# Global Climate Change and Tropical Cyclones

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## Abstract

This paper offers an overview of the authors' studies during a specialized international symposium (Mexico, 22 November–1 December 1993) where they aimed at making an objective assessment of whether climate changes, consequent on an expected doubling of atmospheric $CO_2$ in the next six or seven decades, are likely to increase significantly the frequency or intensity of tropical cyclones (TC). Out of three methodologies available for addressing the question they employ two, discarding the third for reasons set out in the appendix.

In the first methodology, the authors enumerate reasons why, in tropical oceans, the increase in sea surface temperature (SST) suggested by climate change models might be expected to affect either (i) TC frequency, because a well-established set of six conditions for TC formation include a condition that SST should exceed 26°C, or (ii) TC intensity, because this is indicated by thermodynamic analysis to depend critically on the temperature at which energy transfer to air near the sea surface takes place.

But careful study of both suggestions indicates that the expected effects of increased SST would be largely self-limiting (i) because the other five conditions strictly control how far the band of latitudes for TC formation can be further widened, and (ii) because intense winds at the sea surface may receive their energy input at a temperature significantly depressed by evaporation of spray, and possibly through sea surface cooling.

In the second methodology, the authors study available historical records that have very large year-to-year variability in TC statistics. They find practically no consistent statistical relationships with temperature anomalies; also, a thorough analysis of how the El Niño–Southern Oscillation cycle influences the frequency and distribution of TCs shows any direct effects of local SST changes to be negligible.

The authors conclude that, even though the possibility of some minor indirect effects of global warming on TC frequency and intensity cannot be excluded, they must effectively be "swamped" by large natural variability.

## 1. Introduction

As part of the joint World Meteorological Organization/International Council of Scientific Unions (WMO/ICSU) program on tropical cyclone disasters it was agreed that the WMO/ICSU Third International Workshop on Tropical Cyclones (Mexico, 22 November–1 December 1993) would include within it a special symposium, cosponsored by ICSU and WMO, on global climate change (GCC) and tropical cyclones (TCs). This symposium should undertake a dispassionate study, aimed at collectively reaching an objective view on whether or not expected directions of GCC are liable to produce any significant effect either on the frequency or on the intensity of TCs. Like the workshop, the symposium lasted 10 days, on the last of which the participants adopted a report that, after some subsequent editorial refinement, we now present in this paper.

The question is an important one because TCs are among the most damaging types of natural disasters. They are phenomena on a vast horizontal scale (many hundreds of kilometers) that affect large numbers of tropical and subtropical countries, and in which extreme surface wind speeds pose enormous direct threats to human life and property, as well as grave indirect threats to coastal communities from associated storm-surge flooding.

In this paper, the term "tropical cyclone" is used to describe the phenomenon often known locally by names such as "hurricane" or "typhoon," in which surface winds spiral cyclonically inward to attain maximum values at an "eyewall." Vertical motions in the circular wall of dense convective cloud (which surrounds an "eye" that is often nearly free of cloud) raise air to high altitudes, around 15 km or more, before it begins to flow outward in a broadly anticyclonic motion. Although it is in oceanic regions that the TC

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forms, the further intensification of the TC flow pattern as it moves over the ocean begins to pose particularly severe threats as it approaches vulnerable coastlines.

Comprehensive studies of observational records have established (Gray 1979) that one of the conditions essential for TC formation is that the sea surface temperature (SST) be at least 26°C. This conclusion, together with some analyses of SST effects on maximum intensities, makes it natural to ask the question whether global warming is likely to lead to more (or to more intense) TCs.

For seeking an answer to this question, three scientific methodologies seem to be available. Two of these methodologies, which we view as thoroughly sound and appropriate, are developed in this paper; while the appendix briefly describes the third, and explains why at present this is not a methodology from which useful information is available.

The first methodology begins by looking in more detail at the complete list of conditions for TC formation and intensification suggested by the observational record (the above-mentioned condition on SST is, of course, just one of these) and by interpreting these from theoretical considerations including a worst case analysis (Emanuel 1986) of TCs, which (in a certain sense) are of maximum intensity. Against this background, the best available computational models for GCC following a likely doubling of atmospheric $CO_2$ during the next six or seven decades are interrogated in order to find out whether they suggest any likelihood of an increase in TC frequency and intensity resulting from such climate change.

The second methodology investigates from two points of view the variability of the historical record of TC frequencies and intensities. From a strictly statistical viewpoint, questions of whether such variability correlates at all with SST variations are investigated. From a more interpretative standpoint, a small group of natural causes of such variability is identified, and the mechanisms underlying these types of natural variability are investigated to see whether or not the SST changes contribute to these mechanisms.

The scientific basis of both the above methodologies seems to be satisfactory. On the other hand, there are grave scientific objections (see appendix) to the third methodology, directly applying climate models, even though at present these have to use coarse grids just because they must represent changes over many decades, to study the statistics of tropical "disturbances." (Such disturbances are then assumed, in spite of the grid coarseness, to be related to real TCs with very fine structure in their most energetic regions.) Comprehensive climate models are undoubtedly well suited to predicting climate changes, which they do with good consistency among themselves, but that consistency disappears completely when they are misapplied in an attempt to offer direct indications of TC statistics. Study of TC formation and intensification needs, in short, to be based on fine-grid models, which may, however, use as an essential input the climate data derived from coarse-grid models. (In the appendix, nonetheless, we acknowledge the possibility of future development of fine-grid climate models that would not necessarily be subject to the above criticisms.)

We end this introduction with a brief indication of the conclusions derived from interrogating climate models and from analyzing the historical records. First, all of the climate models predict (section 2) that so-called global warming will be far from global; instead, it will have an exceedingly regional distribution. Furthermore, it is above all in the tropical oceans that temperature changes will be least marked with SST increasing by about 1°C only, representing an average of values from 0° to 2°C (Carson 1992).

