NOTES AND CORRESPONDENCE

A Numerical Exploration of the Sensitivity of Tropical Cyclone Rainfall Intensity to Sea Surface Temperature

JENNI L. EVANS,* BRIAN F. RYAN, AND JOHN L. MCGREGOR

Water and Climate Program, CSIRO Division of Atmospheric Research, Mordialloc, Victoria

25 January 1993 and 22 September 1993

ABSTRACT

It is commonly accepted that there is a monotonically increasing relationship between sea surface temperature (SST) and tropical cyclone intensity (as measured by maximum near-surface winds or minimum central pressure). This perceived relationship has been used to extrapolate the effects of climatologically warmer SSTs on tropical cyclones. These warmer SSTs are one of the consequences of doubled CO_2 predicted by climate general circulation models (GCMs). Very few investigations have actually critically addressed this SST–storm intensity relationship, however. In this paper, a limited area modeling study is used to explore the potential links between SST and tropical cyclone intensity. Previous work, including some observational data, is reviewed and its implications for the interpretation of the results given here is presented. Finally, the implications of the changes in SST on the thermodynamic structure of the atmosphere—in particular, the destabilization of the boundary layer—are identified as another possible mechanism of intensification for these modeled storms.

1. Introduction

This paper addresses the potential changes to the characteristics of tropical cyclones—particularly their rainfall intensity and central pressure—due to changes in the underlying SST. The magnitude of the SST changes imposed are between 2°C and 5°C. This is of the order of the climatological SST changes due to the enhanced greenhouse warming that is envisaged through GCM simulations.

High-resolution limited-area models with prescribed boundary conditions have been shown to be capable of simulating some of the more detailed structure of tropical cyclones (e.g., Tuleya 1991). Sensitivity studies using limited-area models have often been used to investigate the response of a particular mesoscale phenomenon to the initial model conditions and to test the effect of various physical processes on the phenomenon being modeled.

In this study, the CSIRO limited area model is used to perform sensitivity studies of the effect of varying SST on two well-observed tropical cyclones. Coupled with physical and theoretical arguments, these results may be used to determine the sensitivity of the modeled tropical cyclone to the SST. Under the assumption that the large-scale tropical atmosphere does not change significantly, this information is used to infer possible changes in tropical cyclone rainfall and minimum central pressure.

As will be discussed later, the results of this, or any single, sensitivity study are not to be directly extrapolated to any future climate. At best, such simulations should provide bounds on the sort of changes that may occur in tropical cyclones in a warmer world. One must also determine the relative importance to a tropical cyclone of the environmental factor—in this case SST—being varied and the validity of varying only that one parameter.

2. The CSIRO Limited Area Model and the experimental design

These simulations were performed using the CSIRO Division of Atmospheric Research Limited Area Model (DARLAM). The properties of the model are briefly summarized in this section. The model has been developed for both mesoscale studies and for nested climate change experiments. It is a two-time-level, semi-implicit, hydrostatic primitive equations model on an Arakawa staggered C grid. An earlier version was described by McGregor (1987). It incorporates semi-Lagrangian horizontal and vertical advection with bicubic spatial interpolation. The efficient scheme of McGregor

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* Current affiliation: Department of Meteorology and Earth System Science Center, The Pennsylvania State University, University Park, Pennsylvania.

Corresponding author address: Dr. Jenni L. Evans, Department of Meteorology and Earth System Science Center, The Pennsylvania State University, University Park, PA 16802.

(1993) is used for the determination of departure points. The present version has been used recently for regional climate simulations by McGregor and Walsh (1991). A version of the model has been adapted by Physick et al. (1993) for small-scale wind field and particle dispersion studies.

Subgrid-scale cumulus convection is performed with a version of the Betts and Miller (1986) scheme as modified by the U.S. National Meteorological Center. The slope of the equilibrium potential temperature profile $(\partial\theta_e/\partial p)$ is 0.82 [i.e., approximately 0.9 of the slope of a virtual moist adiabat (Betts 1982)] and is based on radiosonde and aircraft observations over the Gulf of Carpentaria during the Australian Monsoon Experiment (AMEX). Similarly, the subsaturation parameter in the Betts–Miller scheme (DP) is also based on an analysis of observations.

