POTENTIAL CHANGES IN TROPICAL STORMS, HURRICANES, AND EXTREME RAINFALL EVENTS AS A RESULT OF CLIMATE CHANGE

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Abstract. Our current understanding of the ability of climate models to provide insight into the possible impacts of the enhanced greenhouse effect on the climatology of tropical cyclones and extreme rainfall events is reviewed. At present, because of the insufficient resolution of climate models and their generally crude representation of sub-gridscale and convective processes, little confidence can be placed in any definite predictions of such effects, although a tendency for more heavy rainfall events seems likely, and a modest increase in tropical cyclone intensities is possible. In the view of the authors, it would be unwise to exclude substantial local changes in the climatologies of these phenomena, especially at a regional (sub-continental) scale.

1. Introduction

The conclusions regarding the impact of the enhanced greenhouse effect on the mean climate of the Earth that can be drawn from climate models are naturally bounded by a range of uncertainty. This range is nevertheless reasonably well know for several variables, notably global mean temperature (IPCC, 1990, 1996). There is much less confidence in the ability of models to predict changes in climate for specific regions of the globe. In addition, since the evaluation of climate models has tended to focus on the quality of their simulation of the mean climate (IPCC, 1990, 1992, 1996), less is known about their ability to simulate events of shorter duration in the climate system (e.g. Hulme et al., 1993; Slingo et al., 1994; Hulme and Viner, 1998). These may include phenomena with time scales of several months to a year, such as the El Niño-Southern Oscillation (ENSO) phenomenon (Philander, 1990), to events like tropical cyclones that typically last for several days to a few weeks. Tropical cyclones are short-lived phenomena whose impacts can range from devastating floods, high winds, and storm surges to beneficial drought-breaking rains. For these reasons, it is important to have some understanding of their frequency, intensity, and regions of occurrence in a warmer world.

The peak intensity of tropical cyclones is reached over a small area near their centers, typically only tens of kilometers across (Frank, 1977). This is much smaller than the usual resolution of climate models, which are the main numerical tools for the prediction of future climate. The present generation of global climate models typically has a horizontal resolution on the order of several hundred

Climatic Change **39**: 199–213, 1998.

kilometers, and is thus not suited to modelling the climatology of tropical cyclones. Moreover, the essential physical processes of the formation and development of clouds and precipitation are at present crudely represented in such models, although this does not mean that these models (particularly those of higher horizontal resolution) are incapable of generating systems that have some of the characteristics of observed tropical cyclones (e.g., Bengtsson et al., 1995).

Thus it is not possible at the present time to give definitive answers regarding any possible changes in the regional distribution of tropical cyclones. Nevertheless, the purpose of this paper is to detail our present knowledge regarding the conditions under which tropical cyclones form, and to speculate about such possible changes, based upon our current understanding of the relevant issues. In addition, the conclusions of climate model simulations regarding changes in the frequency of extreme rainfall events in the tropics, whether caused by tropical cyclones or by other meteorological conditions, will be discussed. Finally, directions of future research will be outlined.

2. Formation mechanisms of tropical cyclones

The formation (or "genesis") of tropical cyclones depends upon a number of factors including sea surface temperature (SST), the vertical lapse rate of the atmosphere, vertical wind shear, mid-tropospheric relative humidity, and the prior existence of a center of low-level cyclonic vorticity (Gray, 1979). Thus, to make accurate predictions of the likely changes in tropical cyclone numbers as a result of global warming, good estimates of the changes in these quantities at regional rather than global scales are needed. Since there is little confidence in the predictions of the present generation of climate models at the scales required to make such an estimate, the effect of global warming on the numbers of tropical cyclones is presently unknown. It is however possible to speculate on the effects of plausible changes in the various genesis parameters, based upon what we know about the predictions of climate models.

