Q. J. R. Meteorol. Soc. (2001), **127**, pp. 25–51

Sensitivity of tropical storms simulated by a general circulation model to changes in cumulus parametrization

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(Received 5 June 2000; revised 2 October 2000)

SUMMARY

A number of recent studies have examined the statistics of tropical storms simulated by general circulation models (GCMs) forced by observed sea surface temperatures. Many GCMs have demonstrated an ability to simulate some aspects of the observed interannual variability of tropical storms, in particular, variability in storm frequency. This has led to nascent attempts to use GCMs as part of programs to produce operational seasonal forecasts of tropical-storm numbers.

In this study, the sensitivity of the statistics of GCM-simulated tropical storms to changes in the model's physical parametrizations is examined. After preliminary results indicated that these statistics were most sensitive to details of the convective parametrization, GCM simulations with identical dynamical cores but different convective parametrizations were created. The parametrizations examined included moist convective adjustment, two variants of the Arakawa–Schubert scheme, and several variants of the relaxed Arakawa–Schubert (RAS) scheme; the impact of including a shallow-convection parametrization was also examined.

The simulated tropical-storm frequency, intensity, structure, and interannual variability were all found to exhibit significant sensitivities to changes in convective parametrization. A particularly large sensitivity was found when the RAS and Arakawa–Schubert parametrizations were modified to place restrictions on the production of deep convection.

Climatologies of the GCM tropical atmosphere and composites of tropical storms were examined to address the question of whether the tropical-storm statistics were directly impacted on by changes in convection associated with tropical storms, or if they were indirectly affected by parametrization-induced changes in the tropical mean atmosphere. A number of results point to the latter being the primary cause. A regional hurricane model, initialized with mean states from the GCM simulation climatologies, is used to further investigate this point. Particularly compelling is the fact that versions of the RAS scheme that produce significantly less realistic simulations of tropical storms nevertheless produce a much more realistic interannual variability of storms, apparently due to an improved tropical mean climate.

A careful analysis of the background convective available potential energy (CAPE) is used to suggest that this quantity is particularly relevant to the occurrence of tropical storms in the low-resolution GCMs, although this may not be the case with observations. If the tropical CAPE is too low, tropical storms in the low-resolution GCMs cannot form with realistic frequency.

KEYWORDS: Cumulus convection General circulation models Tropical-storm frequency Tropical-storm intensity

1. INTRODUCTION

Manabe and Holloway (1970) first documented the ability of low-resolution general circulation models (GCMs) to simulate tropical storms. Additional studies (Bengtsson *et al.* 1982, 1995; Broccoli and Manabe 1990; Haarsma *et al.* 1993) demonstrated that these simulated tropical storms in higher-resolution models have a climatology and physical characteristics similar to those of observed tropical storms in many ways. Vitart *et al.* (1997) showed that simulated tropical storms have an interannual variability consistent with observations over the western North Atlantic, eastern North Pacific and the western North Pacific. Vitart *et al.* (1999) linked this interannual variability with the simulated interannual variability of vertical wind shear and 200 and 500 mb vorticity. A GCM's skill in simulating observed interannual tropical-storm variability was related to its skill in simulating the observed interannual variability of the large-scale atmospheric circulation.

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Attempts to develop GCMs with improved tropical-storm simulations led to an investigation of the impact of GCM sub-grid-scale physical parametrizations on simulated tropical-storm statistics. A strong, and sometimes unanticipated, sensitivity to parametrizations was found and is described in the present paper. In particular, details of the parametrization of cumulus convection were found to have enormous impacts on simulated tropical storms. This is probably not surprising as cumulus convection plays a particularly strong role in tropical-storm genesis and development since tropical storms are characterized by the deep convection that occurs at the centre of the storm.

The present study uses 9-year integrations of a GCM forced by observed sea surface temperatures (SSTs) to explore the impacts of a variety of cumulus parametrizations on simulated tropical storms. Attention is focused on differences between moist convective adjustment (MCA) (Manabe 1965) and relaxed Arakawa–Schubert (RAS) (Moorthi and Suarez 1991) schemes, and on the impacts of adding a shallow-convection scheme to these parametrizations. Comparing the performance of these schemes in simulating tropical storms is particularly interesting since they belong to two different classes of parametrizations: MCA is an adjustment scheme (when convection occurs, temperature and mixing ratio are adjusted such that the vertical gradient of equivalent potential temperature is zero, the atmosphere is saturated, and the energy is conserved), RAS is a mass-flux scheme (convection can be represented by a spectrum of clouds composed of entraining plumes of different heights and entrainment rates). In addition, shallow convection is expected to have a significant impact on tropical-storm intensity through its impact on the surface thermodynamic disequilibrium. Investigating the impact of shallow convection on the simulated tropical storms should help to evaluate the importance of the boundary-layer processes for tropical storms. This is important since the role of atmospheric surface mixing is getting an increasing amount of attention and its impact on the atmospheric circulation is still not fully understood.

Documenting differences in tropical-storm statistics generated by changes in convective parametrization is straightforward, but understanding the cause of the differences is not. Convective parametrizations can affect tropical storms in two ways: by changing the nature of convection associated with simulated storms themselves or by changing the tropical mean background state in which the simulated storms evolve. Model climatologies of the background tropical atmosphere and composites of tropical storms are used to assess the importance of these two mechanisms. Regional hurricane model integrations, with identical initial vortices superimposed on background states produced by GCMs with different parametrizations, are also used to isolate the mean-state impacts.

Results indicate that changes in the thermodynamics of the mean tropical background state in the GCM are the primary cause of changes in tropical-storm statistics. In particular, the tropical mean convective available potential energy (CAPE) is found to be strongly related to the frequency of tropical storms. Other aspects of the stability of the background atmosphere can be related to changes in simulated storm intensity and structure. The understanding gained by this analysis may be able to help in the design of low-resolution GCM parametrization packages with improved simulation of tropical storms. A final motivation for this study was to evaluate whether the results presented in Vitart *et al.* (1997, 1999) are dependent on the choice of the GCM.

Section 2 describes the GCM and parametrizations, and section 3 documents the sensitivity of the tropical storms to changes in cumulus parametrization. Section 4 examines the impact of changes in the tropical mean state on tropical storms. A discussion of the results is found in section 5.

2. Experimental design

The GCM used in the present study is a T42 atmospheric model with 18 vertical levels developed at the Geophysical Fluid Dynamics Laboratory (Gordon and Stern 1982). Several versions of the GCM with differences in the physical parametrizations are used. The version referred to as 'MCA' hereafter includes a 'bucket' hydrology (Manabe 1969); large-scale condensation and MCA (Manabe *et al.* 1965) (both using a condensation criterion of 100%); cloud prediction (interactive with the radiation (Gordon 1992)); radiative transfer (12 h average), which varies seasonally; stability-dependent vertical eddy fluxes of heat, momentum, and moisture throughout the surface layer, the planetary boundary layer, and the free atmosphere (Sirutis and Miyakoda 1995); and $k\nabla^4$ horizontal diffusion. The surface temperatures over land and over sea ice are determined by solving surface heat balance equations (Gordon and Stern 1982).

A second version of the GCM, referred to as 'RAS' uses a modified version of the relaxed Arakawa–Schubert convection scheme (Moorthi and Suarez 1991) instead of MCA. In all other details it is identical to the MCA GCM. The RAS scheme is derived from Arakawa and Schubert (1974). It is a mass-flux scheme which assumes that convection can be represented by a spectrum of clouds composed of entraining plumes of different heights and entrainment rates. A quantity called the *cloud work function* represents the stabilization of the atmosphere for each cloud. When the rate of mass entrainment is zero, the cloud work function is equivalent to the CAPE. The stability of the atmosphere for each cloud is modified by large-scale processes such as radiation, vertical motions, heat fluxes, and by the convection itself which has a tendency to reduce the instability. To close the system, Arakawa and Schubert (1974) use the quasi-equilibrium assumption: the large-scale tendency of the cloud work function is balanced by the convective tendency. In other words, the total tendency of the cloud work function is zero during convection. In the RAS scheme, convection occurs only if the cloud work function is larger than a specified value. This threshold value was determined from Marshall Island data by Yanai *et al.* (1973). When convection occurs, the quasi-equilibrium assumption is enforced by maintaining the cloud work function constant. An unrealistic feature of the RAS scheme is its tendency to create clouds as high as 35 mb. In order to avoid the formation of tropical convective clouds with unrealistically high tops, the original RAS scheme was modified by placing a 'cap' on deep convection. This modification of the RAS scheme prohibits deep convection if the cloud top is above 200 mb. Therefore, there are two conditions for deep convection to occur: the cloud work function must exceed a threshold and cloud top must be below 200 mb.

Two additional versions of the GCM are used in which a shallow-convection scheme (Tiedtke 1988) has been added to the RAS and MCA versions (Sirutis and Miyakoda 1995); these are referred to as RAS+SC and MCA+SC respectively. This shallow-convection scheme does not include induced momentum transport. The shallow convection occurs where convective instability exists but no deep convection occurs. The cloud base is determined from the lifting condensation level and the vertical diffusion is invoked between the cloud top and the bottom. A fixed profile of vertical-diffusion coefficients is assigned for the mixing process. The models with shallow convection include several additional modifications to the physical parametrizations. These are the addition of a Beljaars surface flux treatment (Godfrey and Beljaars 1991), Matthews surface albedo and snow albedo (Gordon 1992), three-level soil moisture, minor corrections to mountain gravity-wave drag, a marine stratocumulus linear-regression scheme (Gordon 1992) and Gibbs filtered orography (Navarra *et al.*

TABLE 1. DESCRIPTION OF THE MODELS

Model	Resolution	Cumulus convection	Shallow convection	Limitation on convection
RAS	T42	Relaxed Arakawa–Schubert	No	'Cap' on deep convection
RAS+SC	T42	Relaxed Arakawa–Schubert	Tiedtke	'Cap' on deep convection
MCA	T42	Moist convective adjustment	No	No
MCA+SC	T42	Moist convective adjustment	Tiedtke	No
NEWRAS+SC	T42	Relaxed Arakawa–Schubert	Tiedtke	No
AS	T42	Arakawa–Schubert	Tiedtke	No
AST	T42	Arakawa–Schubert	Tiedtke	'Cap' on deep convection
ECMWF	T42, T159, T319	Tiedtke	Tiedtke	No

See text for further explanation.

1994). Despite the number and variety of these additional changes, results suggest that for the purpose of this discussion, the addition of the shallow-convection scheme is the dominant change.

The fifth GCM version is referred to as NEWRAS+SC which differs from RAS+SC only in that the 'cap' on cloud-top height has been removed. This allows much deeper convection in some instances in the tropics and produces results that are more similar to those obtained using the full Arakawa–Schubert parametrization than to those from RAS+SC.