Moreover, out of some six necessary conditions for TC formation (section 3), the value of SST is only one; while the others, including those concerned with the vertical distribution of temperature and of wind velocity in the atmosphere, have even more critical influence. In particular, any widening of the band of latitudes where the condition on SST is met would be unlikely (section 4) to increase the TC frequency because fundamental characteristics of the atmospheric circulation in the Tropics tend to prevent the condition on vertical distribution of temperature being satisfied at relatively higher latitudes. (At the same time, we acknowledge in section 4 the importance of monsoon troughs as centers for TC formation, and recommend further study of possible effects of GCC on patterns of monsoon behavior.)

In the meantime, comprehensive analyses (section 5) of the historical record in all TC basins of the Northern Hemisphere show a very large year-to-year variability, in which, however, there is no significant correlation between SST and TC frequency. And a slight increase in intensity of the rare worst case Atlantic TCs, as SST increases from 26° to 29°C, may depend on rather too few storms to be of clear statistical significance.

Some of the natural variability can be related to well-established meteorological cycles: the quasi-biennial oscillation (QBO), the El Niño–Southern Oscillation (ENSO) cycle, and a third connected with Sahel rainfall. In every case, analysis of the effect of TC frequency shows it to be associated with changes in other conditions necessary for TC formation rather than directly with any local SST changes.

From all the analysis we have undertaken we are driven to conclude (section 6) that all of the other causes of variability in TC frequency and intensity will "swamp" any changes associated with the modest increases in tropical ocean temperatures that are predicted to emerge from a doubling of atmospheric $CO_2$.

## 2. Models of expected GCC

In any modeling of the greenhouse effect of a likely doubling of atmospheric $CO_2$ during the next six or seven decades it is essential to take into account the fact that the direct greenhouse effect of atmospheric $CO_2$ is far smaller than are the corresponding effects of water vapor and of clouds. Yet such a direct effect is accompanied by an additional positive feedback effect because $CO_2$ doubling can significantly alter both water vapor and cloudiness. Thus, no climate change model can be considered satisfactory (Houghton et al 1990) unless it includes as separate variables not only water vapor but also cloudiness, and allows both to influence radiative heat transfer.

This is a common feature among three highly developed GCC models, operated by the U.K. Meteorological Organization (UKMO) in Great Britain, the Max–Planck–Institute in Germany, and the Geophysical Fluid Dynamics Laboratory (GFDL) in the United States. Moreover, all of them give detailed predictions for (at least) the upper ocean as well as the atmosphere. Admittedly, none of them claim accuracy in the estimation of heat and moisture fluxes between ocean and atmosphere; they freely admit that flux corrections are essential in order to achieve good representations of present-day observations, so that they are obliged to employ similar corrections for predictions of future change. But we regard this procedure as unavoidable in the present state of knowledge.

Because of our special SST interests, we have paid particular attention to the UKMO system (Carson 1992), with a 17-layer ocean model coupled to an 11-layer atmospheric model, and we are very grateful to D. Carson, director of the Hadley Center, UKMO for explaining its conclusions to us in detail. Dr. Carson also commented that its conclusions agreed broadly with those of other models and, especially, that all three models show fair agreement regarding tropical ocean temperatures.

Before concentrating on these tropical SST changes, we give some other illustrations of the fact that predicted climate changes are highly regional in character. Ocean mixing proceeds slowly but surely and makes the global mean of surface temperature changes 1.2° less over sea than over land. The greatest climate changes are found in high-latitude land areas, being accentuated by the snow albedo positive feedback effect. (Warming that removes snow cover is enhanced by permitting more absorption of solar heat.)

Such effects contribute to the prediction that mean temperature rises over 70 years are 2.5°C in the Northern Hemisphere but only 1°C in the Southern Hemisphere. These means represent only 60% of the equilibrium response to an assumed doubling of $CO_2$ over 70 years. On the other hand, the predictions for tropical areas have reached, during the same period, far closer to their equilibrium response; and, even in the Tropics, the computed mean surface temperature is 1.2° less over sea than over land.

Against this background, it is not perhaps surprising that, as mentioned in the introduction, the consistently predicted rise in tropical SST is only about 1°C. Moreover, its variation is limited to within 0°–2°C. Our objective in the rest of this paper is to determine whether or not such a change is likely to affect TC frequency or intensity.

## 3. Considerations tending to suggest SST effects on TC formation and intensification

A widely accepted list of conditions permitting TC formation and intensification (Gray 1979) calls for satisfaction of a total of six requirements, out of which one places, as stated earlier, a lower limit (about 26°C) on SST. The other five are as follows.

(i) Distance from the equator needs to be at least 5° of latitude, to bring into play that Coriolis effect of Earth's rotation, which generates cyclonic spiraling (counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere).

(ii) The gradient of temperature drop with height must be large enough so that air that has become saturated with water vapor near the eyewall will be able to continue to rise as it follows the moist-air adiabat (with less temperature drop than dry air would undergo because of heating associated with precipitation).

(iii) Low values of vertical shear (gradient of horizontal wind with height near the cyclone's center) are needed to avoid excessive departure from a vertically coherent axisymmetric vortical structure.

(iv) Relative humidity has to be high enough in the middle troposphere to avoid drying-out effects of air that is entrained into the eyewall updraft mixing with moist air in the deep convective cloud system.

(v) Finally, there is a requirement for the prior existence at low altitude of a rather substantial level of cyclonic vorticity.

These conditions, derived from extensive observational records, emphasize that much more than just a sufficiently high SST is needed for TC formation and intensification. Condition (iii) on low vertical shear is particularly important, with its suggestion that intensification may develop most drastically under conditions when the ambient atmospheric environment contains no features that are likely to disturb the vertically coherent axisymmetric character of the spiraling motion.

Analysis of this worst case, with strictly axisymmetric spiraling, has thrown useful light on TC energetics. The analysis (Emanuel 1986, 1988, 1991) is in two parts: a thermodynamic study of the mature TC that may emerge after the intensification process has reached a steady state, and numerical modeling studies of how intensification progressively develops the previously existing vortex [see (v) above] into this steady-state motion.