SSTs of at least 26C are required for tropical cyclones to form. Since climate models predict a general increase in tropical SST (Folland et al., 1990), it might be presumed that, other things being equal, new regions of potential tropical cyclone formation would develop in a warmer climate. The genesis of tropical cyclones is however restricted by the equatorward limit of the trade inversion (Lighthill et al., 1994; see also Broccoli et al., 1995; Emanuel, 1995), which decreases the lapse rate and the mid-tropospheric relative humidity, thus decreasing the likelihood of tropical cyclone formation. The results of transient coupled ocean-atmosphere model climate experiments give no clear indication of any movement of this feature (P. Whetton, pers. comm., 1994), although some modelling and observational results suggest that it may move a few degrees on average (e.g., Gibson, 1992; Hall et al., 1994). The effect of changes in atmospheric dynamical factors on tropical cyclone numbers as a result of global warming was assessed by Ryan et al. (1992b), who evaluated the tropical cyclone seasonal genesis parameter (SGP) of Gray (1975) for the warmer climate predicted by a model simulation. Table I shows their results for the ratio of $2xCO_2$ SGP to model control SGP for each of the components of the SGP over those areas of the globe where the control value of the SGP was at least one. The first two components are dynamical terms related to the low-level vorticity and the vertical wind shear respectively, while the last three are thermodynamic terms, representing respectively ocean thermal energy, vertical stability, and mid-tropospheric relative humidity. Their results showed an increase in the SGP, but this was almost entirely caused by terms that were strongly forced by changes in SST rather than in the dynamical components of the SGP. Note that while most of the contribution to the increase in SGP came from the thermal energy term (*E*), there was also a contribution from the vertical stability term $\partial\theta_e/\partial p$, which increased by about 25% (i.e. became more unstable). However, Watterson et al. (1995), in applying the SGP to inter-annual variability, found that both the dynamic and thermodynamic terms contributed to the simulated variability. In addition, Nicholls (1989) showed from observations that there is little relationship between SST and tropical cyclone numbers in several regions of the globe. Thus there is little evidence that changes in SST, by themselves, could cause change in tropical cyclone numbers.

Model results suggest that the vertical lapse rate of the tropical atmosphere may decrease in enhanced greenhouse conditions (e.g. IPCC, 1996). This would tend to decrease cyclone numbers, all other things being equal -- i.e., if there were no changes in the contribution of moisture to the θ_e profile and thereby the stability. Changes in vertical wind shear in an equilibrium climate model simulation using the CSIRO9 model (McGregor et al., 1993) were found by Ryan et al. (1992b) to be small. Regions of cyclonic vorticity for the genesis of tropical cyclones are provided by the monsoon trough and, in the Atlantic, by amplifying easterly waves (Gray, 1968). At present, potential changes in intensities or locations of the monsoon trough are unknown, partly because of the generally poor simulation of this quantity in many climate models (Ryan et al., 1992a). Some experiments conducted for the Australian region suggest little movement may occur (Ryan et al., 1992a; Suppiah, 1994).

In addition, tropical cyclone numbers in some regions are highly correlated with the complex interannual variability of the ocean-atmosphere system associated with ENSO (Philander, 1990; Evans and Allan, 1992), whose state in a changed climate is also presently unknown (Pittock et al., 1996), despite some tentative conclusions from recent experiments. Knutson and Manabe (1994) and Tett (1995) show that transient simulations by coupled ocean-atmosphere models give little significant change or a slight decrease in ENSO amplitude after 50 to

100 years. Until very recently, no coupled GCM simulated the observed ENSO variations adequately (Neelin et al., 1992), although the results of Roeckner et al. (1996) show that a coupled model can give a reasonable simulation of the observed amplitude and period of ENSO variations. Since there is insufficient confidence in the predictions of current models regarding any changes in ENSO, regional changes in tropical cyclone numbers caused by possible changes in the characteristics of ENSO in a warmer world are likewise unknown.