Finally, two versions of the GCM using the original Arakawa–Schubert convective parametrization (Arakawa and Schubert 1974) are used; details of all other parametrizations are identical to the MCA GCM. The first of these is referred to as the AS GCM. The second, referred to as AST, includes a modification (Tokioka *et al.* 1995) that forbids deep convection if the rate of mass entrainment is greater than a threshold value. This modification was originally developed to improve simulations of the Madden–Julian oscillation (MJO) and is similar in function to the 'capped' version of RAS. A summary of the details of the model versions can be found in Table 1.

All of these models produce tropical rainfall distributions that agree reasonably well with observations. A brief summary of the similarities and differences in the biases shared by the models follows: (1) In the east Pacific, the models with MCA have an inter-tropical convergence zone (ITCZ) that is very broad compared with observations. The models with RAS and AS have a sharper ITCZ, and agree much better with observations. (2) In the west Pacific, all the models produce excessive rainfall in the warm-pool region during the summer months. (3) During the winter months, all the models produce excessive rainfall in the South Pacific convergence zone, although this bias is somewhat smaller in the models with RAS and AS. (4) All of the models have good agreement with observations in the Indian Ocean during the summer months, particularly the models with RAS and AS. In the models with MCA, the position of the rainfall maximum is shifted slightly southward compared with observations and the other models. A more detailed discussion of the rainfall distribution produced by the models using MCA is displayed in Stern and Miyakoda (1995).

The MCA, RAS, MCA+SC, and RAS+SC versions of the GCM were integrated for 10 years from 1 January 1979 to 31 December 1988 forced by observed SSTs (Gates 1992). Single runs of the MCA and RAS versions are available while a nine-member (six-member) ensemble of the MCA+SC (RAS+SC) version was made. The initial conditions for the ensembles were taken from analyses starting on 12 December 1978 sampled every 5 days; each of these analyses was then used as an initial condition as if it were the analysis for 1 January 1979. The first year of the integrations was discarded in an attempt to eliminate direct effects of the initial conditions. In addition, 4-month integrations (June to September 1993) of the AS and AST GCMs were created.

The procedure for tracking simulated tropical storms from Vitart *et al.* (1997) was applied to all GCM integrations. Simulated tropical storms must have a maximum vorticity exceeding a certain threshold (3.5×10^{-5} s^{-1}), a minimum sea-level pressure, and a warm core in the upper troposphere that is within 2 degrees of latitude of the sea-level pressure minimum of the storm. In addition, the storm must last at least 2 days and have a maximum wind velocity of at least 17 m s^{-1} within an 8-degree latitude circle, sometime during its lifetime.

The warm-core criteria were applied to the *vertical integral* of the temperature between 200 mb and 500 mb instead of the temperature at a fixed vertical level. Therefore, the objective procedure allows some flexibility in the vertical structure of the tropical storms and is able to detect tropical storms with a warm core at 500 mb as well as tropical storms with a maximum temperature anomaly at 200 mb.

3. Impacts of changes in convective parametrizations on tropical-storm statistics

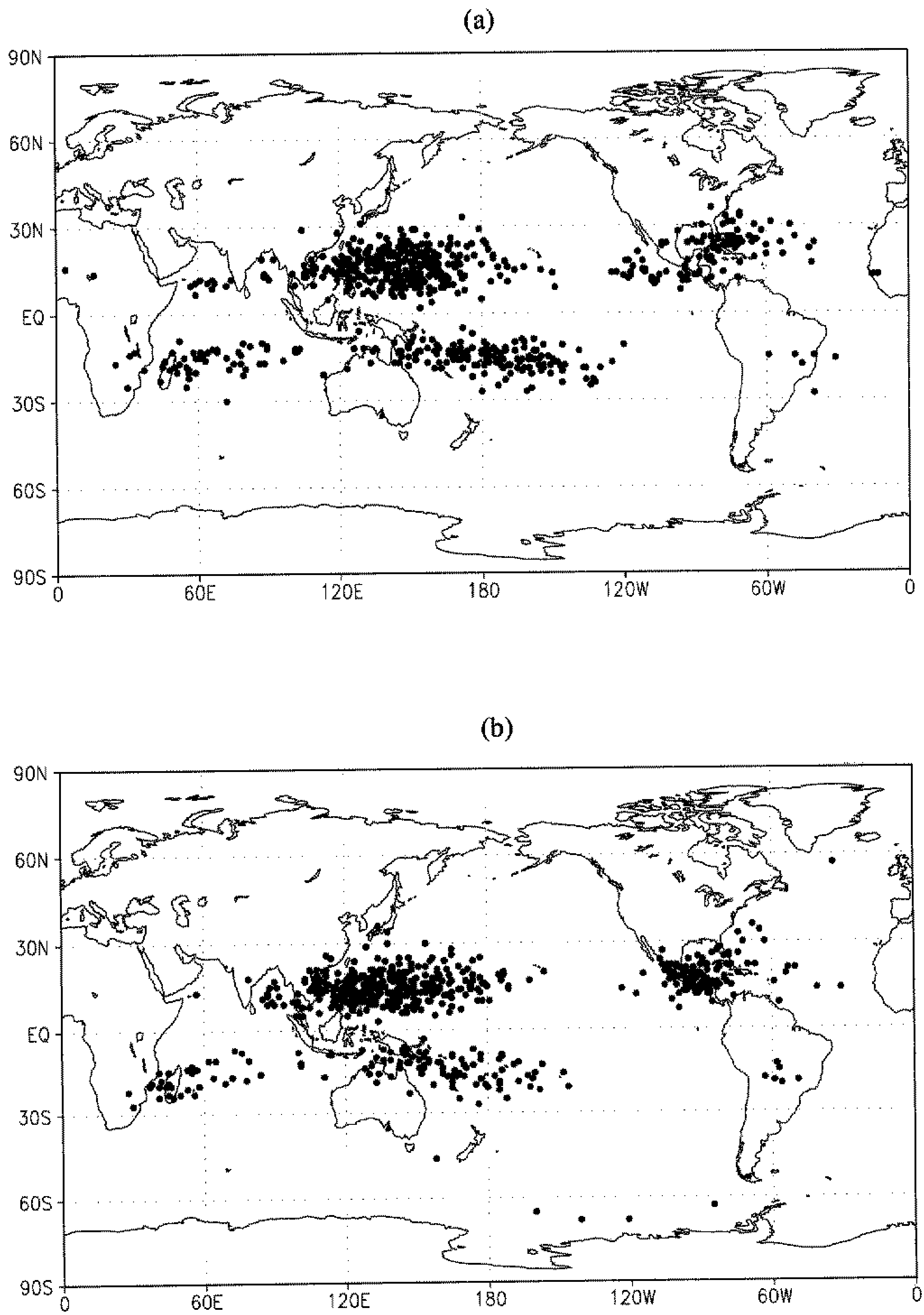
(*a*) *Tropical-storm frequency, spatial distribution, and intensity*

The objective procedure was applied to track the tropical storms simulated by MCA+SC. The ensemble-mean number of tropical storms obtained per year was 70.4 while the observed climatology is 86. The procedure was applied to MCA, RAS+SC, and RAS with 65, 67 and 68 storms produced per year, respectively. These differences do not appear to be statistically significant. Modifying the warm-core criteria such that, for example, the temperature anomaly is detected between 600 mb and 400 mb instead of between 500 mb and 200 mb confirms that MCA+SC produces more tropical storms than MCA, RAS+SC, and RAS, but the difference never exceeds 10%. So global tropical-storm frequency is apparently not very sensitive to changes between MCA and RAS or to the use of the shallow-convection scheme (although regional frequency may be sensitive; see section 3(b)).

However, NEWRAS+SC, in which the 'cap' on deep convection was removed, only produces 15 tropical storms per year. A different, less restrictive procedure for tracking tropical storms was applied: a tropical storm is said to exist if the 850 mb relative vorticity exceeds 3.5×10^{-5} s^{-1} and the sea-level pressure is lower than 990 mb. The number of tropical storms detected with this method is just 26 per year, which is still unrealistically low and suggests that the low number of tropical storms detected with NEWRAS+SC cannot be explained by an inadequacy of the procedure of detection. The significant reduction in tropical-storm frequency from RAS+SC to NEWRAS+SC is in agreement with results obtained contrasting AST and AS. The 4-month integration (June to September 1993) of AS simulates only 10 tropical storms (MCA, MCA+SC, RAS, and RAS+SC produced about 35 tropical storms during this same period). The AST GCM simulates 33 tropical storms during the same period. Apparently, the Tokioka modification limiting deep convection allows the AST GCM to simulate an increased tropical-storm frequency, just as the 'cap' in RAS and RAS+SC leads to many more storms than are found in NEWRAS+SC.

The RAS+SC tropical-storm distribution presents some differences to the simulations using MCA+SC (Fig. 1). Over the western North Atlantic the model with RAS+SC simulates tropical storms everywhere in the basin (some storms are generated close to the African coast as in observations). However, the model has a tendency to simulate an unrealistic cluster of tropical storms near the Mexican coast. Over the Pacific,

(a)



(b)

Figure 1. Tropical-storm first location simulated by the MCA+SC (a) and RAS+SC (b) (see text) models during the period 1980–88 (9 years of general-circulation-model integration). Each point represents the first location of one simulated tropical storm.

