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Reply to Evans

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Our paper (Broccoli and Manabe, 1990; hereafter identified as BM90) proposed a methodology for studying the impact of greenhouse warming on the tropical storm climatology, and applied it to a series of climate model integrations as an example of its utility. Thus the primary emphasis in BM90 was that existing climate models have the ability to "simulate, at least qualitatively, the frequency distribution of tropical storms." BM90 cites this ability, along with the increasing realism of simulated storm structure as resolution is increased, as evidence for the assertion that current generation climate models are "appropriate tools for exploring the mechanisms that control the relationship between greenhouse warming and tropical storm activity." While preliminary results from sensitivity experiments are presented, the primary emphasis of BM90 is not a detailed exploration of the model sensitivity to increased CO_2. Thus most of this reply is devoted to the issue of whether or not the tropical storms simulated by current models have, in Evans' words, "a reasonable physical similarity to the atmospheric systems with which they are compared."

We agree with the assertion by Evans that the degree of correspondence between the simulated and observed spatial and temporal patterns of tropical storm occurrence is a measure of a model's success in simulating the tropical storm climatology. To further enable such a comparison, we have computed maps of tropical storm frequency from the National Climatic Data Center Consolidated Tropical Cyclone data base for comparison with the model results from one of our integrations, the R30VC-1X (Figure 1). [Note: The nomenclature used to identify model integrations is defined in BM90.] The observed and simulated frequencies were expressed as the annual number of tropical storms (tropical cyclones with surface winds > 17 m/s) occurring within each model grid box (2.25^{o} latitude by 3.75^{o} longitude). While the simulation is far from perfect, there are obvious qualitative similarities to observations, such as the large area of frequent storms in the western North Pacific, the greater incidence of storms in the western halves of the South Pacific and North Atlantic oceans, and the smaller number of storms in the Arabian Sea relative to the Bay of Bengal. Discrepancies are equally obvious, such as the gross underestimation of storm frequency in the eastern North Pacific and the unrealistic occurrence of storms in the South Atlantic. While Evans correctly notes that BM90 contains no attempt to explain these discrepancies, a rigorous explanation would probably require additional experiments beyond the intended scope of BM90.

Evans is critical of our use of a six-month season for examining storm statistics. Its use in BM90 resulted from our desire to develop a simple, objective, automated technique for distinguishing tropical and extratropical storms. As a first attempt, we assumed all storms that occurred within a specified spatial and temporal domain were tropical, and those that did not were extratropical. The six-month "hurricane season" in the low latitudes of each hemisphere was chosen as this domain. We agree that this is not the ideal way to perform the analysis. Work is underway to develop an improved technique for discrimination that neither excludes the possibility of tropical storms developing outside the spatial and temporal domain examined in BM90, nor assumes that all storms found within that domain are tropical. If this effort is successful, then the seasonal variability of simulated storms can be examined.

Some inferences can be drawn about the ability of our climate model to simulate seasonal variability by examining the work of Wu and Lau (1992). They studied the influence of interannual sea surface temperature (SST) variability on the frequency of simulated tropical storms in a version of the GFDL climate model that was used for the R15FC-1X integration of BM90. Using a scheme for identifying tropical storms that does not assume a predetermined spatial and temporal domain, they simulate a global tropical storm distribution similar to that of BM90. They document reasonable success in simulating the seasonal variation of tropical storm frequency in their integration, suggesting that the model used for BM90 also may be capable of simulating the seasonal variation.

Evans also asks about the simulated interannual variability of storm occurrence in our model experiments. Table 1 compares the interannual variability of the simulated number of tropical storms

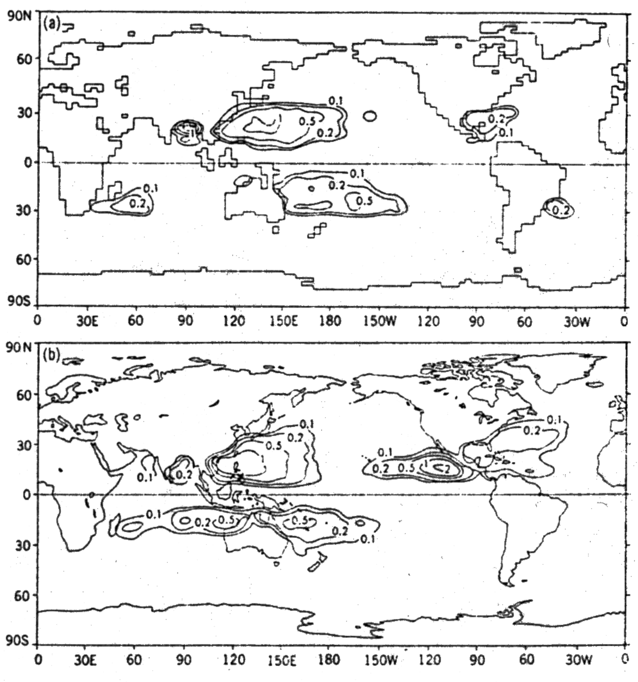

Fig. 1. Average annual tropical storm frequency within each 2.25^{o} latitude by 3.75^{o} longitude grid box. *Top:* Simulated (R30VC-1X integration). *Bottom:* Observed (National Climatic Data Center Consolidated Global Tropical Cyclone data base). Both maps have been smoothed spatially by using a 1-2-1 filter in each direction.