Geleyn's (1987) shallow convection scheme is incorporated. Surface fluxes are calculated according to Monin–Obukhov similarity theory, by means of a modified Louis (1979) parameterization. Over land a roughness length of 0.17 m is used, while Charnock's (1955) formula with a parameter value of 0.018 is used over ocean areas. A bare-soil calculation of surface and soil temperatures is performed with layers of thickness 0.03 m, 0.25 m, and 2.5 m. Deardorff's (1977) treatment is adopted for soil moisture, with a reservoir of depth 0.5 m and a faster-response surface layer of thickness 0.12 m. The Fels and Schwarzkopf (1975) parameterization for long- and shortwave radiation is used in a diurnally varying mode.

ECMWF data for the days 18–21 January 1987 are used for initial and boundary conditions. Using a 16-point Bessel interpolator, these data are transferred to 18 equally spaced vertical sigma levels on a horizontal Lambert conformal projection with 75-km grid spacing on an 81 × 46 grid. The vertical mode initialization scheme of Bourke and McGregor (1983) is used to balance the initial fields. The initial fields used in this modeling study are based on the enhanced, twice-daily ECMWF analyses provided for the WGNE–AMEX tropical intercomparison experiment.

Analysis-derived lateral boundary conditions are used. The outermost grid points are assigned values determined from the ECMWF analysis by linear interpolation between the two closest analysis times. The model fields are solved for all interior points and then the method of Davies (1976) is used to relax the model fields in the boundary region (up to 8 grid points from the boundaries) toward the analysis values.

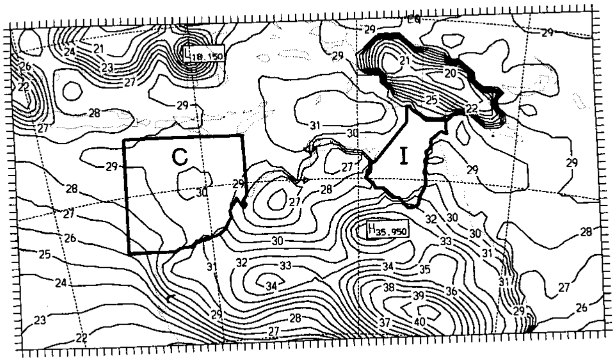

FIG. 1. Areas of SST warmed for the sensitivity experiments: "I" is the area warmed for the Irma experiments; "C" is the region warmed for the Connie experiments; and for the "ALL2" experiment, the entire domain is warmed by 2°C. The rainfall has been averaged over approximately the same area. Land and sea surface temperatures (°C) are plotted from the ECMWF analysis for 0000 UTC 18 January 1987.

SSTs were obtained from the standard ECMWF analyses and are the base from which the SST variations are made. Since the surface temperature analyses have a spatial resolution of only 2.5°, compared with the model resolution for this study of 75 km, considerable care was taken in checking that the interpolated SST values were realistic, especially near the coast. Once the observed SST field had been verified on the finer grid, SSTs were modified over each of the regions shown separately in Fig. 1 (the "I" and "C" experiments) and over the entire model domain (ALL2). SST changes for each of the experiments discussed here are summarized in Table 1. The observed Gulf of Carpentaria SSTs varied from 29° to 30°C and therefore the Gulf of Carpentaria SSTs in the run labeled control were set to a constant value of 29°C. The results of this simulation were compared with the simulation with observed SSTs (OBS) and no significant differences were found in either the storm intensity or rainfall. Each of the regions, "I" and "C," was both warmed and cooled by 2°C from the base experiment labeled control.

Two extreme warming experiments (CP5 and IP4: see Table 1) were included to investigate the effect on one tropical cyclone of a second system with a "limitless" supply of energy. Once again, these experiments

TABLE 1. List of model experiments. "Gulf" is the Gulf of Carpentaria, and the areas affected by the warmings are shown in Fig. 1. OBS refers to observed SST experiment. Control refers to experiment with observed SSTs in all but the gulf region ("I" in Fig. 1). In this region, the SSTs are set to a constant value of 29°C. All other experiments vary from this Control (29°C in the gulf) SST field.