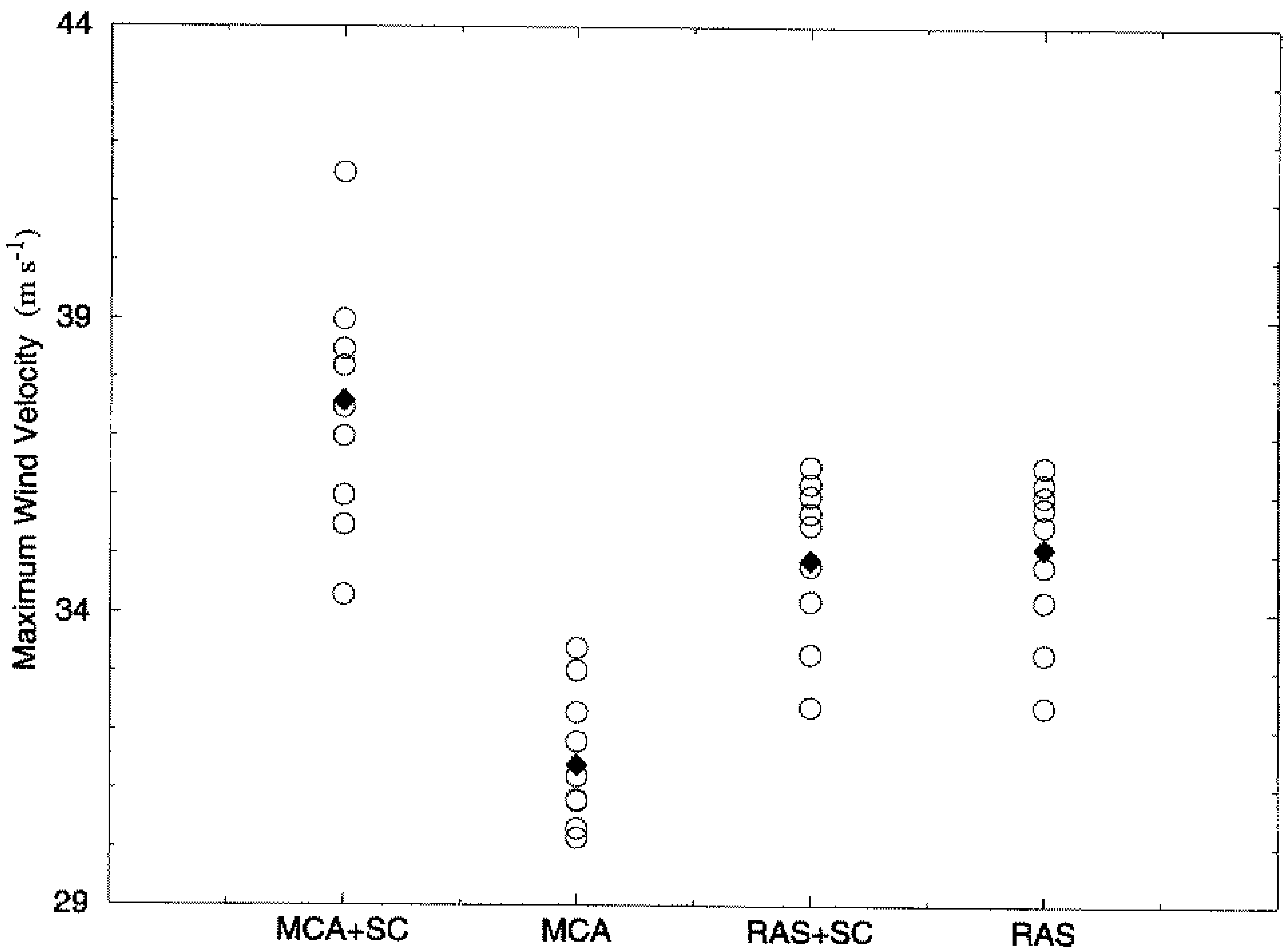


Figure 2. Ensemble distributions of the mean intensity (maximum wind velocity) of all the tropical storms averaged over 1 year of integration (circles) by four different general circulation models (GCMs): MCA+SC (a), MCA (b), RAS+SC (c), and RAS (d), (see text). The diamonds represent the tropical-storm intensity averaged over the 9-year period of GCM integration.

RAS+SC generates fewer tropical storms in the central part of the basin where observed tropical storms are rare. On the other hand, RAS+SC simulates an unrealistically low frequency of tropical storms over the Arabian Sea. Over the other ocean basins, the distribution of tropical storms with RAS+SC does not display major differences compared with the distribution obtained with MCA+SC (Fig. 1). Both models produce tropical cyclones over South America which suggests a deficiency in the physics of both GCMs.

The maximum 850 mb wind velocity within a 5° radius of the tropical-storm centre was chosen to measure the *intensity* of a tropical storm. The use of the minimum pressure in the centre of the tropical storm gives results consistent with those obtained with the maximum wind velocity. The maximum wind velocity was averaged over all the tropical storms detected for each year from 1980 to 1988 (Fig. 2). The tropical storms are significantly more intense with MCA+SC than with RAS+SC (Fig. 2) with a confidence larger than 95% according to the Kolmogorov–Smirnov (KS) test (Knuth 1981; Press 1986). Shallow convection seems to significantly increase the intensity of tropical storms when applied to MCA, but its impact on RAS does not seem to be significant (Fig. 2). This difference in tropical-storm intensity persists when modifying the criteria for detecting the tropical storms.

(*b*) *Vertical structure of the tropical storms*

To investigate differences in the vertical structure of simulated tropical storms with MCA, MCA+SC, RAS, and RAS+SC, composites of tropical cyclones were created over the tropical western North Pacific (120°E–180°E, 0°N–20°N) during the period from June to October. This region was chosen because it is the area where all model versions simulate the largest number of tropical storms and should give the most stable composite statistics. The average number of tropical cyclones in this region varies from one parametrization to another. For instance, MCA+SC simulates about four times *fewer* tropical storms here than RAS+SC. This is probably because the MCA+SC parametrizations impact on the large-scale circulation resulting in an ITCZ that is too far poleward. Although the composite sample sizes vary, the samples are large enough that the composite statistics are relatively stable.

For the purpose of these composites, a tropical cyclone is said to exist if the 850 mb relative vorticity exceeds 3.5×10^{-5} s^{-1} and the sea-level pressure is lower than 990 mb. The warm-core criterion imposed in Vitart *et al.* (1997) and in the previous section is not enforced in order to allow changes in the vertical thermal profile to be studied in the composites. Composites were formed by averaging over all days of occurrence during the 9 years of integration and over all members of the ensembles.

The MCA+SC and MCA composites have a similar temperature profile with a warm core located at 350 mb, but the warm core is significantly more intense with MCA+SC (Fig. 3). The warm cores simulated with RAS+SC and RAS are significantly lower and less intense, at about 500 mb, than those from MCA+SC. The MCA+SC and MCA composites also display a stronger anomaly of *specific humidity* near the centre of the cyclone (Fig. 4). The *relative humidity* reaches 100% within 3 degrees of latitude of the centre of the cyclone with all four parametrizations. The relative humidity is generally higher with RAS (or RAS+SC) than with MCA (or MCA+SC) throughout most of the troposphere, especially in areas further away from the storm centre (not shown). In summary, the structure of the tropical storms simulated with MCA (or MCA+SC) seems more in agreement with observations (Frank 1977) than the structure simulated with RAS+SC (or RAS).

The comparison between MCA and RAS is a 'clean' comparison, but other modifications have been introduced between MCA+SC and MCA, and RAS+SC and RAS (section 2). Several intermediate integrations were performed to study the impact of these additional changes on simulated tropical storms, and no significant impacts appeared. Therefore, the differences in tropical cyclones between MCA+SC and MCA (RAS+SC and RAS) can be attributed primarily to the shallow convection, and the differences between MCA+SC and RAS+SC to the change in convective parametrization.

In summary, the RAS and RAS+SC schemes have a tendency to produce tropical cyclones with less intense and lower warm cores than those produced with MCA or MCA+SC. This is opposite to what might have been expected since the RAS scheme is designed specifically to produce more penetrative convection than MCA. On the other hand, when shallow convection is combined with MCA, the tropical-cyclone warm-core intensity increases substantially, but when combined with RAS, shallow convection leads to a slight decrease in warm-core intensity (Fig. 3). Qualitatively similar behaviour is found for composites of tropical storms over all other basins (not shown). Although shallow convection has a significant impact on the tropical-storm intensity, its impact on tropical-storm structure (position of the warm core) is not significant (Fig. 3). This suggests that the difference in tropical-storm structure between MCA and RAS may be quite robust and not dependent on the other physical parametrizations of the GCM.

(*c*) *Tropical-storm interannual variability*

As seen in the previous sections, changing the convective parametrization can have significant impacts on the warm-core intensity and vertical structure of tropical storms, even though the climatological global-mean number of storms is essentially unchanged. This section explores whether changes in simulated warm-core intensity and vertical

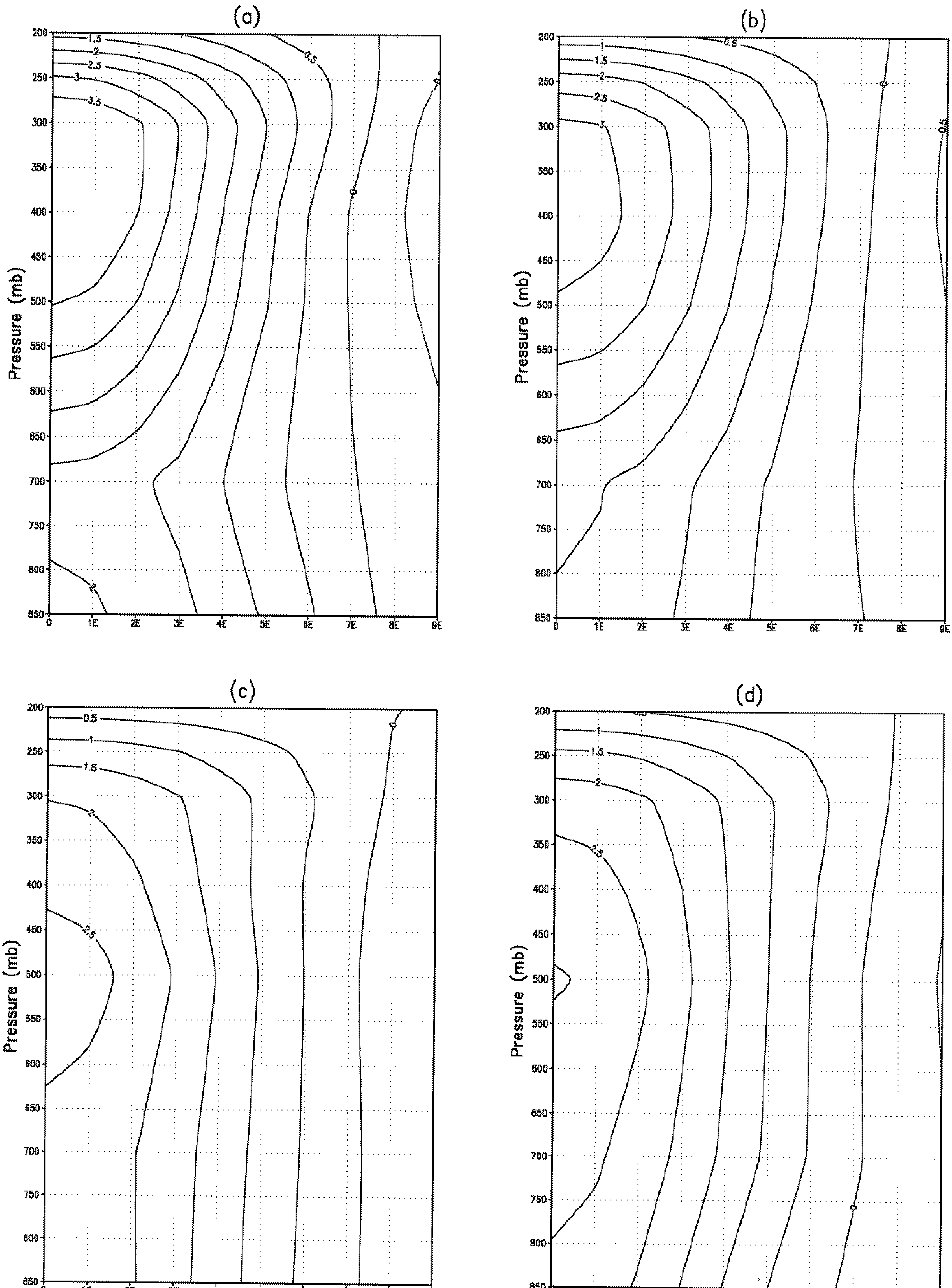


Figure 3. Temperature anomaly (K) cross-section of a composite of an intense (i.e. minimum sea-level pressure lower than 990 mb) tropical cyclone over the tropical western North Pacific from June to October. The x-axis represents the distance from the centre of the storm. The tropical cyclones were simulated with general circulation models using four different convective cumulus parametrizations: MCA+SC (a), MCA (b), RAS+SC (c) or RAS (d) (see text).