Here, we outline only the thermodynamic analysis of the mature TC as a heat engine, operating on something close to a Carnot cycle. The long spiral path followed by air over the ocean surface raises its water vapor content from an initial ambient value to that fully saturated value, which permits it to rise so high in the eyewall. If the heat engine's working fluid is taken to be the intimate mix of air with water in different forms (vapor, drops, ice crystals) that makes up the atmosphere and is particularly evident in convective cloud, then this fluid's ascent in the eyewall approximately follows [see (ii) above] an adiabatic curve, that is, a curve of constant entropy.

However, this entropy has previously increased by (say) $\Delta S$ per unit mass over the long spiral path, from the rise in water vapor content (with its associated latent heat) as well as from the pressure drop. Yet, it is only after its ascent to around 15–18 km that restitution of this increased entropy to ambient values occurs at the outflow temperature $T_o$.

The Carnot cycle approximation takes this outflow temperature $T_o$ as a constant (essentially, tropopause) temperature. Also it views the entropy input as taking place at another constant temperature $T_s$, that of the ocean surface, on the grounds that temperature equilibration is fast in the atmospheric boundary layer.

Frictional dissipation in that layer is, of course, important and can be shown to be directly responsible for the component of entropy rise due to pressure drop. In a steady state, the associated energy dissipation must be balanced by the net input of mechanical energy given by the difference $T_s\Delta S - T_o\Delta S$ between energy input and output at the respective temperatures $T_s$ and $T_o$.

This simple conclusion from the heat engine analysis can be represented by an equation linking the ratio $p_a/p_c$ between ambient and central pressure to $T_s$ and $T_o$ and to the difference $q_c - q_a$ between central and ambient water vapor content. Of course, the saturated value $q_c$ is itself a steeply increasing function of $T_s$, which makes the central pressure $p_c$ (a common measure of TC intensity) depend sensitively on the SST value $T_s$.

Recalling that the whole analysis is designed to apply to worst case storms, we note its implications that values of central pressure attainable in these rare worst cases may depend sensitively on SST as well as, less sensitively, on $T_o$ and $q_a$. We acknowledge too that the theory has been given considerable support by comparing historical records of central pressure in exceptionally intense Northern Hemisphere TCs with values predicted by the above-mentioned equation when average September figures are taken for the geographical distributions of $T_s$, $T_o$, $p_a$, and $q_a$.

In addition to its value for modeling worst cases, the above representation of a TC as a heat engine with the appropriate choice of working fluid has some more general instructive uses, especially, in its clear characterization of the ocean as the engine's source of energy. This throws light, for example, on condition (v), indicating the need for a previously formed vortex to be in contact with an (warm enough) ocean if TC formation is to be possible.

## 4. Considerations that may limit SST effects

We have sketched in section 3 how SST effects on TC frequency and intensity are suggested by two important considerations; namely, that the observational record shows TC formation to require SSTs in excess of 26°C; while a worst case thermodynamic study indicates that maximum intensities may increase substantially with SST, mainly through the steep dependence thereon of $q_c$, the saturation water vapor content. Now we outline some other considerations that appear likely to limit these effects.

First of all, we reemphasize that, in addition to the SST requirement, five other conditions need to be satisfied [see (i) to (v)] if TC formation is to be possible. Accordingly, it is by no means certain that a future widening of the oceanic areas where SST exceeds 26°C will substantially widen the areas liable to TC formation.

Thus, whereas condition (i) imposes a lower limit on those latitudes (north or south) where TC formation can occur, something like an upper limit on such latitudes is imposed by condition (ii). This upper limit, between 15° and 20°C, is set by the lower-latitude boundary of that region (Schneider 1977) where subsidence in the Hadley cell generates the "trade inversion," which, far from allowing a parcel of (even saturated) air to rise to great heights, has a temperature distribution (Betts and Ridgway 1988) that, above the well-mixed layer at the base of the atmosphere, strongly opposes such vertical motions.

Here, nonspecialist readers will need an explanation of why the Hadley cell's geometry, determined to first order by the shape of the earth and the adage that "what goes up must come down," is expected to be resistant to climate change. Essentially, the cell's ascending branch (air rising from hot regions near the equator) is balanced by subsidence of air in its descending branch, stretching poleward from a latitude of some 15°–20°. This, moreover, is necessarily a slow subsidence. Accordingly, unlike the fast ascent of moist air in a TC eyewall that takes place almost adiabatically, the subsiding cold air loses by radiation much of the heat it gains by compression. Then the gradient of temperature drop with height becomes far too low for condition (ii) to be satisfied; although, as already noted, there is a layer of air near the base of the atmosphere that becomes well mixed because of the temperature contrast between descending air and air near the surface.

***After giving careful consideration to the question of whether the strengths of monsoon wind fields or (especially) the intensities of monsoon troughs would be increased significantly by global warming, we can say only that we see no reason to suppose that they would.***

These arguments have been carefully set out because of their relevance to TC formation. Any future increases of SST must widen the band of latitudes where it exceeds 26°C, yet there is little likelihood of any consequential widening of the area of TC formation because subsidence in the descending branch of the Hadley cell prevents condition (ii) and, actually, condition (iv) as well, from being satisfied therein. Therefore, if TC frequency depends, essentially, on the frequency of occurrence of situations in which all six conditions for TC formation are satisfied, then there can be little direct effect of global warming on it since such warming will lift SST above 26°C mainly in regions where conditions (ii) and (iv) cannot be satisfied.

After giving this answer to the main question about TC frequency that we have set out to address, we add a brief discussion of whether global warming might have any indirect effect. This would mean an influence on global wind fields that would make them more prone to satisfy conditions (iii) and (v).