Table I

Ratio of 2 x CO2 SGP to model control SGP over the area of the globe in which control values of SGP are at least one. The ratios of the separate components of the SGP are listed for each season: January-March (JFM), April-June (AMJ), July-September (JAS) and October-December (OND). From Ryan et al. (1992b)

Parameter		JFM	AMJ	JAS	OND
$\zeta_r f/\lvert f\rvert^{-1} + 5$		0.99	0.96	0.99	1.00
$(S_z + 3)^{-1}$	0.98	1.01	1.02	1.09	
E		2.13	2.01	2.10	2.18
$(\partial\theta_e/\partial p + 5)$		1.27	1.27	1.27	1.25
(RH-40)/30		1.09	1.08	1.06	1.07

3. Changes in tropical cyclone intensities

The intensity of tropical cyclones is also governed by a number of factors. The maximum possible intensity (MPI) has been found empirically to be a function of SST (e.g. DeMaria and Kaplan, 1994). Some theoretical justification for this relationship has been given by Emanuel (1988, 1991). An alternative formulation of MPI has been proposed by Holland (1997). Climate model simulations show that tropical SSTs are likely to slowly increase in enhanced greenhouse conditions. Experiments with limited-area models have shown some increase in intensity with SST (Evans et al., 1994). It is also possible that evaporative feedbacks may lower SSTs in the central region of a tropical storm (Fairall et al., 1994), thus tending to minimize any increase in intensity. Analysis of historical data shows little dependence of MPI on SST (Evans, 1993), with the possible exception of some intense storms in the North Atlantic. A recent summary by Henderson-Sellers and Zhang (1997), based on the work of Tonkin et al. (1997), suggests a modest increase in tropical cyclone intensity of up to 20% is possible, as measured by wind speeds. A similar conclusion using a different technique was reached by Knutson et al. (1997).

One effect of generally increased SSTs may be to increase the longevity of storms in higher latitudes, thus increasing the observed intensity of storms in these regions (N. Nicholls, pers. comm., 1994). This may also extend the regions of common occurrence (rather than formation) of tropical storms poleward of their present limits; once the storm has formed, it may lose energy more slowly if the underlying water surface is warmer as a result of an increase in SST.

Table II

Number of observed tropical cyclones per month versus number of tropical cyclone candidates in the 1xCO2 and 2xCO2 simulations of Bengtsson et al. (1995, 1996), for the Northern and Southern Hemispheres. Observations from Gray (1979).

	Northern Hemisphere			Southern Hemisphere		
	Obs.	1xCO2	2xCO2	Obs.	1xCO2	2xCO2
Jan.	0.7	2.2	0.2	6.1	5.2	3.2
Feb.	0.3	1.0	0.8	5.9	6.2	2.8
Mar.	0.3	2.0	0.6	4.7	4.6	2.2
Apr.	1.0	1.4	1.8	2.1	4.0	1.4
May	2.9	3.4	3.0	0.5	1.0	0.4
Jun.	4.5	6.0	4.0	0.	0.	0.6
Jul.	8.6	3.2	4.6	0.	0.	0.
Aug.	10.9	9.6	4.4	0.	0.4	0.2
Sep.	11.5	10.8	8.6	0.	0.	0.
Oct.	7.9	7.6	6.6	0.4	0.4	0.
Nov.	4.8	4.8	3.8	1.5	1.8	0.
Dec.	4.2	4.2	1.4	3.6	3.2	0.2
Total	54.6	56.2	42.0	24.5	26.8	11.6

Changes in the height of the tropopause may affect the maximum intensity of tropical cyclones, and climate models generally suggest that tropical tropopause heights could decrease, thus reducing MPI. Likewise, since the models suggest that the tropical atmosphere will become more stable, this may tend to limit intensities, although as mentioned above Ryan et al. (1992b) found that the inclusion of moisture led to a decrease in tropical stability under $2xCO_2$ conditions.

4. Direct simulation of tropical cyclones in climate models

Several attempts have been made to determine the ability of climate models, even at relatively coarse resolutions, to simulate low pressure systems that may then be identified as tropical cyclones. The earlier work of Broccoli and Manabe (1990) and Haarsma et al. (1993) was of limited use because of the low horizontal resolution of the climate models employed, about a few hundred kilometers. The more recent studies of Bengtsson et al. (1995, 1996) were performed at a much higher resolution (T106, roughly equivalent to a grid spacing of 120 km) using a coupled ocean-atmosphere climate model. Examination of the composite characteristics of tropical cyclones (Frank, 1977) suggests that a climate model of this resolution may have some hope of simulating several of the features of a tropical cyclone.