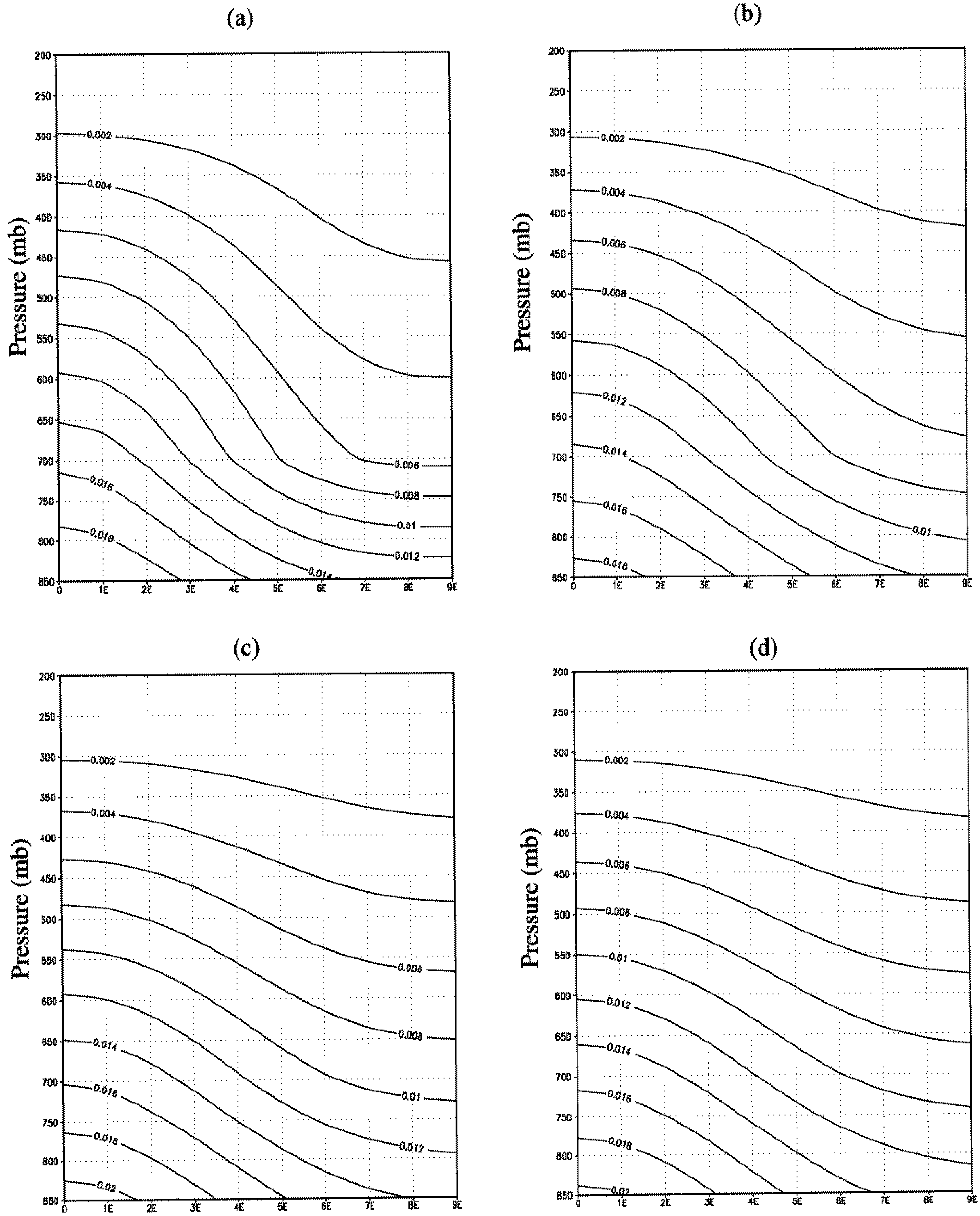


Figure 4. As in Figure 3 but for the specific humidity (kg kg^{-1}).

structure affect the interannual variability of simulated tropical-storm frequency over different ocean basins. The discussion will focus on differences between the RAS+SC and MCA+SC integrations for which ensembles are available.

The procedure for tracking simulated tropical storms was modified to take account of the difference in vertical structure of the simulated tropical storms in the RAS+SC integrations. A temperature anomaly between 600 mb and 400 mb is now used when establishing the existence of a warm core instead of an anomaly between 500 and

TABLE 2. LINEAR CORRELATION BETWEEN THE SIMULATED AND OBSERVED INTERANNUAL VARIABILITY OF TROPICAL-STORM FREQUENCY FOR THE PERIOD 1980–88

	WNA	ENP	WNP	NI	SI	AUS	SP
MCA+SC warm core between 200 and 500 mb	0.56 (89)	0.54 (88)	0.66 (94.5)	−0.63 (93)	−0.66 (93)	0.57 (87)	−0.775 (97.7)
MCA+SC warm core between 400 and 600 mb	0.52 (86)	0.30 (57)	0.68 (95)	−0.50 (78.2)	−0.72 (96)	0.45 (72)	−0.70 (96.5)
RAS+SC warm core between 400 and 600 mb	0.77 (98.4)	0.43 (75.6)	0.75 (98)	0.44 (77)	−0.72 (96)	0.70 (94.8)	0.66 (92.5)

WNA = Western North Atlantic; ENP = Eastern North Pacific, WNP = Western North Pacific; NI = North Indian Ocean; SI = South Indian Ocean; AUS = Australian Basin; SP = South Pacific. Figures in parentheses are confidence levels. See text for further explanation.

200 mb, as was used in Vitart *et al.* (1997), and in earlier sections. The number of simulated tropical storms was counted over each basin for each tropical-storm season. The linear temporal correlation between the six-member ensemble mean of RAS+SC tropical-storm frequency and the observed frequency was calculated (Table 2) and compared with that for MCA+SC. The MCA+SC correlations were produced using both the 500 to 200 mb and 600 to 400 mb warm-core criteria.

Modifying the warm-core criterion has some impact on the MCA+SC simulation of interannual variability of tropical storms with the lower warm-core criterion generally resulting in less significant correlations with the observed time series (Table 2). However, the changes in interannual variability caused by changing the warm-core criterion are small compared with those caused by changing to RAS+SC. RAS+SC displays larger positive correlations with observations over the western North Atlantic, the western North Pacific, the Australian Basin and the South Pacific with the confidence level of the correlations exceeding 90% over these four basins.

Over the South Pacific, RAS+SC simulates an interannual variability of tropical-storm frequency positively and significantly correlated with observations, while MCA+SC has a significant negative correlation (Table 2). At least part of this huge improvement appears to be because RAS+SC simulates tropical storms mostly in the north-western part of this basin as is observed, unlike MCA+SC which simulates a large number of tropical storms in the central part of the South Pacific (Fig. 1). The RAS+SC climatological-mean vertical wind shear is much more intense over the southern part of this basin (between 20°S and 30°S) (not shown), which inhibits the formation of tropical storms over the southern and eastern parts of the basin. In that case, changes in the GCM climatology may be the primary factor leading to an improved simulation of interannual tropical variability in RAS+SC.

RAS+SC also has a much more significant correlation with the observed interannual tropical-storm variability over the western North Atlantic. A large portion of simulated tropical storms have their origin in the south-western part of the Atlantic basin. In this region, RAS+SC simulates a more realistic interannual variability of vertical wind shear with a linear correlation with observations higher than 0.8 (significant at the 0.5% level) in many places (Fig. 5). This improvement is particularly visible during the period from August to October. This improved simulation of the large-scale vertical shear may explain the higher correlation with RAS+SC than with MCA+SC, over the North Atlantic.