Two types of wind field are known (Gray 1968) as especially conducive to TC formation because they help to satisfy condition (v), in which case TC formation is facilitated, provided the other conditions are satisfied as well. One of them, the monsoon trough (a region of low pressure associated with a monsoon), is responsible for most TC formation in the west Pacific and Indian Ocean regions. In the Atlantic TC formation usually originates from a midtroposphere wind field pattern of wavelike form that becomes amplified as it propagates to the west. (In the east Pacific, TC formation of both kinds is found.) Postponing discussion of these waves to section 5, we here consider possible effects of climate change on monsoons.

Modern understanding of the great south Asian system of monsoons (southwest in the summer, northeast in the winter) recognizes them as an essentially global phenomenon (Lighthill and Pearce 1981). Very briefly, the world's distribution of landmass, if spectrally analyzed into spherical harmonics, has in addition to the zonally averaged components with zonal wavenumber $n = 0$, some very large components with $n = 1$, corresponding to the area of Eurasia–Africa being vastly greater than that of the Americas. The spectrum of the global wind field has correspondingly large components where $n = 0$ and 1 that account for much of the seasonal monsoon activity, with a strong low-level wind field balanced by still stronger high-level winds that are broadly opposite in direction. In the southwest monsoon, for example, the region of strong low-level wind begins over the southern part of the Indian Ocean, passes over East Africa, and continues over south Asia to areas of the west Pacific, while the northeast monsoon, after passing over south Asia, becomes transmuted on crossing the equator into Australia's northwest monsoon. Troughs derived from these large-scale wind fields and from the associated precipitation fields are areas of cyclonic vorticity conducive to TC formation.

After giving careful consideration to the question of whether the strengths of monsoon wind fields or (especially) the intensities of monsoon troughs would be increased significantly by global warming, we can say only that we see no reason to suppose that they would. (The modest predicted increase by 1.2° in land–sea temperature difference would be accompanied by a rather larger reduction in equator–pole temperature difference, while little change is expected in some still more important heat transfer aspects of land–sea contrast.) But we acknowledge that the matter remains open, and we would warmly welcome detailed study by GCC experts of likely future changes in patterns of monsoon behavior.

We next review a particular detail of the instructive heat engine analysis of worst case TCs that suggested that increases of SST should make them more intense. This detail consists of an assumption that appeared wholly appropriate when the analysis was first published but needs revision in the light of new observations and new analysis of the air–sea interface at very high speeds.

Essentially, the heat engine analysis views the energy input to the working fluid as taking place at the sea surface temperature $T_s$, on the grounds that temperature equilibration (by both turbulent and radiative transfer) is fast in the atmospheric boundary layer. Yet recent data (Pudov 1993) show that, at very high wind speeds, this equilibration is not fast enough to counter the air temperature drop due to spray evaporation.

Actually, at wind speeds below about 20 m s$^{-1}$, the observations are consistent with the supposition that the difference between SST and air temperature takes a small constant value around 1°C. If this continued to be the case at higher wind speeds, then there would still be a systematic increase of TC intensity in response to rises in SST.

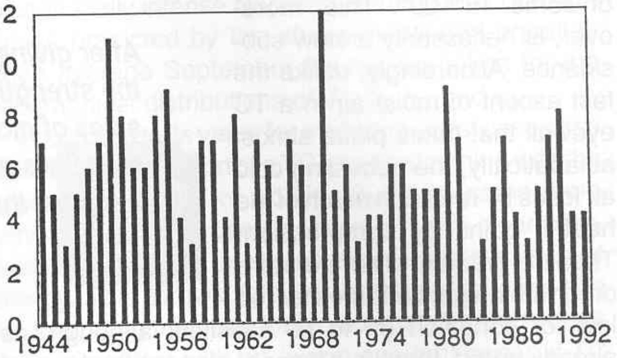
However, the sea–air temperature difference climbs steeply at wind speeds above 20 m s$^{-1}$, so that, even at a wind speed of just 26 m s$^{-1}$, it has already reached values of at least 4°C. Moreover, a recent theoretical study (Fairall et al. 1994) has shown this behavior to be consistent with knowledge of spray at such high wind speeds and of the air cooling that must result from its evaporation.

Two opposing considerations make it difficult to extrapolate this result to average wind speeds around 50 m s$^{-1}$, typical of eyewall regions. On the one hand, approach to thermodynamic equilibrium between air and sea surface might be accelerated because rates of transfer of both heat and water vapor in a turbulent boundary layer increase in approximate proportionality to wind speed. Yet a feature tending to work the other way is the presumption that concentrations of spray must be even greater at high wind speeds. This would allow air in contact with spray to reach saturation (so that deep convection is initiated) at a temperature less than SST—in other words, in thermodynamic equilibrium with spray clouds rather than with the ocean's well-mixed layer. All of these considerations, taken together, seem to indicate that air ascending in the eyewall will not have reached full thermodynamic equilibrium with the sea surface. However, the extent of departure remains uncertain. We recall too the acknowledgment about historical records of exceptionally intense TCs given at the end of section 3.

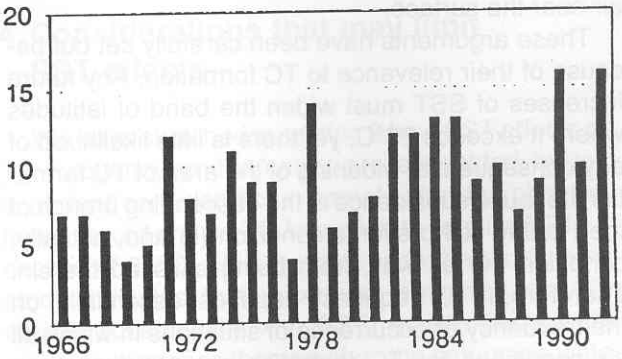
Nevertheless, there are indications here that intensification associated with increased SST may have a self-limiting character because intense winds at the sea surface receive their energy input at a temperature significantly depressed by evaporation of spray. We conclude that the theoretical argument gives no clear support for any continued increase of maximum intensity with rising SSTs.