Bengtsson et al. impose several detection criteria (derived from observations) that need to be satisfied for a tropical cyclone to be detected in their simulations. Based upon these criteria, their simulation of the present-day climatology of tropical cyclone areas of occurrence and frequency is reasonable. Under enhanced greenhouse conditions, the number of storms is substantially reduced, particularly in the Southern Hemisphere (see Table II). According to Bengtsson et al. (1995, 1996), this result is largely related to increases in tropical tropospheric stability. The horizontal resolution of this study clearly is still too coarse to make any statement about possible changes in tropical cyclone intensity from the simulated storms themselves.

There are, however, differences in the stability changes seen in the transient coupled-atmosphere ocean used in Bengtsson's work and those calculated for the slab ocean model used by Ryan et al. (1992b). In particular, transient model simulations of climate change tend to display smaller changes in temperature, a result of the thermal inertia of the deep ocean (Gates et al., 1992). England (1995) suggests that many current transient models may be sequestering heat at too fast a rate in several regions of the deep ocean, including the high latitudes of the Southern Hemisphere. Changes in the amount of simulated heat uptake may change the simulated response to climate change, particularly in the Southern Hemisphere, although recent transient simulations that include the effects of anthropogenic aerosols give a good simulation of the changes of global mean temperature observed this century (Hasselmann et al., 1995; Mitchell et al., 1995). It is possible that better coupled models may be needed in order to give a good estimate of the precise effect of tropical stability on cyclone numbers.