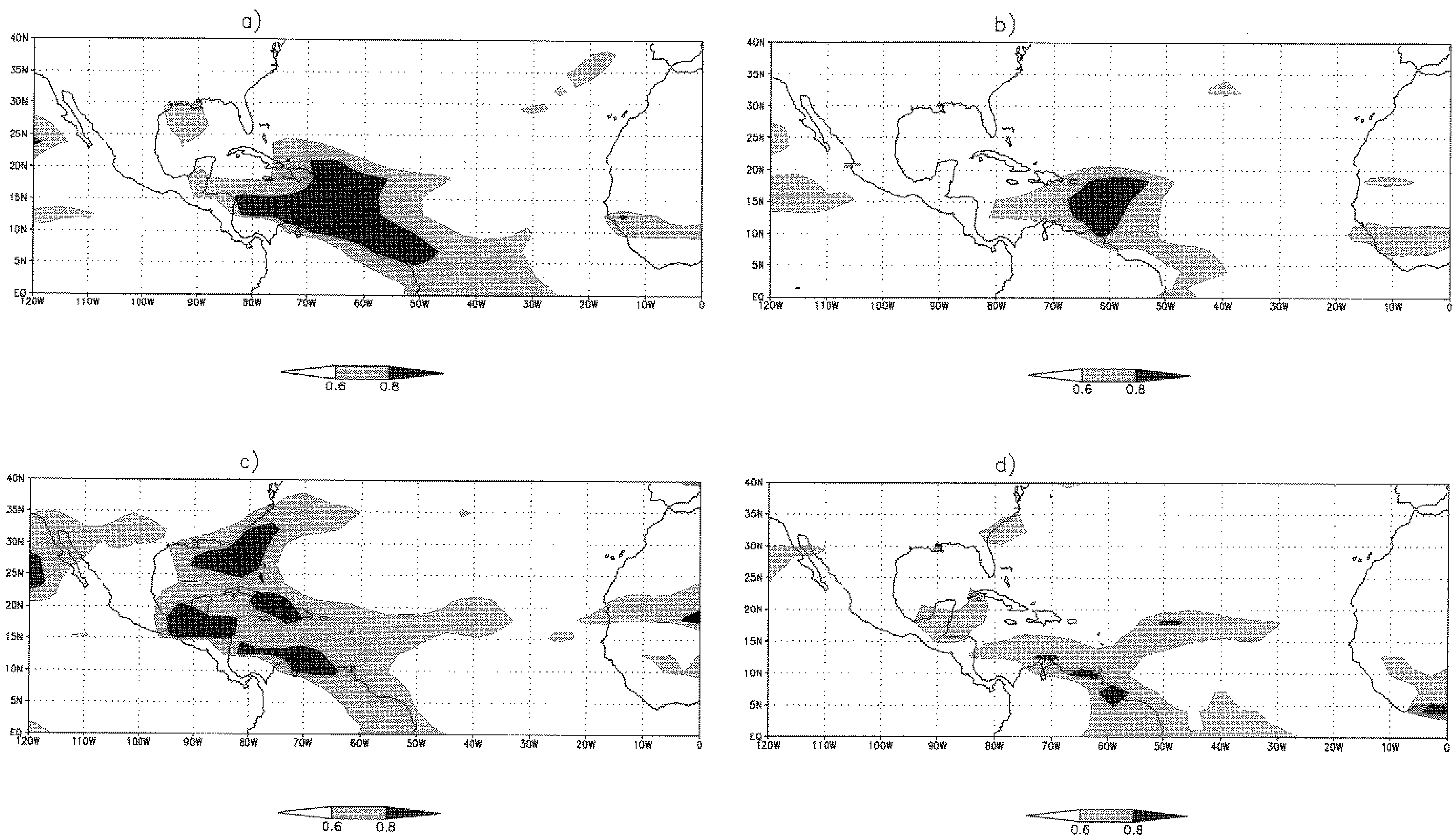


Figure 5. Linear correlations were calculated between the observed and the simulated interannual variability of the vertical wind shear averaged over the period from June to October ((a) and (c)) and from August to October ((b) and (d)). Shaded areas represent regions where the linear correlation exceeds 0.6 (90% confidence). Dark shaded areas represent regions where the linear correlation exceeds 0.8 (99.5% confidence). Results obtained with the RAS+SC (see text) ((a) and (b)) and MCA+SC GCMs (see text) ((c) and (d)) are displayed.

In general, the interannual variability of simulated tropical storms is more realistic with RAS+SC than with MCA+SC. However, the simulated structures of the tropical storms themselves are weaker and less realistic. Improved simulations of the regional large-scale circulation with RAS+SC is likely to be the main factor that leads to improved simulation of tropical-storm interannual variability. In the next section, the impact of parametrization-induced changes to the simulated large-scale circulation and basic state on the simulated tropical storms is explored further.

4. Impact of changes in convective parametrizations on the tropical mean state

(*a*) *Dynamics*

Previous studies (Vitart *et al.* 1999) have shown that the dynamics of the large-scale circulation play a significant role in the simulated interannual variability of tropical-storm frequency. Large-scale parameters that have a particularly strong impact on simulated tropical storms are the 850 mb vorticity, 200 mb vorticity, and the vertical shear of the horizontal wind. It is possible that a change in the cumulus parametrization changes these parameters, and that the intensity and structure of simulated tropical storms are changed globally. To evaluate this possibility, June to October mean climatologies of 850 mb vorticity, 200 mb vorticity, and vertical wind shear over the tropical western North Pacific were created (these climatologies cover the same region and time as the tropical-storm composites discussed in section 3(b)).

Tropical storms are part of the mean state, and their frequency could impact on the mean vertical wind shear and the mean vorticity. Vitart *et al.* (1999) showed that the impact of tropical-storm frequency on the interannual variability of the mean state is probably second order compared with the impact of the large-scale circulation on the model tropical storms. In addition, MCA displays a tropical-storm frequency over the tropical western North Pacific very close to RAS+SC, but the difference in large-scale circulation between MCA+SC and MCA is much smaller than between MCA+SC and RAS+SC. Therefore, the difference in large-scale circulation between MCA+SC and RAS+SC is unlikely to be the *consequence* of differences in tropical-storm frequency between MCA+SC and RAS+SC.

The vorticity at 850 mb (not shown) tends to be higher with RAS+SC and RAS than with MCA+SC and MCA over most of the region, apparently due to a shift in the position of the ITCZ. There is no significant difference in the 200 mb vorticity (not shown). The vertical shear of the horizontal wind between 200 mb and 850 mb is generally more intense, often by more than 5 m s^{-1} with the RAS models, except over the north-western quadrant and the centre of the basin. The RAS GCMs tend to create more low-level vorticity (implying increased tropical-storm activity) but with more vertical wind shear (implying reduced activity).

The differences between RAS and MCA over the western North Pacific may be strong enough to impact significantly on the tropical storms over this basin. However, these differences cannot be generalized to the other basins. For example, over the south Indian Ocean, the vertical wind shear is significantly lower with the RAS models than with the MCA models. Therefore, there is no systematic bias in the large-scale dynamic parameters simulated by the different models. Since the differences in tropical-storm structure were found to be the same over all ocean basins, it is unlikely that the changes in large-scale circulation could explain the globally consistent changes found in tropical-storm structure.

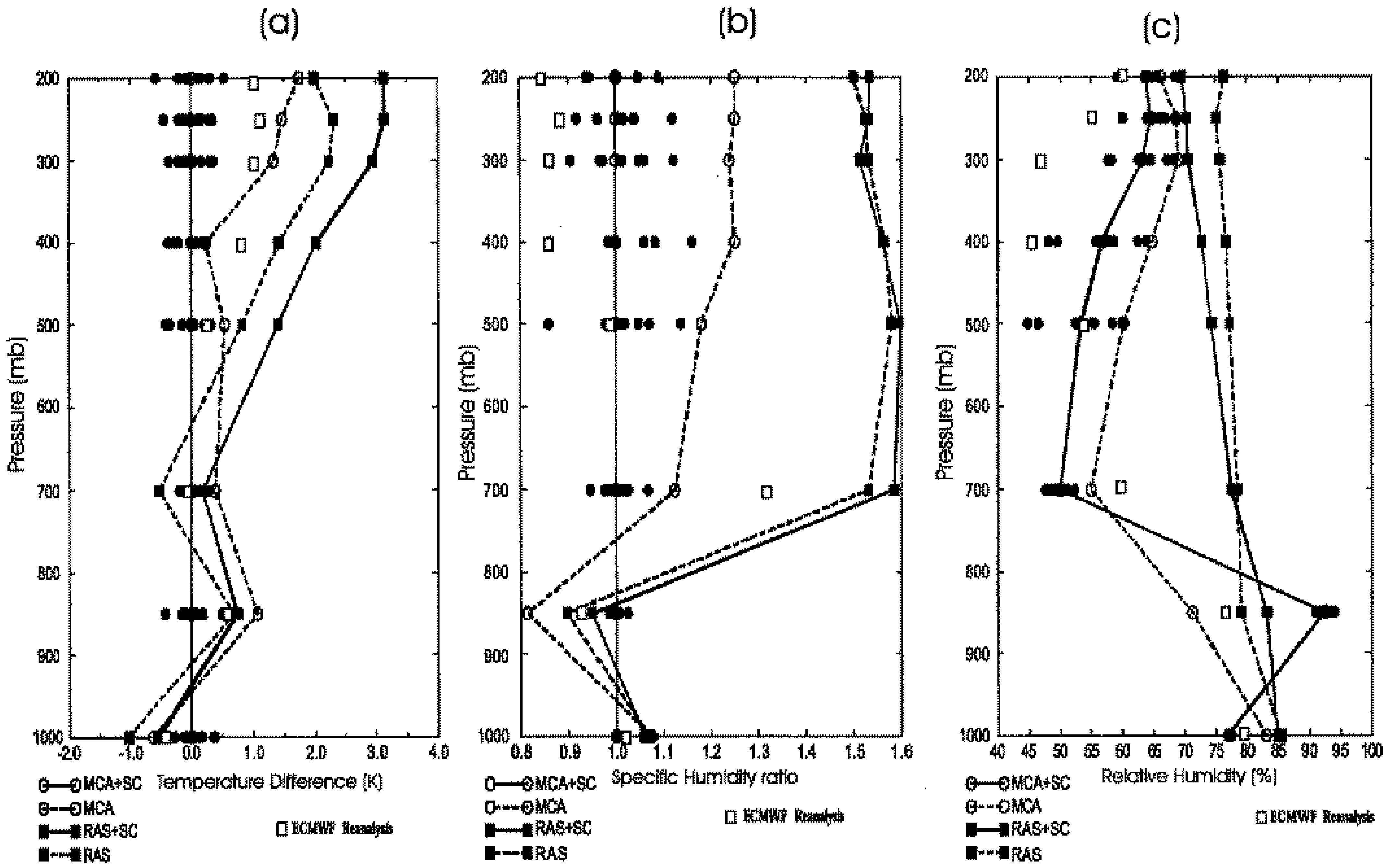


Figure 6. Vertical profiles of (a) the temperature differences between the general circulation models and MCA+SC (see text), (b) the specific humidity divided by the specific humidity of MCA+SC (see text) and (c) the relative humidity. The vertical profiles were obtained by averaging the temperature, specific humidity and relative humidity over the western tropical North Pacific and over the period from June to October from 1980 through 1988. The solid black circles represent results from each individual year for MCA+SC. The white squares represent the temperature, specific humidity and relative humidity obtained with the European Centre for Medium-Range Weather Forecasts re-analysis.

(*b*) *Thermodynamics*

It is possible that a modification of the large-scale background thermodynamic structure in the tropics by the convective parametrizations is responsible for the changes in tropical-storm statistics. Regional climatological averages of the vertical profile of simulated temperature, and specific and relative humidity were created over the tropical western North Pacific region for June to October for 1980 to 1988 for MCA, MCA+SC, RAS+SC, and RAS (Fig. 6).

The impact of the shallow-convection scheme is addressed first. The shallow-convection scheme coupled with RAS removes humidity from the surface and distributes it around 800 mb. This may explain the higher specific humidity at 800 mb in RAS+SC than in RAS. Above 800 mb, RAS+SC transports the additional moisture to higher levels giving a moister upper troposphere up to 400 mb in RAS+SC (Fig. 6(b)).