A further consideration is the modification of the ocean's temperature structure by the TC itself. Large and/or intense TCs have been found to modify the

(a) **North Atlantic Hurricanes** (1944–1992)



(b) **Northeast Pacific Hurricanes** (1966–1992)



(c) **Northwest Pacific Typhoons** (1960–1992)

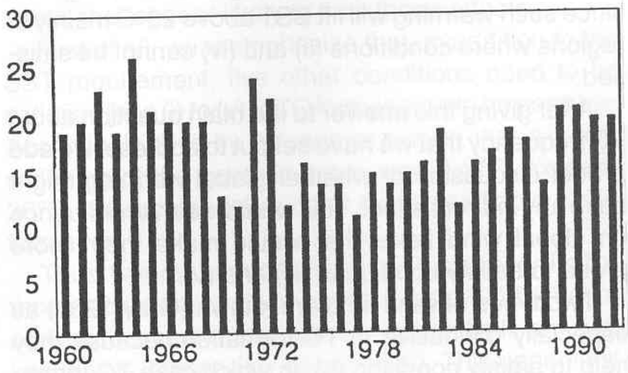


Fig. 1. Time series of hurricane-force (>33 m s$^{-1}$) TCs for (a) North Atlantic, (b) northeast Pacific, and (c) northwest Pacific.

underlying ocean by vertical mixing and upwelling, leading to SST decreases of a few degrees Celsius (Pudov 1993; Black and Holland 1994). There is insufficient objective research on this process, which may be expected to be dependent on the TC's translational speed and on the ambient oceanic structure. However, the net effect should always be to reduce the maximum TC intensity below that expected from thermodynamic principles applied to the initial SST field alone, thus introducing a further self-limiting mechanism.

## 5. Analysis of variability in the historical record

The second methodology suggested in section 1 focuses on what was there described as the very large year-to-year variability of the historical records of frequency and intensity in most TC basins. We illustrate this first for basins in the Northern Hemisphere.

Comprehensive historical records exist for the North Atlantic since 1944, for the northeast Pacific since 1966, and for the northwest Pacific since 1970. Variability in annual numbers of all three basins is shown in Fig. 1. In no basin is there any obvious general trend except the incessant variability itself.

To study a possible influence of global warming on intensities, it has been argued (Idso et al. 1990) that the principal time series of adequate length that is available for describing warming in the Northern Hemisphere needs to be used. This is the mean air temperature averaged over the hemisphere's landmasses. Figure 2 investigates whether the fraction of TCs reaching a certain level of intensity shows any relationship to anomalies in this hemispheric mean temperature but finds none in any basin.

Another approach toward investigating a possible effect of global warming on TC intensity is pursued, for basins in both hemispheres, in Fig. 3. In this figure (Evans 1993) each recorded TC is represented by a single point, referring to the location where it reached maximum intensity on a wind speed scale, which is plotted against the (actually observed) value of SST at that location and time. (Note that the diagram shows that a few Atlantic TCs, although formed where SST exceeded 26°C, were then intensified as they moved over the ocean and reached maximum intensity where SST had become considerably less.) The statistical patterns exhibited in Fig. 3 are not, in general, favorable to a view that maximum intensity depends significantly on local SST.

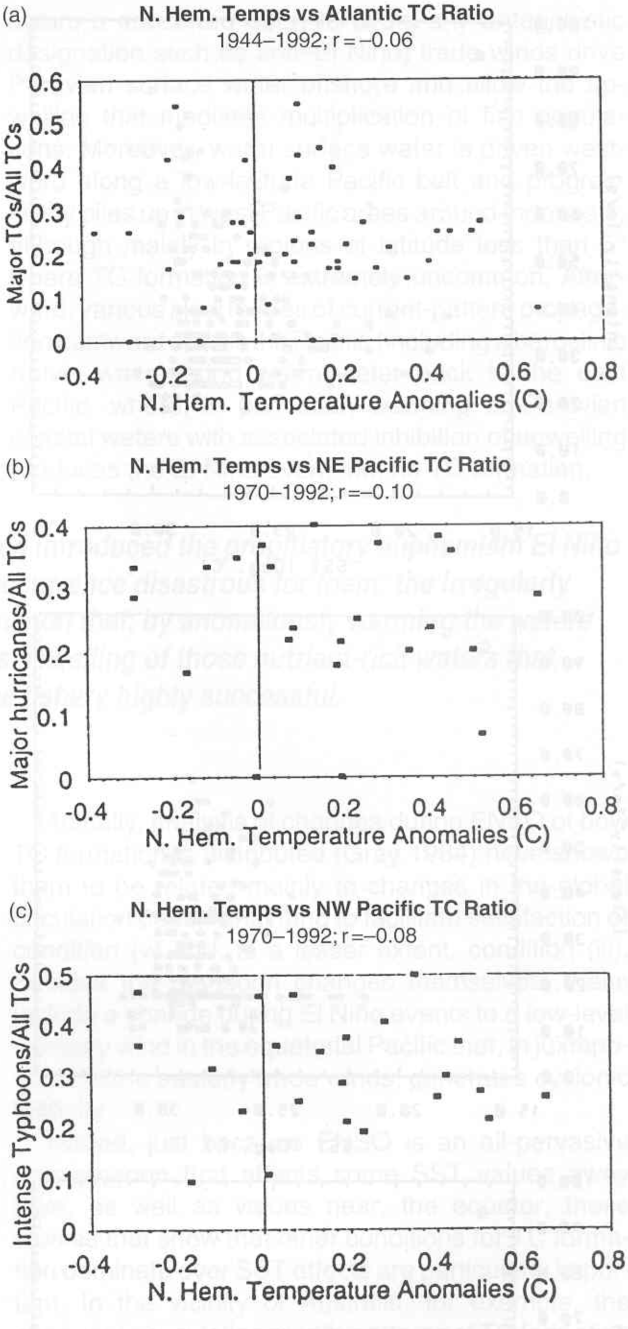


FIG. 2. Scatter diagrams (Landsea and Gray 1994), in which the fraction of all tropical cyclones reaching a level of intensity > 50 m s$^{-1}$ is plotted against Northern Hemisphere land surface temperature anomaly (relative to its 1951–70 average), for (a) North Atlantic, (b) northeast Pacific, and (c) northwest Pacific.