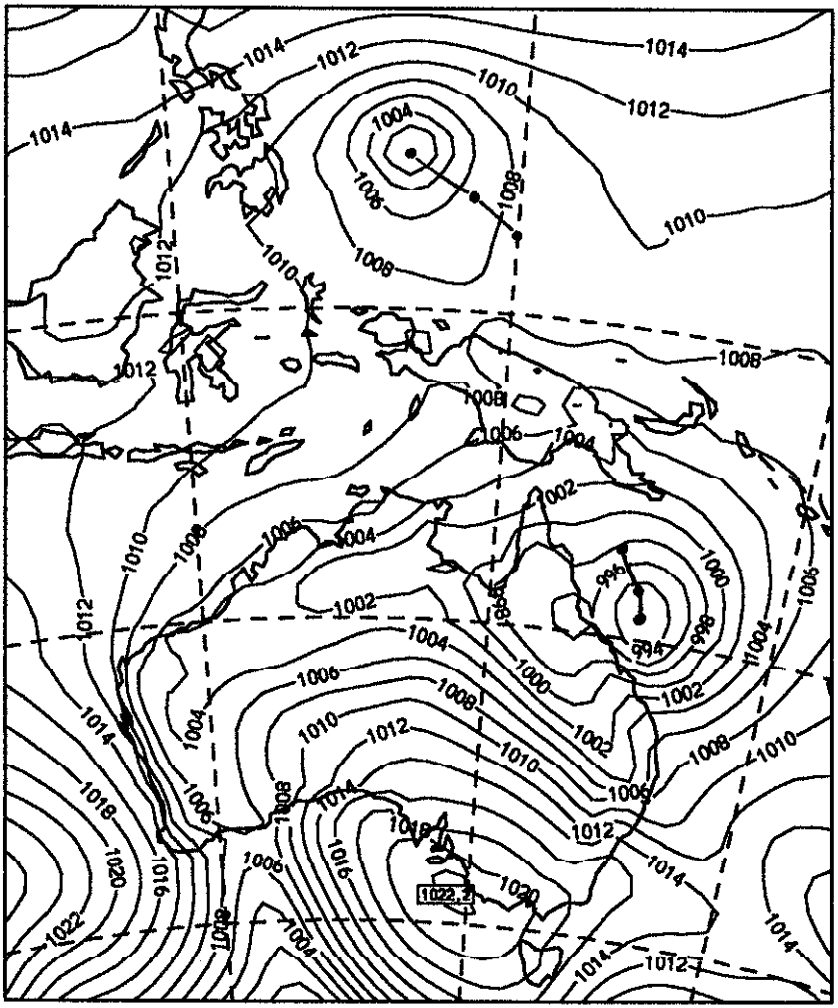

Figure 1. Snapshot and tracks of tropical low pressure systems as simulated by DARLAM with January 1982 sea surface temperatures. Contour interval is 2hPa.

Another modelling approach has been the use of limited area climate models (e.g. Giorgi et al., 1994; Walsh and McGregor, 1995), in which a climate model is implemented over a small section of the globe and forced at its boundaries by fields extracted from a coarser-resolution global model. The advantage of these models is that they can provide a better simulation of climate than the global model in most regions, while remaining relatively economical to run. Figure 1 shows an instantaneous mean sea level pressure field from a CSIRO limited area model (DARLAM, Walsh and McGregor, 1995) simulation using the SSTs of January 1982. In this simulation, DARLAM is forced by the output of the CSIRO GCM, and is run with a horizontal resolution of 125 km. A more detailed analysis is given in Walsh and Watterson (1997). Tracks are shown for low-pressure systems, generated by DARLAM, which have some of the characteristics of tropical cyclones. They follow tracks that are typical of tropical cyclones in this region; they both have "warm cores" or positive mid-tropospheric temperature anomalies near their centers, and both have low-level wind speed maxima. Nevertheless, much more validation of the climatology of these systems in DARLAM needs to be performed.

Such simulations are still limited by relatively coarse resolution and especially by their greatly simplified representation of convective processes. As Lighthill et al. (1994) note, a high resolution climate model with very realistic parameterizations would be an excellent tool for studying changes in the climatology of tropical cyclones.

5. Extreme rainfall events

This discussion summarizes the conclusions of Fowler and Hennessy (1995). There are sound theoretical reasons to suppose that, in a warmer world, average precipitation would be higher. The water-holding capacity of the atmosphere increases with temperature (e.g., Stephens, 1990), and in the absence of a substantial change in the atmospheric dynamics, this should lead to higher precipitation intensity. Higher precipitation either may be in the form of more precipitation events and/or an increase in precipitation intensity. For the purposes of evaluating return periods (the average interval between events of a given magnitude) for heavy or extreme rainfall events, increases in rainfall intensity are much more important, as they substantially enlarge the tail of the rainfall frequency distribution above a certain specified intensity limit.

There is some evidence from climate model studies that, in a warmer climate, rainfall events will be more intense (Mitchell et al., 1990; IPCC, 1992; Gregory and Mitchell, 1995; Cubasch et al., 1995; Henderson-Sellers et al., 1997). Gordon et al. (1992) attempted to estimate the changes in the frequency distribution of simulated daily rainfall using the CSIRO4 climate model. They found that return periods for simulated heavy rain events under $2xCO_2$ conditions decreased by factors ranging from 2 to 5 over Australia, the midwestern U.S., Europe, and India. Similar results were found for the CSIRO9 model (McGregor et al., 1993) and with the UKMO high resolution model (Fowler and Hennessy, 1995; Hennessy et al., 1997). At most latitudes, including tropical regions, convective precipitation generally increased in intensity. This suggests the possibility of decreases in return periods and increases in the maximum rainfall that might be expected in a given interval. Such changes have implications for the modification and development of large infrastructure projects such as flood control systems, and for the location of settlements and industry. A similar result was found in the transient model experiments of Murphy (1995) and Murphy and Mitchell (1995). As summarized in Hulme and Viner (1998), the frequency of rainfall events larger than 25 mm per day increased throughout much of the tropics, but there were also regions of decrease, most notably in south central Africa.