Shallow convection in MCA+SC removes moisture from the surface to distribute it up to 850 mb. However, MCA is not a very penetrative convection scheme and most of the additional moisture brought to 850 mb stays there. This explains the unrealistic peak of 90% relative humidity at 850 mb in Fig. 8. MCA+SC is expected to create a moister and warmer upper troposphere than MCA, since shallow convection removed moisture from the surface. However, the impact of shallow convection on MCA seems to dry and cool the upper troposphere significantly (Figs. 6(b) and (c)). A possible explanation for this surprising result may be the presence of dynamic or thermodynamic feedbacks. It is possible that the cooler and drier upper troposphere in MCA+SC compared with MCA is due to radiative feedbacks associated with spurious clouds created around 850 mb.

Although the impacts of shallow convection on the background thermodynamic state are not trivial, they are generally small compared with the differences generated by changing the convective parametrizations (Figs. 3 and 4). The rest of the discussion focuses on a comparison of differences between RAS+SC, MCA+SC, and NEWRAS+SC. In general, the results presented would also be valid for a comparison between the same schemes without the inclusion of shallow convection.

RAS+SC has an upper troposphere that is moister and warmer than MCA+SC (Fig. 6). The temperature difference between RAS+SC and MCA+SC exceeds 3 K at the top of the troposphere (Fig. 6(a)), and the specific humidity simulated with RAS+SC is about 60% greater than the specific humidity simulated with MCA+SC. The differences greatly exceed the range of the interannual variability of these fields in MCA+SC, so the tropical storms simulated with MCA+SC and RAS+SC are evolving in different thermodynamic environments. These thermodynamic differences are consistent throughout the tropics, unlike the dynamic changes discussed in the previous section, and seem a more likely explanation for the consistent response of tropical-storm statistics in all basins.

These convective schemes produce very different temperature and humidity profiles, and none of them are in good agreement with European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis (Gibson *et al.* 1997). RAS+SC produces a temperature that is consistent with ECMWF re-analysis in the lower troposphere, but its upper-tropospheric temperature is warmer by about 2 K (Fig. 6(a)). On the other hand, MCA+SC is colder than ECMWF re-analysis in the upper troposphere by about 1 K. In addition, all schemes produce an upper troposphere that is moister than in the ECMWF re-analysis (Figs. 6(b) and (c)).

(i) *Effect of thermodynamical changes on tropical-storm intensity.* One way to measure the stability of the atmosphere is to calculate the CAPE (e.g. Williams and Renno 1993). For the CAPE calculations, pseudo-adiabatic ascent was assumed for an air parcel lifted from the lowest model level. Water condensate loading (Xu and Emanuel 1989), ice physics, and the convective inhibition energy contribution (Williams and Renno 1993) were not included. CAPE is significantly higher with MCA+SC than with RAS+SC (Fig. 7(a)). An alternative CAPE measure, called CAPE90 (Knutson and Tuleya 1999), assumes an environmental relative humidity of 90% for the air parcel lifted from the lowest level. This is motivated by the fact that a parcel with an initial relative humidity of 90% is more representative of what would occur in the eye-wall region (Holland 1997; Shen *et al.* 2000). Differences in CAPE90 between MCA+SC and RAS+SC are larger than differences in CAPE (Fig. 7), with an application of a KS test to evaluate differences in the ensemble distributions giving a significance at the 0.01% level. The stronger values of CAPE90 with MCA+SC may explain the stronger tropical-storm intensity with MCA+SC than with RAS+SC (Figs. 2 and 3).

An ensemble of integrations was realized with the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model (Kurihara and Bender 1980) to check whether this model displays the same sensitivity of tropical-storm intensity to thermodynamic profiles as the global model. The GFDL hurricane model is a primitive-equation system with 18 sigma levels in the vertical. The domains of the three meshes of this study are $75° \times 75°$, $11° \times 11°$ and $5° \times 5°$ with resolutions of 1°, 1/3° and 1/6°, respectively. Model physics include cumulus convection treated by the parametrization scheme of Kurihara (1973) with some additional modifications (Kurihara and Bender 1980,

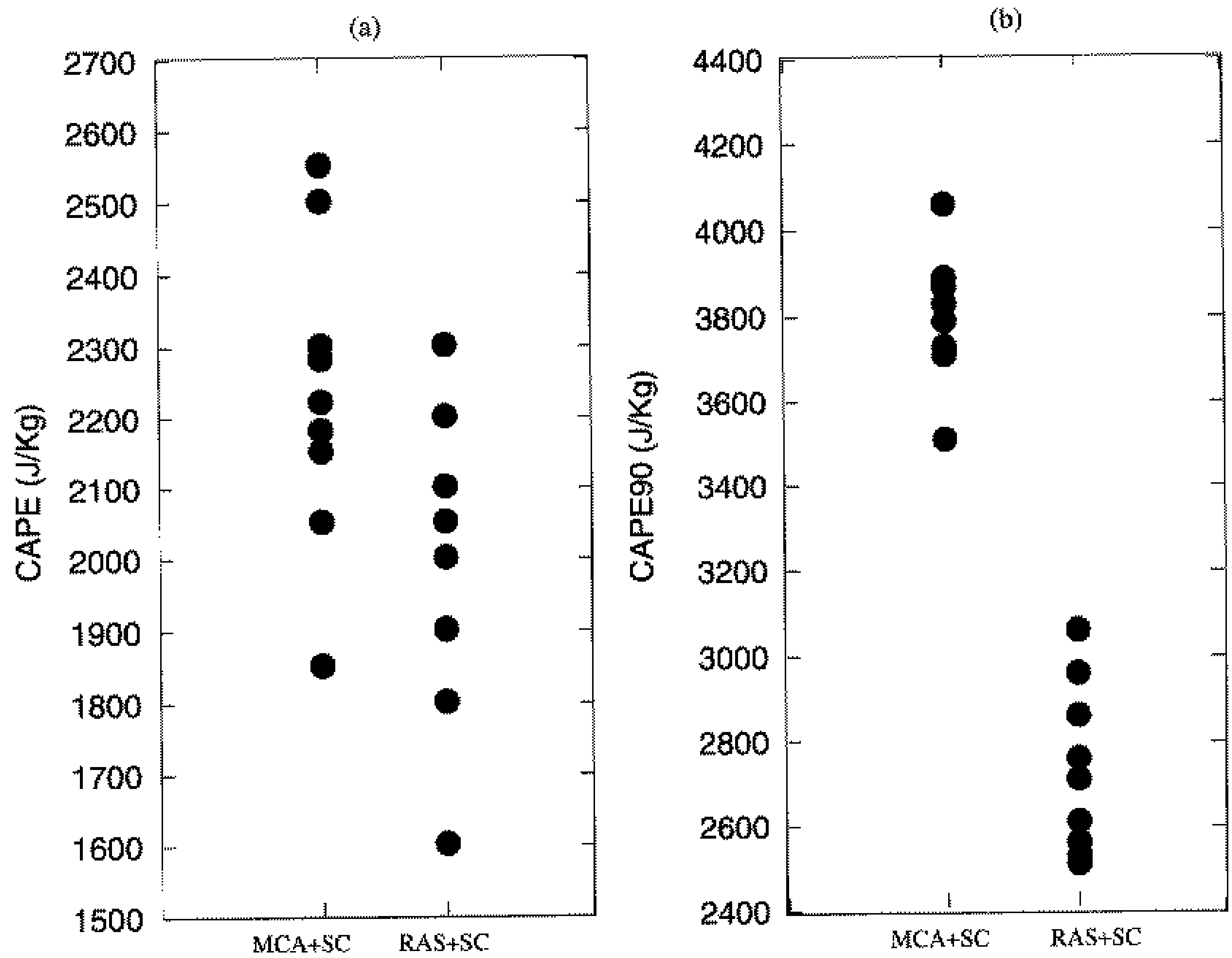


Figure 7. Ensemble distribution of (a) convective available potential energy (CAPE) and (b) CAPE90 (see text). Each circle represents mean results from one year of integration.

appendix C). Knutson and Tuleya (1999) and Shen *et al.* (2000) have shown that, at least for simulations of a few days range, hurricane intensities are significantly correlated with variations in the initial thermodynamic state.

An idealized framework similar to that used in Shen *et al.* (2000) and Knutson *et al.* (1998) was used. In this framework, an idealized hurricane is introduced into different background states. The initial large-scale thermodynamic environment for the experiments was derived from the time-averaged (June to October) SSTs, temperature and water vapour from either the MCA+SC or RAS+SC GCM for each year from 1980 to 1988, so for each GCM case nine background conditions were defined. The initialization scheme of Kurihara *et al.* (1993) with some modifications (Kurihara *et al.* 1995) is applied for the hurricane-model initialization. A vortex of model-produced axisymetric and β-effect-related asymmetric components is superposed on the background field. The initial vortex has a near-surface wind speed of 17.5 m s^{-1} and a radius of maximum wind of 175 km. The hurricane model is integrated for 5 days for each set of initial conditions. Although the initial thermodynamic backgrounds were provided by low-resolution GCMs with different convective schemes to the GFDL hurricane model, the differences between the two initial mean states is approximately maintained for the 5-day integrations.

The initial vortex develops into a stronger hurricane with the background state initialized from MCA+SC than with the background from RAS+SC (Fig. 8). During the 5 days of integrations, the hurricane central pressure for the MCA+SC mean-state case intensifies by roughly 15 mb more than that for the RAS+SC mean state. The fact that all nine of the MCA+SC hurricanes are more intense than any of the RAS+SC hurricanes after the first few hours, and throughout the remainder of the 5 days, gives a confidence of greater than 99.9% that this is a significant difference when evaluated with the KS test.