	SST variation (°C)	
Experiment name	Connie	Irma
OBS	0.	Gulf as observed
IM2	0.	−2. (gulf = 27°C)
Control	0.	0. (gulf = 29°C)
IP2	0.	+2. (gulf = 31°C)
IP4	0.	+4. (gulf = 33°C)
CM2	−2.	0.
CP2	+2.	0.
CP5	+5.	0.
ALL2	+2.	+2

involve warming over either region "I" or "C," beginning from the control SST field. These last experiments were designed to test the potential effects of increasing SST on tropical cyclone frequency—Do very intense storms control their environment and so suppress other systems? If so, a scenario that envisaged more intense tropical cyclones may actually be at odds with the prediction of an increased number of storms. At the time of simulation the two cyclones were some 20° apart—more than twice the distance expected for tropical cyclones to affect each other's motion (see, e.g., Brand 1970). Rather than examining the direct interaction of the flow fields of Connie and Irma, these experiments indirectly examined the effect of changes in the large-scale field forced by the stronger cyclone Connie in the vicinity of the weaker tropical cyclone Irma, and vice versa.

Changes in the minimum central pressure and area-averaged rainfall of two tropical cyclones due to SST variations are the focus of this study. One novel aspect of this study compared to previous work in this area is that the two tropical cyclones—Connie and Irma—occurred simultaneously over northern Australia and during a period of enhanced observations (AMEX). A detailed discussion of the synoptic situation and the life cycles of these two systems is presented in the following section.

3. Synoptic summary of the period 18–21 January 1987

Seven tropical cyclones occurred in the Australian region during the 1986–87 tropical cyclone season (Manchur 1987), four of these occurring during intensive observation periods of AMEX. Two of these well-observed tropical cyclones, Connie and Irma, form the basis of this study. Best tracks of these two cyclones, as issued by the Australian Bureau of Meteorology, are plotted in Fig. 2. The solid line indicates the period for which the system was named as a tropical cyclone.

Manchur (1987) reports that Tropical Cyclone Connie formed from a center of low pressure that originated over the land. The low drifted northwest, moving out to sea where it rapidly intensified and reached tropical cyclone intensity by 1200 UTC 17 January 1987. At that time the center of the cyclone was located at 17.1° S, 121.9° E. Tropical Cyclone Connie then moved southwest and continued to intensify, reaching its maximum intensity of 950 hPa and estimated mean maximum wind speed of 149 km h^{-1} by 0600 UTC 19 January 1987. Three hours later, Connie crossed the coast at 20.3° S, 118.0° E. Connie continued to move inland on a southerly track, weakening slowly, so that by 1200 UTC 20 January it was below the intensity of a tropical cyclone. No deaths or injuries were reported from Connie and only moderate coastal damage (beach erosion and minor flooding) was sustained (Manchur 1987).

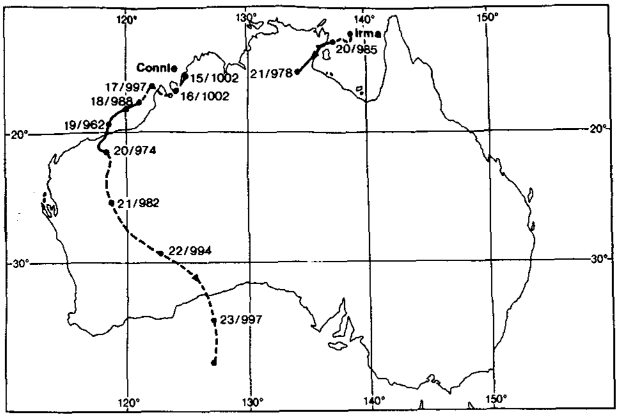

FIG. 2. Best tracks for tropical cyclones Irma and Connie. Positions are shown at 0000 UTC on the dates indicated. Central pressures (hPa) are also given. The solid line indicates the period for which the system was named as a tropical cyclone.