The one basin that seems to offer a partial exception to this general conclusion is the North Atlantic, where moreover a specialized study of how maximum surface wind for the very small number of worst case Atlantic TCs is related to climatological values of local SST (Merrill 1987, 1988) has found an increase from about 50 m s$^{-1}$ at 26°C to about 75 m s$^{-1}$ at 29°C. We note this exception without especially underscoring its significance, particularly because in a plot (Fig. 3) where each TC is represented by a single point the

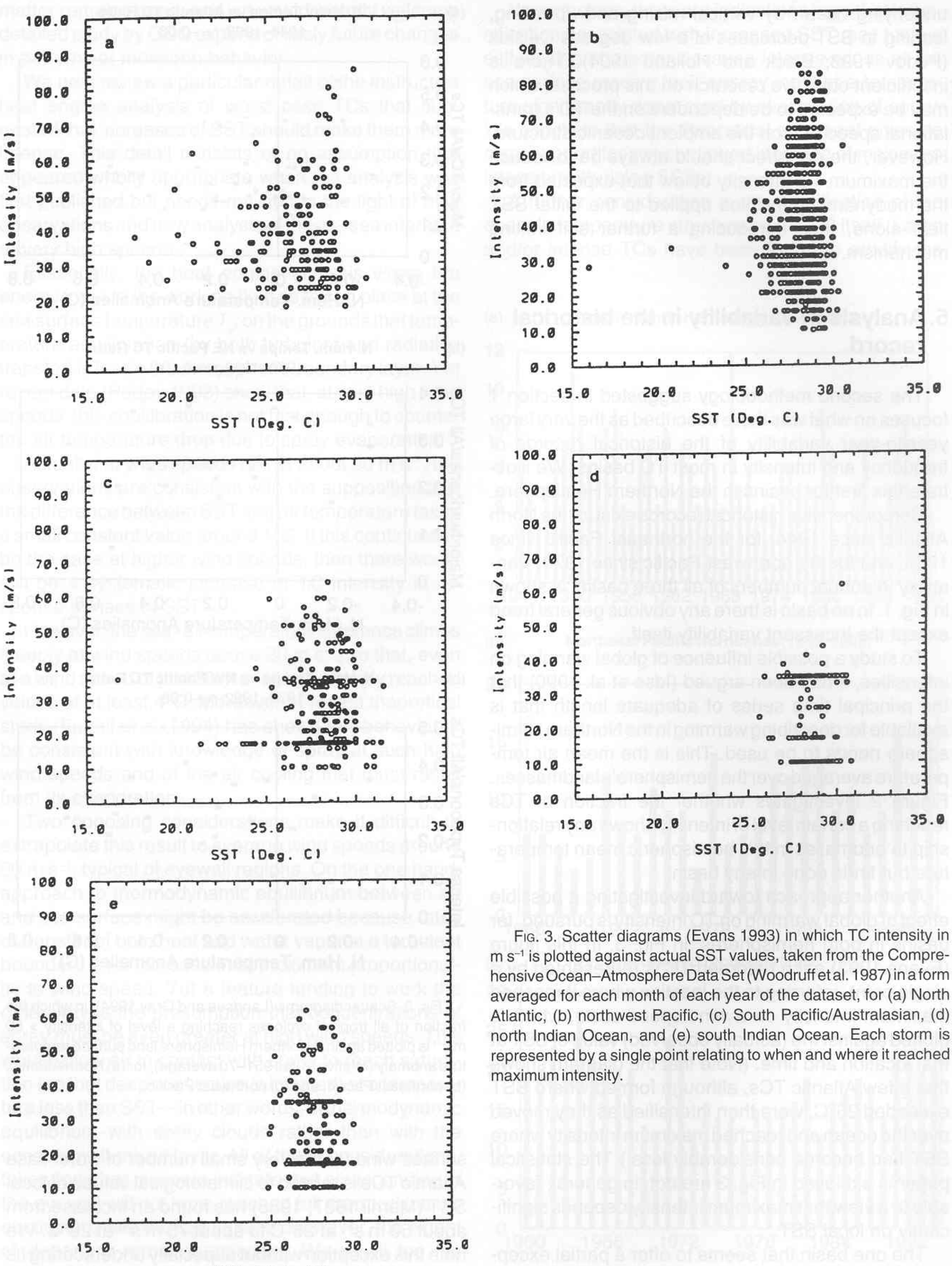


FIG. 3. Scatter diagrams (Evans 1993) in which TC intensity in m s$^{-1}$ is plotted against actual SST values, taken from the Comprehensive Ocean–Atmosphere Data Set (Woodruff et al. 1987) in a form averaged for each month of each year of the dataset, for (a) North Atlantic, (b) northwest Pacific, (c) South Pacific/Australasian, (d) north Indian Ocean, and (e) south Indian Ocean. Each storm is represented by a single point relating to when and where it reached maximum intensity.

conclusion is seen to derive from just half a dozen storms, too few to be statistically significant. We have reservations too about the use of climatological values of local SST because they pick out geographical regions without excluding the possibility that some characteristic of such a region other than climatological SST may facilitate TC formation and intensification.

Apart from statistical studies of variability in the historical record, some relationships of that variability to certain well-established shifts back and forth between different extreme meteorological conditions have been observed. Out of them, the one that demands careful analysis in this paper, because the shifts include changes in patterns of SST, is the ENSO phenomenon.