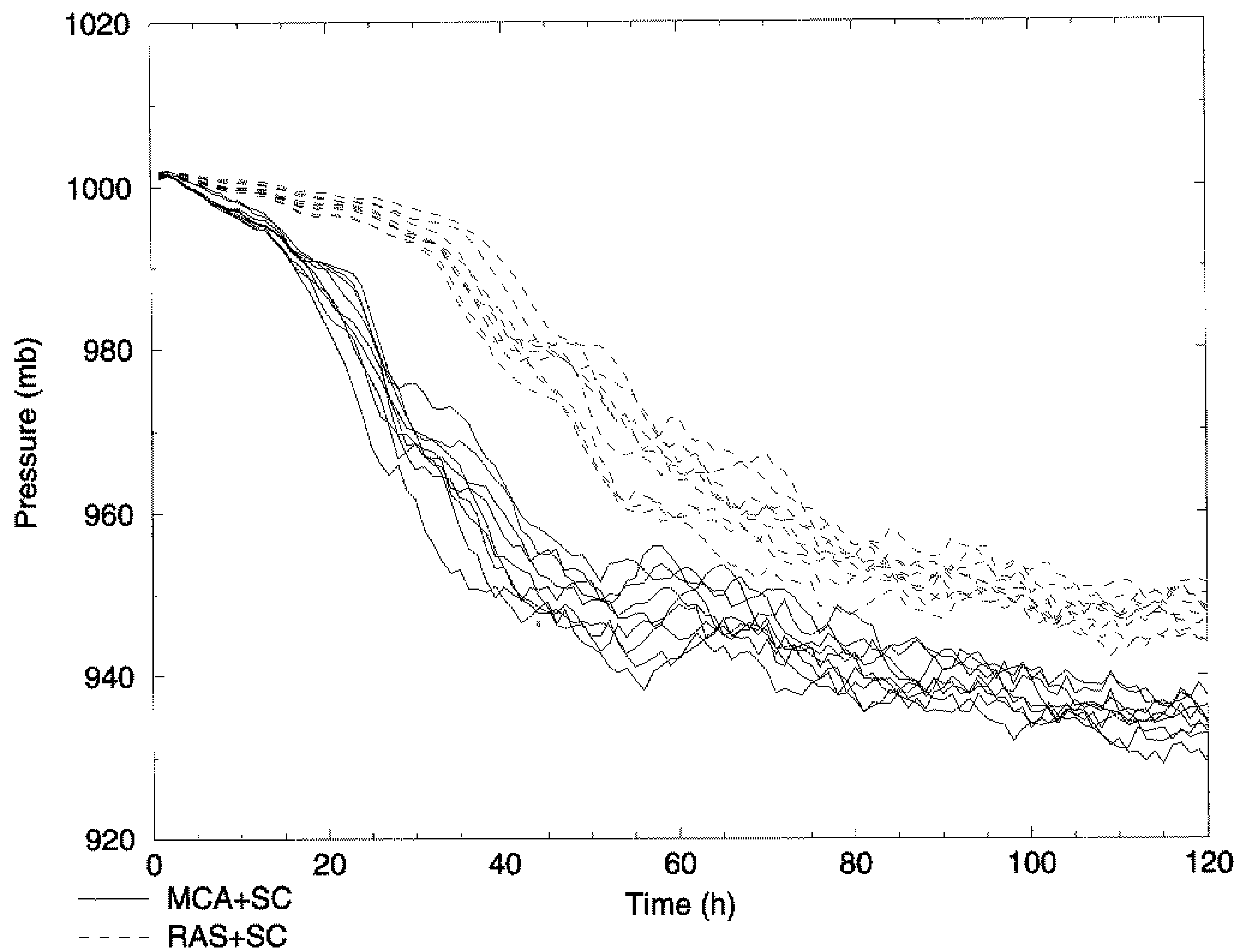


Figure 8. Evolution with time of the minimum sea-level pressure of the hurricanes simulated by the Geophysical Fluid Dynamics Laboratory hurricane model with the nine MCA+SC (see text) mean states and with the nine RAS+SC (see text) mean states under idealized initial conditions of uniform zonal flow of 5 m s^{-1} and initial vortex intensity of 17 m s^{-1}.

The only difference between the two sets of experiments is the difference in the initial temperature and moisture mean states. Therefore, the significant differences in hurricane intensities (Fig. 8) indicate that the difference in the thermodynamic profile of the mean state has a significant impact on the hurricane intensity. This is in agreement with Shen *et al.* (2000) and Knutson and Tuleya (1999) and this may be due to differences in temperature and moisture impacting on the stability of the atmosphere.

To further confirm this result, maximum potential intensities (MPIs) of hurricanes using the methodology of Emanuel (1986, 1988, 1995) and Holland (1997) were calculated for the nine thermodynamic profiles with MCA+SC and RAS+SC (Fig. 9). Emanuel's method derives an estimate of the minimum possible central pressure based on the environmental temperature and moisture profiles and the SSTs. For Emanuel's MPI calculations, a pseudo-adiabatic rather than reversible ascent is assumed and dissipative heating contributions were neglected. Holland's MPI method uses the environmental air-temperature profile as input. Both methods indicate that the MCA+SC environment should produce storms with a stronger maximum intensity than with the RAS+SC environment. This result is in agreement with the experiment using the GFDL hurricane model. However, the MPI methodologies do not agree on the strength of the difference between the MCA+SC and RAS+SC impacts on tropical-storm intensity. Both MPIs agree remarkably well to predict a minimum central pressure of about 930 mb with RAS+SC. However, Holland's MPI method predicts much stronger

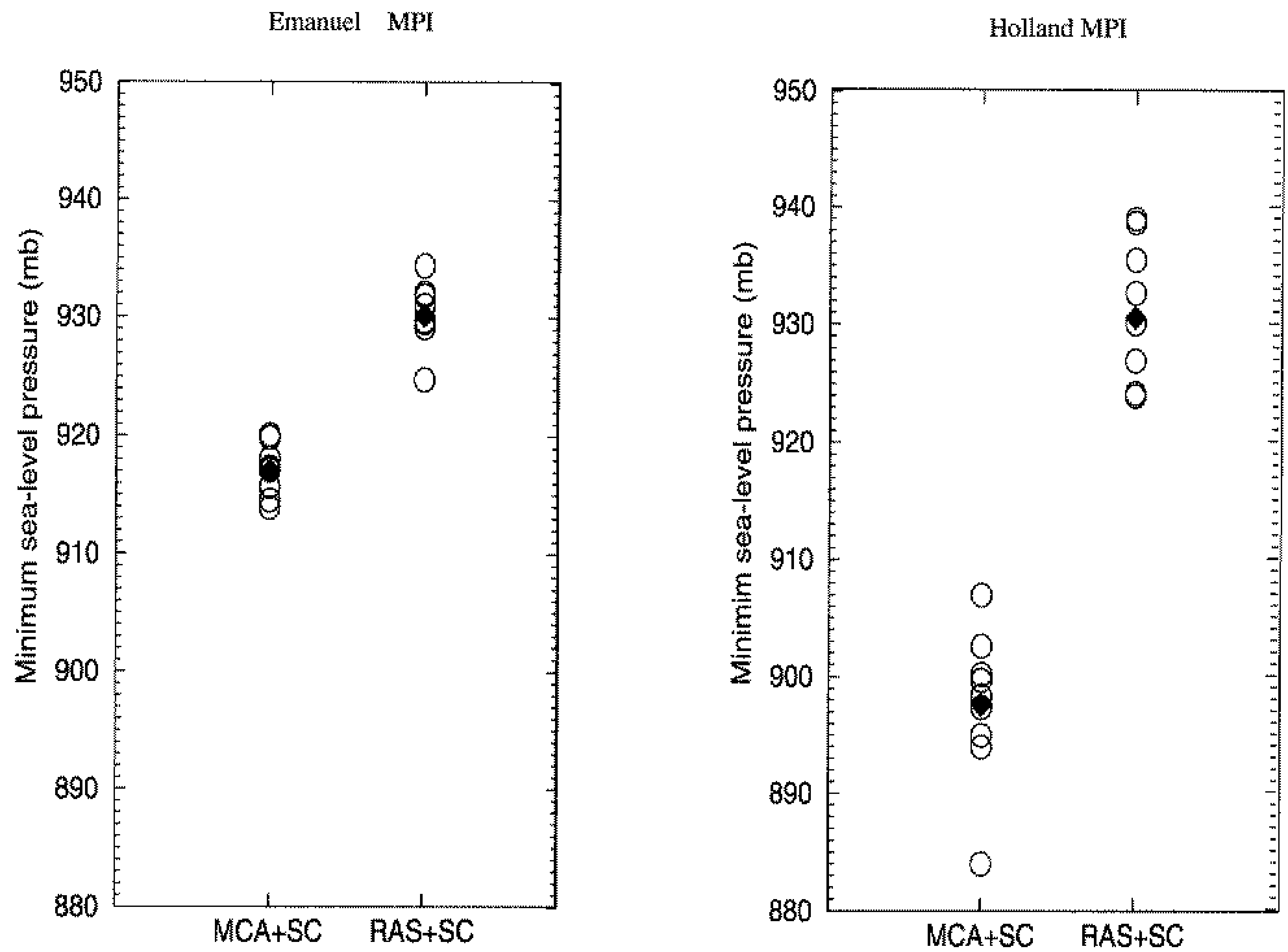


Figure 9. Ensemble distribution of Emanuel's (1986, 1988, 1995) and Holland's (1997) maximum potential intensity (MPI) of hurricanes. The MPIs were calculated from mean states averaged over the tropical western North Pacific and over the period from June to October for each year of integration.

storms with MCA+SC than Emanuel's MPI. Knutson and Tuleya (1999) noticed that Emanuel's MPI was less correlated to CAPE and CAPE90 than Holland's MPI.

In summary, the differences in thermodynamic profiles between MCA+SC and RAS+SC seem to be strong enough to explain the significant difference in the tropical-storm intensity generated by both GCMs. The GFDL hurricane model displays the same sensitivity to the thermodynamic background state. In addition, calculations of CAPE90 and MPI confirm that both profiles would produce significantly different tropical-storm intensities. The drier and colder upper troposphere with MCA+SC may explain the stronger CAPE90 and MPI with MCA+SC than with RAS+SC, in agreement with Riehl (1954) and Shen *et al.* (2000). It could also explain the difference in tropical-storm intensity between MCA+SC and MCA since MCA produces a moister and warmer environment than MCA+SC, and between RAS and RAS+SC since RAS produces a colder environment than RAS+SC (Fig. 6). Shallow convection increases the surface thermodynamic disequilibrium when applied to MCA (Fig. 6(b)). This may lead to more ocean energy input to the atmosphere, and, therefore, may also contribute to the intensification of tropical storms.

(ii) *Effect of thermodynamical changes on the position of the warm core.* A significant difference between tropical storms generated by the GCM integrations of MCA+SC and RAS+SC is that RAS+SC storms have a lower warm core (Fig. 3). When computing the CAPE, it is possible to calculate the level at which the maximum of ($T_c - T_{env}$) occurs when the parcel is lifted from the lowest level of the model. T_c represents the temperature of the parcel and T_{env} represents the temperature of the environment. The height of this maximum gives an estimate of the height of the warm core. A small difference of 10 mb is found when applying this calculation to the background thermodynamic profiles obtained with MCA+SC and RAS+SC. However, CAPE90 calculations give a difference of 50 mb, more consistent with the warm-core height differences in the GCM tropical-storm composites (Fig. 3). This suggests that the mean state may partly explain the differences in warm-core height between MCA+SC and RAS+SC. The GFDL hurricane model integrations do not show a significant difference in the warm-core position. However, the hurricane model experiment was not designed to evaluate the impact of background state on warm-core height since the initial vortex had a fixed-height warm core at about 300 mb. Additional experimentation would be required to answer this question with more confidence and to determine to what extent the warm-core structure depends on the large-scale environment, the convective parametrization and the model resolution.