Tropical Cyclone Irma developed from an area of deep convection in the northern Gulf of Carpentaria that had persisted for several days. Irma was declared a tropical cyclone at 0300 UTC 18 January 1987 when its center was located at 12.2° S, 138.9° E. Tropical Cyclone Irma crossed the gulf coast near Gove at 1200 UTC 20 January after which it was downgraded to a tropical depression. The lowest estimated central pressure was 978 hPa. As a rain depression, Irma produced areas of flooding in the central Northern Territory including a 24-h total of 409 mm at Larrimah. Several people had to be evacuated from Berrima Station as flood waters threatened their homestead (Manchur 1987).

Tropical Cyclone Connie formed between the coast and an SST maximum of 31°C that remained quasi-stationary during the life cycle of the tropical cyclone, in an SST temperature gradient of 1°–2°C across subregion C in Fig. 1. In the case of Tropical Cyclone Irma, the temperature in the Gulf of Carpentaria was fairly uniform at about 29°–30°C; however, there was a pool of warmer water in the Arafura Sea (to the northwest), with SSTs up to 32°C.

4. Control simulation and verification

The control and enhanced simulations were all initialized at 0000 UTC 18 January 1987. The observed mean sea level pressure (MSLP) verifying fields and the control simulation for 12 and 36 h are plotted in Fig. 3. The simulation predicts the motion of the two tropical cyclones reasonably well, although the intensity of both storms is underestimated. The model fields are comparable with similar model data reported by Puri et al. (1992). A significant difference between these two model simulations was that Puri et al. (1992) used the Kuo convective parameterization scheme, whereas in the simulations presented here, the Betts–Miller pa-