Peruvian fishermen introduced the propitiatory euphemism El Niño to designate an occurrence disastrous for them: the irregularly recurring phenomenon that, by anomalously warming the waters off Peru, prevents upwelling of those nutrient-rich waters that normally make the fishery highly successful. In sympathy, the world's oceanographers began comprehensively to investigate the El Niño phenomenon and were increasingly drawn to collaborate with meteorologists in that investigation.

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Over half a century earlier, Walker (1928) had been driven by his studies of variability in features of the Indian southwest monsoon to recognize that such variability appeared to be related to changes extending over large areas of the earth's more southerly oceans. He introduced the term "Southern Oscillation" to describe these different synchronized changes at different locations ("teleconnections"), although he appreciated that it was not a strictly regular oscillation but rather an irregularly timed patterns of shifts back and forth between extremes.

Much more recently, a remarkable interdisciplinary collaboration between oceanographers and meteorologists was to establish (Philander 1990) not only that the teleconnections stretched from India to Peru but that the El Niño and Southern Oscillation phenomena were all part of a single phenomenon, now called "ENSO," involving essentially synchronous, although irregularly timed, changes in both atmospheric and oceanic flow patterns extending over half the globe. They include wide-ranging monsoon changes, equatorial wind changes, and also major changes in Pacific oceanography, but here just the changes relevant to TC formation are mentioned.

At the phase of the cycle called "La Niña" (with, again, a concerted effort to avoid any antagonistic designation such as anti–El Niño) trade winds drive Peruvian surface water offshore and allow the upwelling that mediates multiplication of fish populations. Moreover, warm surface water is driven westward along a low-latitude Pacific belt and progressively piles up in west Pacific areas around Indonesia, although mainly in regions of latitude less than 5° where TC formation is extremely uncommon. Afterward, various slow modes of current-pattern propagation eastward across the Pacific (including a baroclinic Kelvin wave) bring warm water back to the east Pacific, where, in particular, warming of Peruvian coastal waters with associated inhibition of upwelling produces the El Niño event, but no TC formation.

Actually, analysis of changes during ENSO of how TC formation is distributed (Gray 1984) have shown them to be related mainly to changes in the global circulation pattern that tend to facilitate satisfaction of condition (v) and, to a lesser extent, condition (iii). Besides the monsoon changes themselves, these include a change during El Niño events to a low-level westerly wind in the equatorial Pacific that, in juxtaposition to the easterly trade winds, generates cyclonic vorticity.

Indeed, just because ENSO is an all-pervasive phenomenon that affects some SST values away from, as well as values near, the equator, these studies that show that other conditions for TC formation dominate over SST effects are particularly important. In the vicinity of Australia, for example, the changes in circulation modify patterns of TC formation (Evans and Allan 1992) from being predominantly toward the north and toward the northwest during El Niño to being predominantly toward the northeast during La Niña. When that part of the annual variability in TC formation that is directly correlated with ENSO is removed (Holland et al. 1988), the remainder (Fig. 4) shows no significant correlation with local SST.

Far less space in this paper needs to be devoted to relationships of TC statistics with two other established types of shift back and forth. This is because neither involves SST alterations.

The QBO is a remarkable phenomenon involving regular changes of direction of an equatorial jet in the stratosphere. Here we simply note that, for reasons of an essentially dynamical character (Gray 1984), some more intense TCs tend to form when the high-level jet is from the west than when it is from the east.

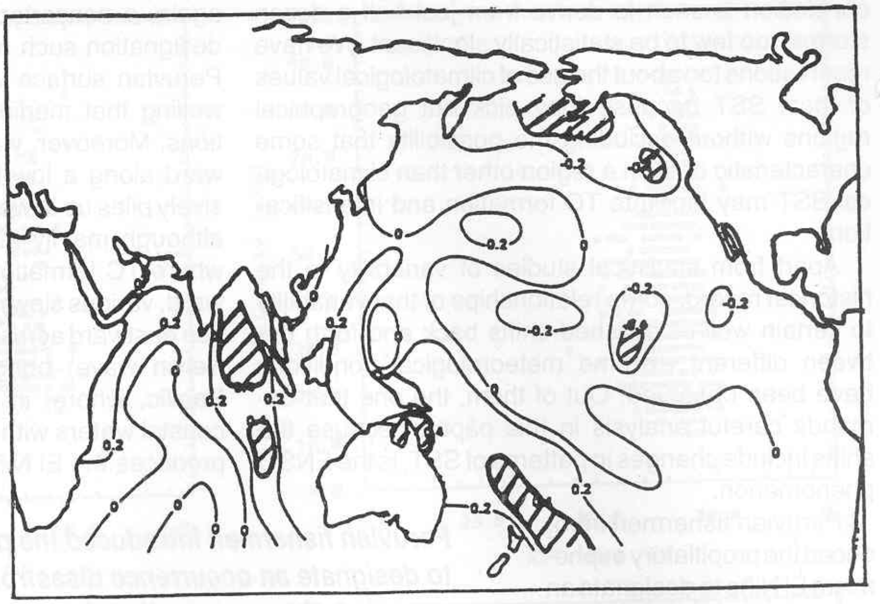

FIG. 4. Partial correlation with mean seasonal SST (after the ENSO-related part, varying linearly with the Southern Oscillation index, has been removed) of seasonal numbers of TCs in the Pacific and Indian regions (Holland et al. 1988). Only in the shaded areas is the partial correlation > 0.4 or < –0.4.

Last, we return to those midtroposphere wind field patterns of wavelike form that become amplified as they propagate toward the west and that (see section 4) have increasingly been recognized as making key contributions toward most TC formation in the North Atlantic and northeast Pacific. They are generated in the massive land area of Africa north of the equator, and so they remain in the Northern Hemisphere as they propagate westward. If amplification reaches the point where a parcel of strong midlevel vorticity becomes intense enough to serve as a necessary center (Tuleya 1991), certain processes too complicated to describe here can progressively lead, provided other conditions are favorable, to the requirement for TC formation becoming satisfied.

