- Regional variability, which is very large, is being quantified slowly by a variety of methods.
- Empirical methods do not have skill when applied to tropical cyclones in greenhouse conditions.
- Global and mesoscale model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill.

The IPCC "Science of Climate Change" report stated that "it is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of tropical cyclones will change" (Houghton et al. 1996, p. 334). We believe that it is now possible to improve on this statement. In particular:

- there is no evidence to suggest any major changes in the area or global location of tropical cyclone genesis in greenhouse conditions;
- thermodynamic "upscaling" models seem to have some skill in predicting maximum potential intensity (MPI); and
- these thermodynamic schemes predict an increase in MPI of 10%–20% for a doubled CO_2 climate but the known omissions (ocean spray, momentum restriction, and possibly also surface to 300 hPa lapse rate changes) all act to reduce these increases.

Acknowledgments. The process used to generate this state-of-the-art review extended from June 1996 to March 1997. The 10 members of the WMO/CAS/TMRP Committee (A. Henderson-Sellers, G. Berz, R. Elsberry, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster) submitted up-to-date assessments. These were synthesized into a single paper by the rapporteur (Dr. H. Zhang) and the chairman (Professor A. Henderson-Sellers). This draft was circulated to all committee members and also reviewed by attendees at the ONR Symposium on Tropical Cyclones in December 1996. Eleven scientists (K. McGuffie, W. Gray, R. Elsberry, M. Lander, F. Wells, G. Holland, J. Evans, L. Avila, I. Ginis, C. Landsea, and R. Abbey) reviewed the document during a working session of the ONR symposium. The resulting final version was circulated to all the committee members for agreement. We are very grateful to all those who participated in this process.

Appendix: List of Acronyms

AGCM	Atmospheric General Circulation Model
CAPE	Convective available potential energy
CAS	Commission for Atmospheric Sciences
CLIVAR	Climate Variability and Predictability Programme, WCRP
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño–Southern Oscillation
GCM	General circulation model or global climate model
GFDL	Geophysical Fluid Dynamics Laboratory
ICSU	International Council of Scientific Unions
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone

MECCA	Model Evaluation Consortium for Climate Assessment
MLO	Mixed-Layer Ocean (model)
MPI	Maximum potential intensity
NCDC	National Climate Data Center
OAGCM	(coupled) Ocean–Atmosphere General Circulation Model
QBO	Quasi-biennial oscillation
SGP	Seasonal genesis parameters
SST	Sea surface temperature
TC	Tropical cyclone
TMRP	Tropical Meteorology Research Programme
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

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