Table III

Comparison of 24-h accumulated rainfall for control (C) and enhanced SST (E) simulations for four storm cases off the coast of New South Wales; from McInnes et al. (1992).

Case Number	Simulation type	Peak rainfall	Areal rainfall
1	Control (C)	22 mm	7 mm
	Enhanced SST(E)	32 mm	8 mm
	Ratio (E/C)	1.45	1.14
2	Control (C)	170 mm	64 mm
	Enhanced SST(E)	286 mm	134 mm
	Ratio (E/C)	1.68	2.09
3	Control (C)	419 mm	121 mm
	Enhanced SST(E)	754 mm	171 mm
	Ratio (E/C)	1.80	1.41
4	Control (C)	120 mm	31 mm
	Enhanced SST(E)	181 mm	55 mm
	Ratio (E/C)	1.51	1.67

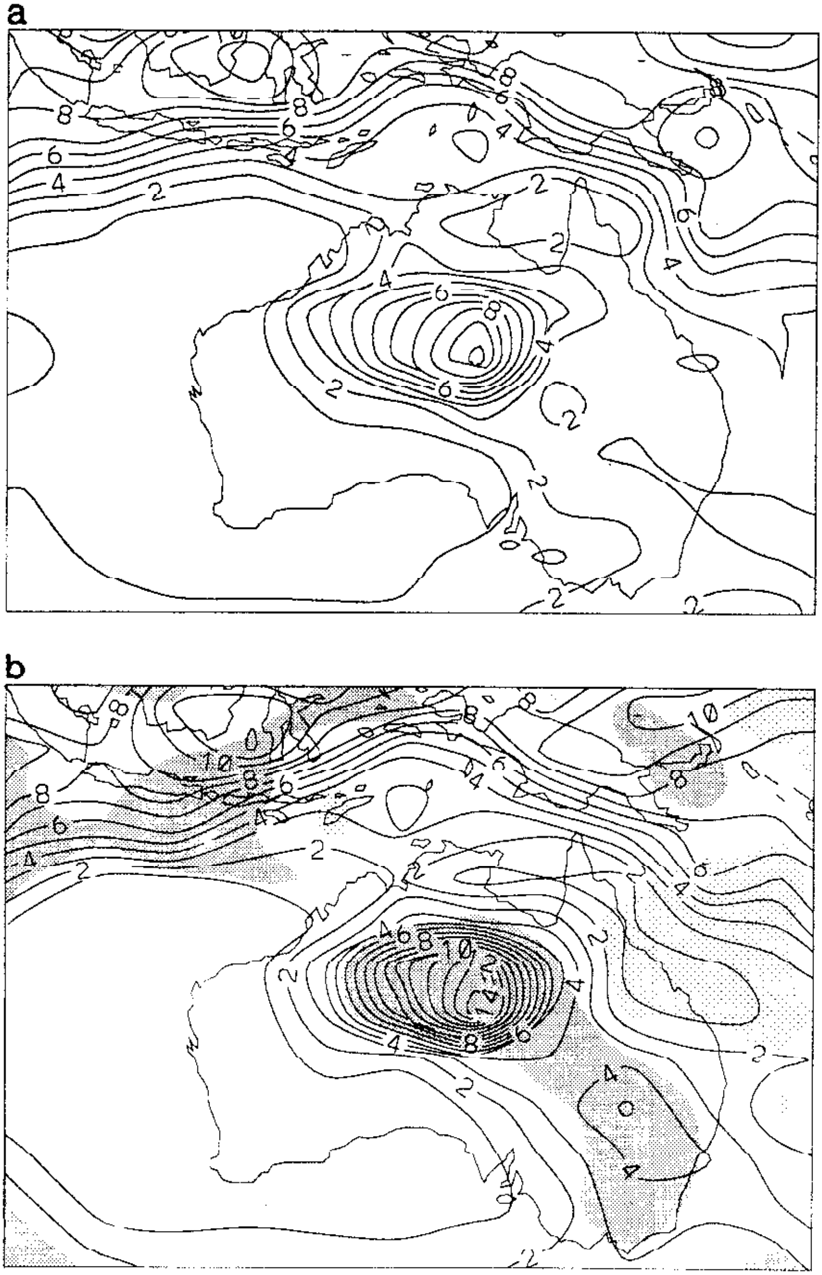

Figure 2. Composite rainfall for wet conditions (99.5 percentile of all rainfall events) in central Australia under (a) $1xCO_2$ experiments and (b) $2xCO_2$ experiments. Areas showing an increase in rainfall greater than 1 mm day^{-1} are densely shaded while while areas indicating a decrease in rainfall of more than 1 mm day^{-1} are lightly shaded.

Supporting evidence is given from an analysis by Suppiah (1994), using the CSIRO9 model. Figure 2 shows the mean rainfall of precipitation events in the highest 0.5% (99.5 percentile) of all such events, for 1x and $2xCO_2$ conditions. The change in rainfall between Fig. 2a and 2b is thus a measure of the change in the intensity of extreme rainfall events. The results show that simulated extreme rainfall events over tropical Australia increase in intensity as a result of climate change. Similarly, the experiments of McInnes et al. (1992), using DARLAM at high horizontal resolution implemented over a domain off the east coast of Australia, showed that there was a strong response in the model's simulation of extreme rainfall events to an increase in SST typical of that expected in a doubled CO_2 climate. Peak rainfall amounts over the adjacent land regions for selected storm cases increased by about 50% (Table III).

6. Conclusions

While there is some confidence in the ability of climate models to predict changes in the global mean climate as a result of the enhanced greenhouse effect, there is much less confidence in their ability to predict changes in the climate of specific regions or of short-lived phenomena such as tropical cyclones. Some conclusions can be reached from current climate model simulations regarding such issues as possible changes in tropical cyclone numbers, regions of occurrence, and intensities, but these are of low confidence.