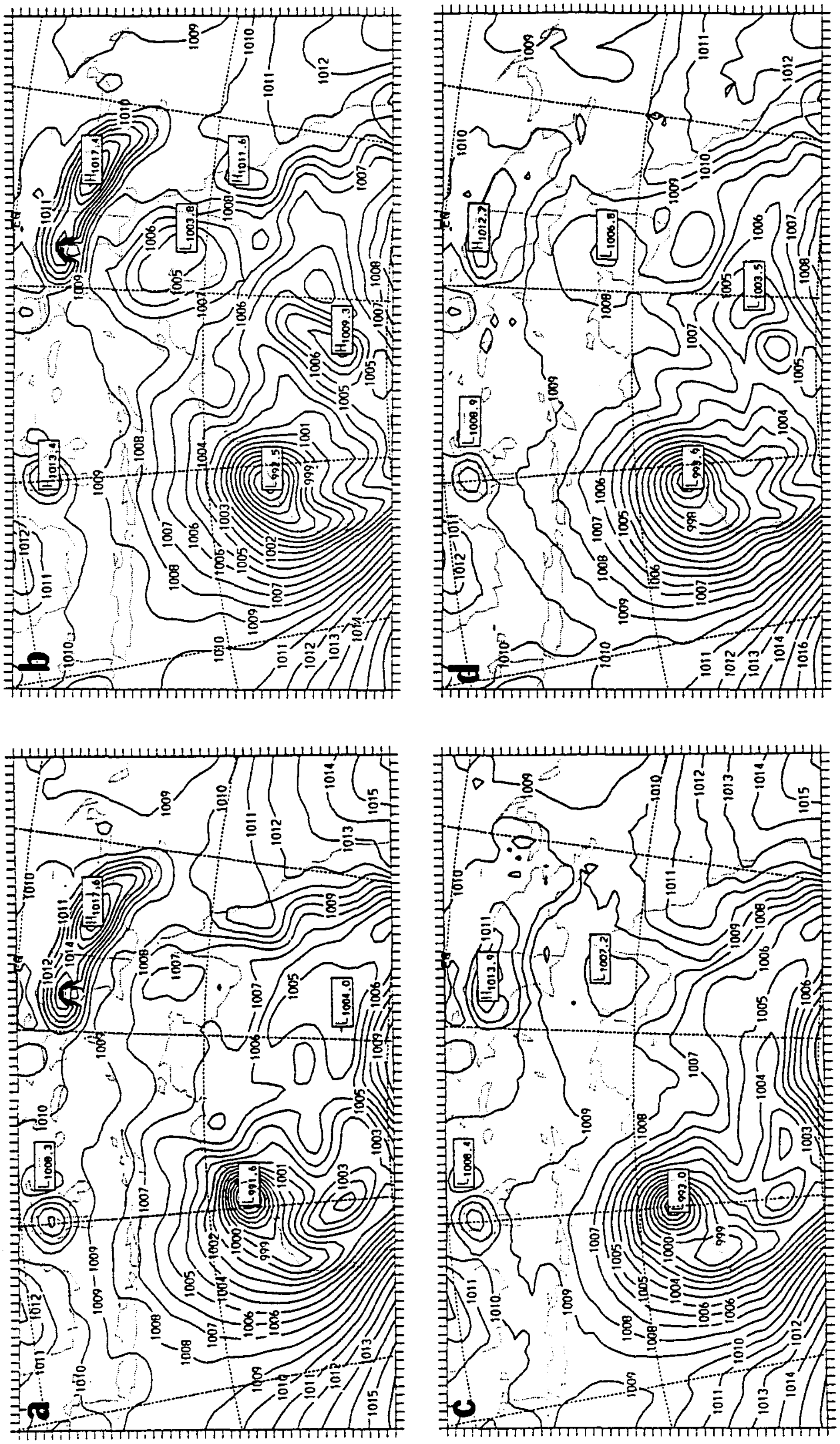

FIG. 3. ECMWF/WGNE-AMEX MSLP analyses for (a) 1200 UTC 18 January 1987 and (b) 1200 UTC 19 January; Model MSLP prognoses for (c) 1200 UTC 18 January 1987 and (d) 1200 UTC 19 January 1987.

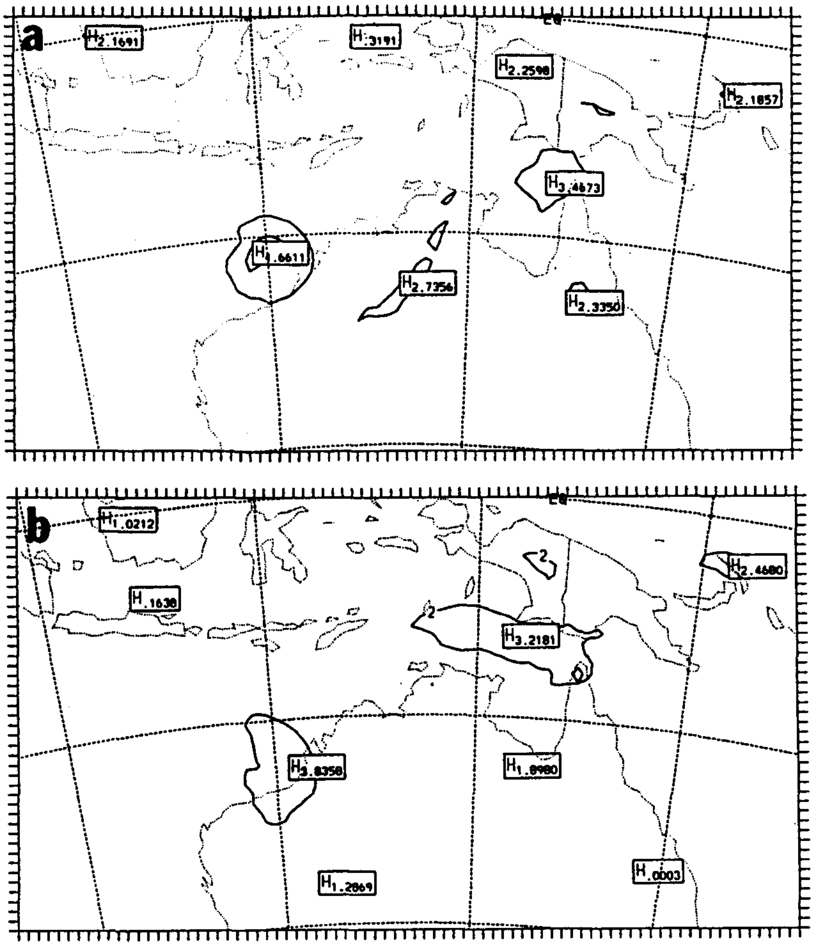

FIG. 4. Model rainfall (mm) (a) 0–12 h starting 0000 UTC 18 January and (b) 0–12 h starting 0000 UTC 19 January.