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with observed data (Frank, 1985). For all regions but the Northeast Pacific, where the simulated number of storms is much too small, the simulated and observed standard deviations are similar for three of the four integrations. The exception is the R30FC-1X integration, whose five-year length is insufficient for the robust determination of storm variability. Because the models used in BM90 lack the interannual variability in tropical SST associated with the El Nino-Southern Oscillation (ENSO) phenomenon, the simulated standard deviations may be slightly smaller than they would have been had ENSO variability been included. Nevertheless, it is encouraging that the simulated interannual variability is comparable to the observed.

There appears to be a misunderstanding on the part of Evans in interpreting the results of the CO_2 sensitivity experiments. The purpose of such experiments is to evaluate how the model response changes while varying one model characteristic and holding all others constant. Thus it is important to distinguish between the effect of resolution on (1) simulated tropical storm frequency, and (2) the *response* of simulated storm frequency to doubled CO_2. Evans is correct that the number of model storms (and storm-days) depends upon resolution when CO_2 content and cloud treatment are held constant. However, this does not preclude studying the response to CO_2 by comparing integrations with the same resolution. In BM90, the response of the simulated number of storms to a doubling of CO_2 is quite insensitive to the model resolution, as evidenced by the percent changes in storm-days in Table 2 of that paper.

In conclusion, we agree that the usefulness of global climate models for studying the tropical storm climatology depends on the existence of a "reasonable physical relationship" between the simulated and actual storms. Much of the disagreement between our interpretation of BM90 and that of Evans concerns the definition of "reasonable." The perfect simulation of all aspects of the climate system is the ultimate goal of climate modeling. But since perfection is clearly unattainable, discrepancies between simulations and reality can readily be found, as acknowledged by Bengtsson et al. (1984). However many of the features of observed tropical storms with spatial scales resolvable by current climate models can be simulated, as shown previously by Manabe et al. (1970) and Bengtsson et al. (1982). These include (1) the characteristic "warm core" structure, with a cyclonic low-level circulation and an anticyclonic circulation in the upper troposphere, (2) strong upward motion near the cyclone center, and (3) heavy precipitation accompanying this region of ascent. BM90 extended this work by demonstrating the ability of the models to qualitatively simulate the climatological distribution of tropical storms. We believe that the similarities in the resolvable structure and the regions of formation of simulated and observed tropical cyclones make it probable that there is a concomitant similarity in the physical mechanisms responsible for their existence.

In the future, it may be useful to determine if the empirical relationships that have been documented between a variety of environmental factors (e. g., SST, low-level vorticity, vertical wind shear) and observed tropical cyclogenesis also exist in climate model integrations. Confirmation of this possibility would enhance our confidence in the use of global climate models in studies of anthropogenic changes in tropical cyclone climatology. We do not believe it possible, however, to apply these empirical relationships to the output from climate models to obtain an indirect estimate of such changes. Because the large spatial scale of the pattern of greenhouse gas-induced environmental change differs substantially from that of observed interannual variability, the relationships derived from the climate record may not be applicable. Thus our rationale for the use of global climate models is their ability to represent the simultaneous, nonlinear effects of various environmental factors on tropical cyclogenesis. Much work remains to be done in refining their use, and we appreciate the critical scrutiny of Dr. Evans in identifying some of the areas where improvement may be necessary.

Table 1. Standard deviation of number of tropical cyclones reaching storm strength (surface winds > 17 m/s) by region during the six-month "hurricane season" from the 1X integrations of BM90. The observed standard deviations of the annual mean number of storms, based on Frank (1985), are given for comparison.

	R15 FC	R30 FC	R15 VC	R30 VC	Obs.
N.W. Pacific	5.0	4.4	4.8	6.0	5.5
N.E. Pacific	1.8	0.6	1.8	1.8	3.8
N. Atlantic/Caribbean	2.9	0.7	3.2	2.4	3.0
N. Indian	1.4	2.4	1.1	3.3	1.5
Australia./S. Pacific	2.6	1.1	4.2	5.4	3.8
S. Indian	3.1	2.6	3.9	2.1	2.8

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