There is considerable uncertainty at the regional scale whether tropical cyclone numbers may decrease or increase, or whether regions of origin will remain the same. Likewise the impact of climate change on tropical cyclone intensities is uncertain, although evidence now supports modest increases. Regions of occurrence, as opposed to formation, may increase poleward as a result of increasing SSTs. Year-to-year variations in tropical cyclone numbers are great and in many regions strongly correlated with ENSO, whose state in a changed climate is uncertain. Some substantial local changes (decreases or increases) in the climatology of tropical cyclones therefore cannot be excluded.

It is clear that any substantial changes in numbers or intensities would have consequences (positive or negative) in the tropics and vulnerable regions of the extratropics for return periods of wind damage, storm surge, and damaging floods. In particular, tropical cyclones of differing intensities cause varying degrees of storm surge damage (e.g., Hubbert et al., 1991). This damage would be increased by any substantial rise in sea level as a result of global warming (Warrick et al., 1996), even if numbers and intensities of tropical cyclones do not change.

There is considerable evidence that the frequency of extreme rainfall events may increase in the tropics, which would also cause increases in flood return periods. Nevertheless, there are substantial local variations in the predictions of this variable, with at least one study showing a region where extreme events decrease in frequency. As with the conclusions for tropical cyclones, the regional impacts of climate change remain uncertain, and await improvements in model resolution and parameterizations. The use of higher-resolution climate models, including nested models, is being actively pursued.

Acknowledgments

This paper draws on the work of other members of the Climate Impact Group of the CSIRO Division of Atmospheric Research, most notably Rob Allan, Kevin Hennessy, Ramaswamy Suppiah, and Peter Whetton. Constructive comments were made on an earlier draft of this paper by Debbie Abbs and Brian Ryan. In addition, we would like to thank the Climate Modelling Group of CSIRO (particularly Ian Watterson) for access to the results of their simulations. We would particularly like to thank John McGregor for his work on both CSIRO9 and DARLAM. The comments of two anonymous reviewers were appreciated. We gratefully acknowledge the financial support of the governments of the Northern Territory, Western Australia, and Queensland.

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(Received 8 August 1995; in revised form 8 August 1997)