rameterization was used. The predicted rainfall for 12 h commencing at 0000 UTC 18 January and 12 h commencing at 0000 UTC 19 January associated with Tropical Cyclones Connie and Irma is plotted in Fig. 4. The 12-h rainfall totals in the following 12 h were similar to the rainfall totals shown here. In the case of Tropical Cyclone Irma, the precipitation commences in the Gulf of Carpentaria and moves toward the warm pool in the Arafura Sea (see Fig. 1). For Tropical Cyclone Connie the precipitation moves more with the track of the storm and is over the land after the first 24 h. Simulations were also made using a Kuo scheme; however this option produced an inferior simulation; in particular, convection over the sea associated with Tropical Cyclone Irma almost ceased in the second 24 h of the simulation.

5. Results of sensitivity studies

Alterations made to the SSTs over northwest Australia and the Gulf of Carpentaria for the sensitivity experiments were described in section 2. The sensitivity experiments are analyzed only for the first 24 h of the simulation. In the second 24 h the storm either moved over the land (Connie) or out of the region of enhanced SSTs (Irma). The experiments are listed in Table 1. Minimum central pressures (in hPa) and area-averaged rainfall amounts for each of these experiments after 24 h are documented in Table 2. Rainfall amounts are averaged separately over the two regions marked in Fig. 1 and are presented as millimeters of rain in the 24-h period. Results for the control simulation are underlined and those that are directly affected by warming of the underlying water are in boldface type. One sees that generally a system over warmer water has increased area-averaged rainfall and deepens more than the control. Conversely, a system over cooler than observed SST produces less rain and is generally weaker than the control, although for a reduction of 2°C in the underlying SST, the change in pressure is typically 1 hPa or less. This relatively small change in the cooler water case is of interest as it shows some nonlinearity in the SST–intensity relationship being explored here.

When the water under the weaker system, Irma, is warmed (IP2 and IP4) with respect to the run labeled control (uniform gulf temperature of 29°C), an increase in the area-averaged rainfall around Irma of 12% and 39%, respectively, is evident after 24 h. The central pressure over Irma decreases from 1008.5 hPa for an SST of 29°C to 1006.6 hPa when the SST is 33°C for this experiment. After 24 h, there is no substantial change in either the rainfall or central pressure of Connie compared to the control run. Similarly, when the water under Tropical Cyclone Connie is warmed (CP2), enhancement of rainfall and decreased central pressures are evident for Connie. The central pressure of Tropical Cyclone Irma (downstream of Connie) is essentially unchanged, although there is a slight decrease ($\approx$4%) in rain amount over the 24-h period. When the water under Tropical Cyclone Connie is unrealistically increased by 5°C (CP5) there is a significant decrease in the pressure and corresponding increase in the rainfall of Connie; however, there is still no marked change in the development of Tropical Cyclone Irma. There is also no obvious effect within 24 h of the initially stronger Connie on the weaker Irma when SSTs over the entire model domain are uniformly warmed by 2°C (ALL2). In this case, both Tropical Cyclones Irma and Connie are in regions of enhanced SSTs and react in much the same way as if only the local SSTs were enhanced (see Table 2). Thus for moderate (i.e., 1°–2°C) or strong (i.e., 5°C) increases in the SST, there is no support for the hypothesis that a cyclone such as Connie may become sufficiently intense that it "takes over" and begins to change the far-field environment in a way that suppresses the development of the other system.

In summary, when the water below either storm is warmed, that storm increases in rainfall intensity and there is some evidence of enhanced deepening of the system. The increase is nonlinear with an increase of 4°C in the SST producing more than twice the effect of a 2°C increase. The effect is consistent with the nonlinear increase in the precipitable water with temperature. These results are consistent with the findings of McInnes et al. (1992) for similar sensitivity experiments applied to Australian east coast cyclones. If the entire region is warmed by 2°C, in accordance with the GCM predictions for an equilibrium 2 × CO_2 world, then increased rainfall and decreased pressure occur for both storms. There is no evidence to suggest that one storm is dominating the other, however.