Furthermore, slow shifts in the multidecadal Sahel rainfall cycle seem to be related, for primarily dynamical reasons (Landsea and Gray 1992), to changes in the generation of intense TCs in this region. It has been suggested that this effect may be responsible for a slight downward trend found during later decades of the past 50 years in TC formation over the North Atlantic (Fig. 1). (Actually, numbers of intense TCs show an even larger downward trend.)

South of the equator, the African landmass is less extensive (and different, too, in other ways) and does not significantly tend to generate similar waves. Correspondingly, TC formation is absent in the South Atlantic, notwithstanding the fact that SST values by themselves are sufficient to permit it. This offers yet another illustration of the dominance of conditions (i)–(v) over simple SST criteria.

## 6. Conclusions

Arguments outlined in section 4 have suggested to us reasons for concluding that direct first-order effects of global SST changes on TC frequency and intensity should not be expected. On the other hand, we in no way exclude possibilities of more modest effects of global warming, which could either be second-order effects of SST changes or might otherwise take the form of those indirect effects, related to possible changes in monsoon circulations, on which we have in section 4 recommended further study.

Analysis of historical variability in section 5 has, effectively, led to the same conclusions. More fundamentally, however, this analysis suggests that the incessant year-to-year variations (see Fig. 1, for example) are so great that they must effectively "swamp" any quite modest effects of GCC on TC frequency and intensity, which (we believe) are all that can rationally be expected.

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## Appendix. A third methodology

In this appendix, we consider quite briefly a third methodology that has been proposed (Broccoli and Manabe 1990; Haarsma et al. 1993; Manabe et al. 1994) for studying links between GCC and TCs. It is simply to run one of the climate models for different climate forcings and to count the number of transient tropical disturbances that can be discerned in each year, and then to study whether this number exhibits any change. If so, then this change is assumed to imply a similar change for TCs in the real atmosphere.

This seems to be a false analogy. Present climate models, for some excellent reasons (because they need to be integrated forward over several decades), have a low spatial resolution, typically around 300 km. Inherently, then, they cannot resolve those important parts of a TC that are most energetic.

A second false analogy is to regard the procedure as related to those techniques by which positions and strengths of fronts are extracted from numerical weather prediction models. This is a process of sharpening some continuous transition suggested by the model into the presumed real discontinuity. But the front, though important, is not the site of most of the system's energy as is the central part of a TC.

Third, we recall how fine is the balance that in the body of this paper has been shown to determine whether or not a TC forms. This seems to make it most unlikely that a model with 300-km resolution can possibly yield data relevant to real TC formation.

These are fundamental objections to the proposed methodology. Some other objections can be added that depend on certain only partly satisfactory features of current climate models, including above all their treatments of the important feedback interactions between cloud distribution and radiative transfer.

Admittedly, in spite of these features, there is a certain broad consistency in climatic predictions from different models. But, on the contrary, such consistency disappears altogether when their predictions of the statistics of tropical disturbances are compared.

For example, disturbances appearing in the GFDL model are far stronger than those in the UKMO model. After global warming they are predicted to become considerably fewer in the GFDL model but a little more frequent in the UKMO model. A global model developed at the Japan Meteorological Agency shows no disturbances of any substantial strength.

Again, the frequency of formation of such disturbances is a quantity particularly sensitive to how the model treats cloud radiative feedback. One model predicts an increase in frequency when this is ignored and a decrease when it is taken into account.

But we attach no importance to details of these variations and merely regard the fundamental reasons (see above) for rejecting this methodology as underlined still further by such inconsistency of the different results to which it has led. This, of course, is why the methodology was not developed in the body of this paper alongside those two methodologies to which we attach real weight.

At the same time, we acknowledge the clear possibility of future development of fine-grid climate models that would not necessarily be subject to the above criticisms. A future climate model with excellent model physics and with very high resolution might indeed be a suitable tool for studying how GCC may affect TC statistics.

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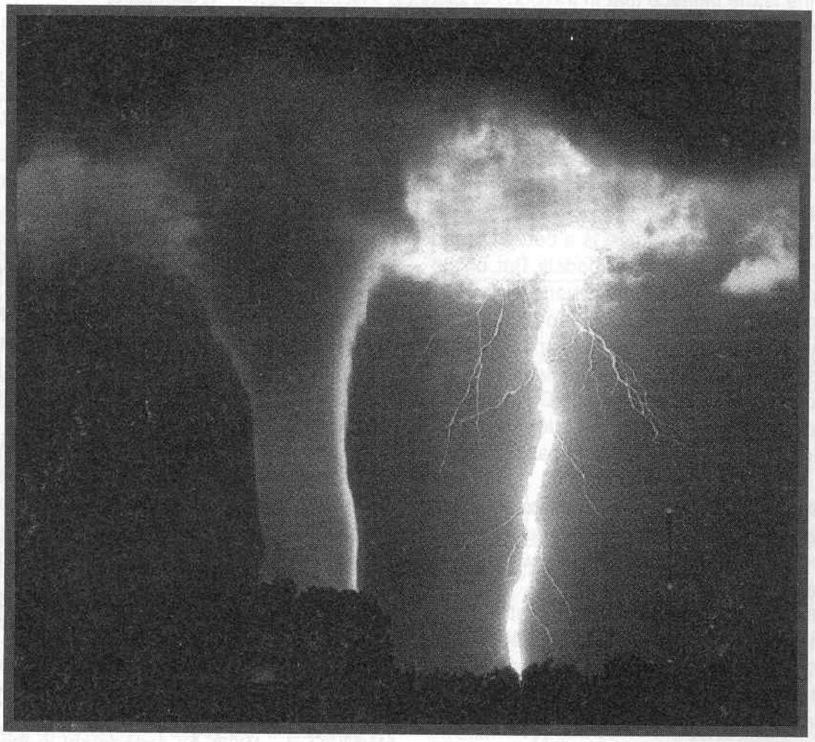

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