The track and size of the cyclone were not significantly changed as a result of the SST changes. Since the model resolution of 75 km is unable to resolve the core structure, it was considered that an analysis of the wind structure was not appropriate for this experiment.

TABLE 2. Twenty-four hour area-averaged rainfall (mm) and minimum central pressure values (hPa) for each tropical cyclone in the experiments listed in Table 1. Results for the Control and OBS simulations are italicized, and results that are directly affected by warming of the underlying water are in boldface type.

	Connie		Irma	
Experiment 24-h results	Rain	Pressure	Rain	Pressure
OBS	*33.5*	*993.0*	*29.0*	*1008.0*
IM2	34.8	993.1	26.3	1008.7
Control	*33.4*	*993.1*	*28.5*	*1008.5*
IP2	33.7	992.9	**32.1**	**1007.7**
IP4	33.6	993.0	**39.7**	**1006.6**
CM2	30.4	993.9	29.4	1008.7
CP2	**37.5**	**992.2**	28.7	1008.6
CP5	**54.0**	**984.3**	28.5	1008.1
ALL2	**37.4**	**992.2**	**33.3**	**1007.6**

6. Synthesis of modeling study and previous work

The magnitude of the SST has been mentioned as a key factor in the formation and intensification of tropical cyclones (e.g., Gray 1982; Miller 1958; Emanuel 1987) and experiments to test tropical cyclone sensitivity to this variable form the focus of this paper. Indeed, tropical cyclones are not observed to form over waters cooler than 26°C in the current climate, but does this mean 1) that there is a direct relationship between SST and tropical cyclone intensity or frequency and 2) that this relationship dominates over the other environmental factors? These are questions that must be addressed before the modeling results presented here can be interpreted sensibly. Merrill (1988), in a study of the factors affecting tropical storms in the Atlantic, concluded that environmental factors other than SST were at least as important as SST in determining the intensity of a storm. McBride and Keenan (1982) studied the genesis locations of tropical cyclones in the Australian region over a 5-year period and found that over 90% of tropical storms formed in the gradient-level (850 hPa) monsoon trough. This result agrees with Gray's (1968) empirical work on formation criteria of tropical cyclones. The monsoon trough is a region of strong low-level vorticity, and when it occurs with weak vertical wind shear, it is a most favorable region for genesis. Even in the North Atlantic, where storm genesis does not depend on a monsoon trough, the environment in which the tropical cyclone matures is critical to its development. In the tropical North Atlantic, SST exceeds 26°C for 4–6 months in the average year (e.g., see Shea et al. 1992); however, the hurricane (tropical cyclone) season is relatively short.

The fact that SSTs greater than 26°C are observed in the South Atlantic Ocean and tropical cyclones have not been observed there in recorded history, provides another indicator that SST is just one factor affecting tropical cyclogenesis. The environment in the South Atlantic region simply is not favorable for tropical cyclogenesis, regardless of the SST. Hence, it seems that SST alone cannot determine the strength of tropical cyclones or their frequency of occurrence.

Evans (1993) has studied the historical data records. This study considered all ocean basins in which tropical cyclones currently form; it was restricted to 20 years to increase the data reliability by considering only the time since satellite coverage commenced. These records show no obvious correlation between SST and the maximum intensity of a tropical cyclone. Again, the most likely reason for this lack of correlation is that factors other than SST are masking any relationship that may exist between SST and central pressure (or maximum wind) of a storm.

In spite of all this, the modeling results presented here do demonstrate that when all other factors are held constant, a reasonably coherent relationship between intensity and SST exists both in terms of the central pressure and, especially, the rainfall. Consideration of both the historical data and the model results might lead one to conclude that these sensitivity studies have artificially frozen the environment in a way that would not occur naturally. One obvious implication of warming the surface while holding "all else constant" is that the surface air is now more unstable with respect to its environment than in the unwarmed case. This point has been further explored by Drury and Evans (1993).

One final question is, How valid are our sensitivity studies? The modeling studies of warmer SSTs presented here have quite a large region of SSTs warmer than 33°C and the extreme modeling case (SST + 5°C for Connie) had regions of SSTs up to 36°–37°C. Using records of observed daily maximum temperature data for 1850 stations, Priestley (1966) showed that maximum surface temperatures of more than 33°C are rarely observed over very moist ground and in the rare cases (one-tenth of one percent of his sample) that this limit was violated, advection of dry air into the region played a very strong part in determining the temperature. Presumably then, this value of 33°C provides a reasonable upper bound for temperatures over the ocean in the present climate and that limit has been violated by the extreme experiments (IP4 and CP5) used here. Recently, Ramanathan and Collins (1991) suggested that cirrus clouds may limit SSTs to 32°C. This hypothesis has been challenged by Fu et al. (1992). At this point in time, the question of a "cirrus cloud thermostat" over the tropical oceans remains unresolved. Also unresolved is the sign and magnitude of the net oceanic mixed-layer response to tropical cyclone activity. One expects that the enhanced upwelling and evaporation induced by these systems may result in a net cooling of the mixed layer and so a "lower thermostat." Limited observational studies (e.g., Chang and Anthes 1978) support this expectation.

7. Conclusions

In this paper, a limited area modeling study has been used to address the question of potential changes to tropical cyclone central pressure and rainfall intensity due to varying SSTs. One novel aspect of this study is that it considers two tropical cyclones, Connie and Irma, that existed simultaneously during an intensive observing phase of AMEX. The sensitivity of each of these storms to various patterns of warming or cooling of SST has been investigated. To put these results in context, recourse has been made to observational data studies.

In summary, the sensitivity studies presented here indicate that, if all other environmental conditions are held constant and only SSTs are increased, there is a very real potential for tropical cyclones to become stronger than in the current climate. Three major caveats apply to this work:

1) It is unlikely that the environment in which a storm is intensifying will remain unchanged when the SST changes. In the current climate, examples of the atmosphere adjusting to changing SST abound. For example, the switch from El Niño to anti–El Niño phases of the Australasian summer monsoon discussed by Evans and Allan (1992).
2) Historical data indicate that SST is not the overriding factor in determining the maximum intensity attained by a storm, so other environmental changes will be critical to the ultimate intensity attained by a tropical cyclone.
3) Historical data from the middle of this century is very suggestive of a natural upper limit to surface temperatures over very moist ground, based on radiative arguments. In the present climate this upper limit is found to be near 33°C. Whether there is a natural limit to oceanic surface temperatures is currently unresolved.

Finally, by simply raising the SST, it should be recognized that one has not simply increased the potential evaporation at the surface [a problem explored in some detail by Tuleya and Kurihara (1982)], but that the entire boundary layer in the region of the tropical cyclone has been destabilized and dried (since the surface air has been warmed, but no additional moisture has been added). This has much wider implications for increased convective activity and a possible CISK-type feedback on intensity that is not associated simply with the increased evaporation. The impact of changing atmospheric stability on tropical cyclone intensity forms the basis of a separate study (Drury and Evans 1993). Some distinction needs to be made between the two effects of warming SST: increased evaporation and moisture cycling due to SST directly, and enhanced convective activity due to destabilization and drying of the atmospheric boundary layer. Until the effects of these two processes can be separated, questions such as, "Will tropical cyclones become more intense in a world with warmer SST?" cannot really be answered, since the atmosphere in such a world would be unlikely to maintain an unstable boundary layer, and so the response observed here to instantaneously warmed SST would probably not be appropriate to that longer, climatic time scale.

Acknowledgments. Thanks to Sytske Drury for her assistance with the model and her organizational abilities. Thanks also to Drs. Greg Holland, Jack Katzfey, John McBride, Kathleen McInnes, Peter Whetton, and Barrie Pittock for many useful discussions on this project. This study was supported in part by special funding from the Commonwealth Department of the Environment, Sports Territories and the Northern Territory Government.

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