(iii) *Effect of thermodynamical changes on tropical-storm frequency.* MCA+SC produces more tropical storms than RAS+SC, but the difference is very small compared with the difference in tropical-storm frequency between RAS+SC and NEWRAS+SC (section 3(a)). The results of section 3(a) indicate that the statistics of tropical storms are particularly sensitive to the suppression of deep convection. Dynamic parameters like vertical wind shear are unlikely to be the main reason for the scarcity of tropical storms in NEWRAS+SC, since this model displays a large-scale circulation that is globally close to the one simulated by RAS+SC. The previous section suggests that details of the stability of the background atmosphere may play a large role in the statistics of simulated tropical storms. Therefore, it is possible that suppressing deep convection impacts on the time-mean stability properties of the tropical atmosphere and the associated CAPE. This subsection explores this possibility by using a detailed analysis of the CAPE and its impact on tropical-storm simulations, although other factors like potential intensity or frequency and intensity of wave disturbances that initiate tropical storms, could also contribute to the difference in tropical-storm frequency between RAS+SC and NEWRAS+SC.

In RAS and the original Arakawa–Schubert schemes, CAPE can accumulate until an 'observed' threshold value is reached. After that, if there is large-scale destabilization, convection can occur. In theory, while convection is occurring, CAPE can never increase (the quasi-equilibrium assumption). In NEWRAS+SC, the background CAPE may be too low to favour tropical-storm genesis. This is not the case with RAS+SC since prohibiting deep convection prevents the quasi-equilibrium assumption from ever being enforced. If this hypothesis is correct, increasing the threshold value of CAPE for which convection can begin to occur in the NEWRAS+SC scheme, should increase the tropical-storm frequency.

A control run of NEWRAS+SC was integrated for seven August months from 1979 to 1985. Similar sets of integrations were performed with the CAPE convection threshold parameter changed by −100% (convection can occur without a minimum positive CAPE value), +20%, +40%, +60%, +80% and +100%. In each case, tropical storms were detected using the same procedure as for RAS+SC. The tropical-storm intensity is defined as the maximum sustained wind of the tropical storms detected by the objective procedure. The available seven months of integrations is a short period for this study and the number of tropical storms detected may be significantly impacted by sampling noise. To reduce this sampling problem, the number of tropical-storm days was also examined. This statistic uses the vorticity and warm-core criteria outlined in section 2 and Vitart *et al.* (1997) but does not require the storm to persist for two days or to have a maximum wind intensity.

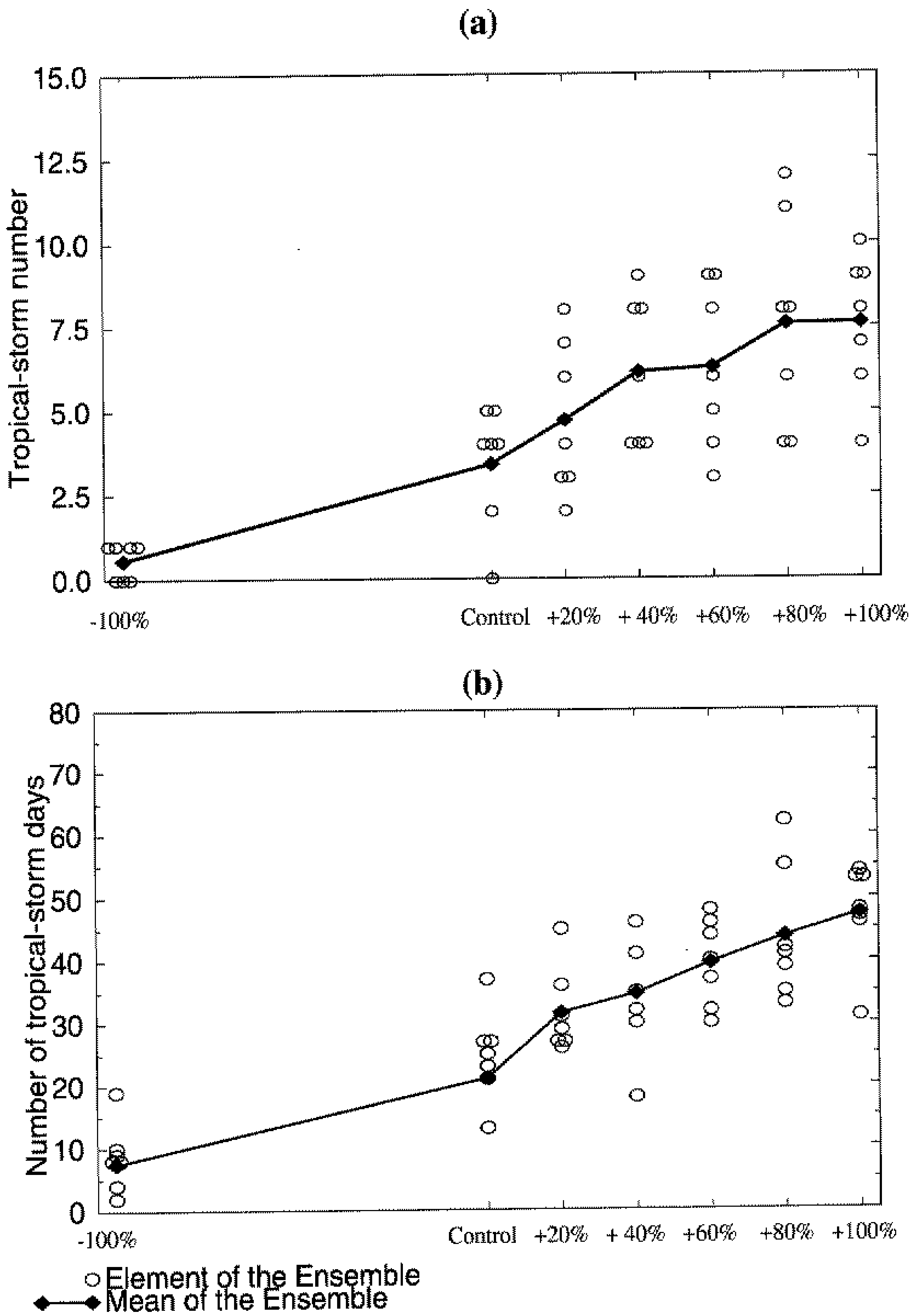
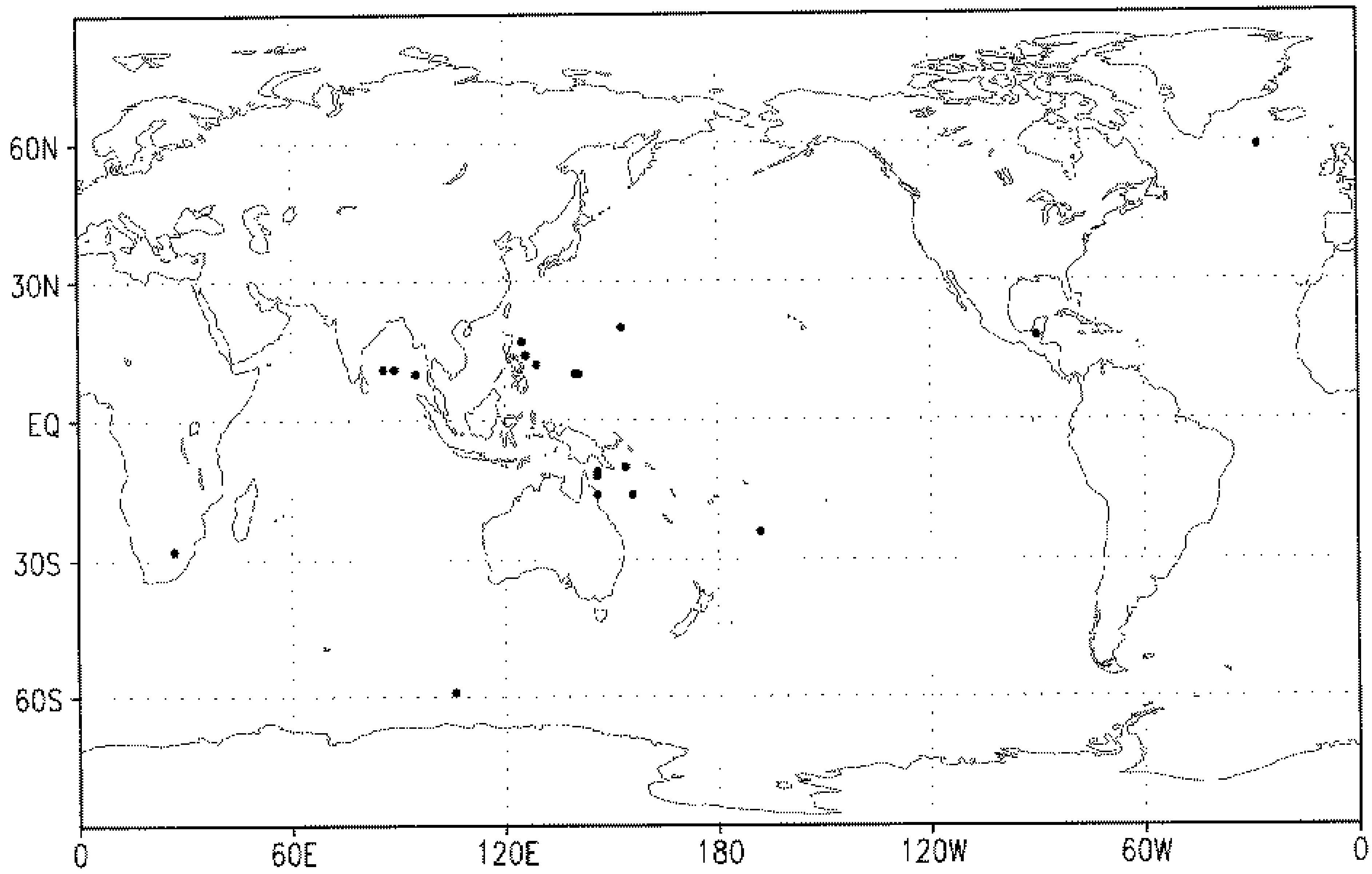


Figure 10. Ensemble distribution of (a) number of tropical storms and (b) number of tropical-storm days when changing the convective threshold criteria in RAS (see text).

The number of tropical storms and tropical-storm days increases when the convective threshold increases (Fig. 10). The significance of the difference was measured with a KS test. For tropical-storm frequency, the difference compared with the control run is significant (95% significance) for a threshold increase larger than 80%, while a threshold increase of 40% or greater results in a significant increase in tropical-storm days. The tropical-storm intensity (not shown), defined as the maximum wind velocity, does not increase significantly compared with the control run when the convective threshold is increased.

To evaluate the impact of the change in convective threshold over a complete year, NEWRAS+SC was integrated for all of 1979 with the CAPE threshold increased by

(a)



(b)

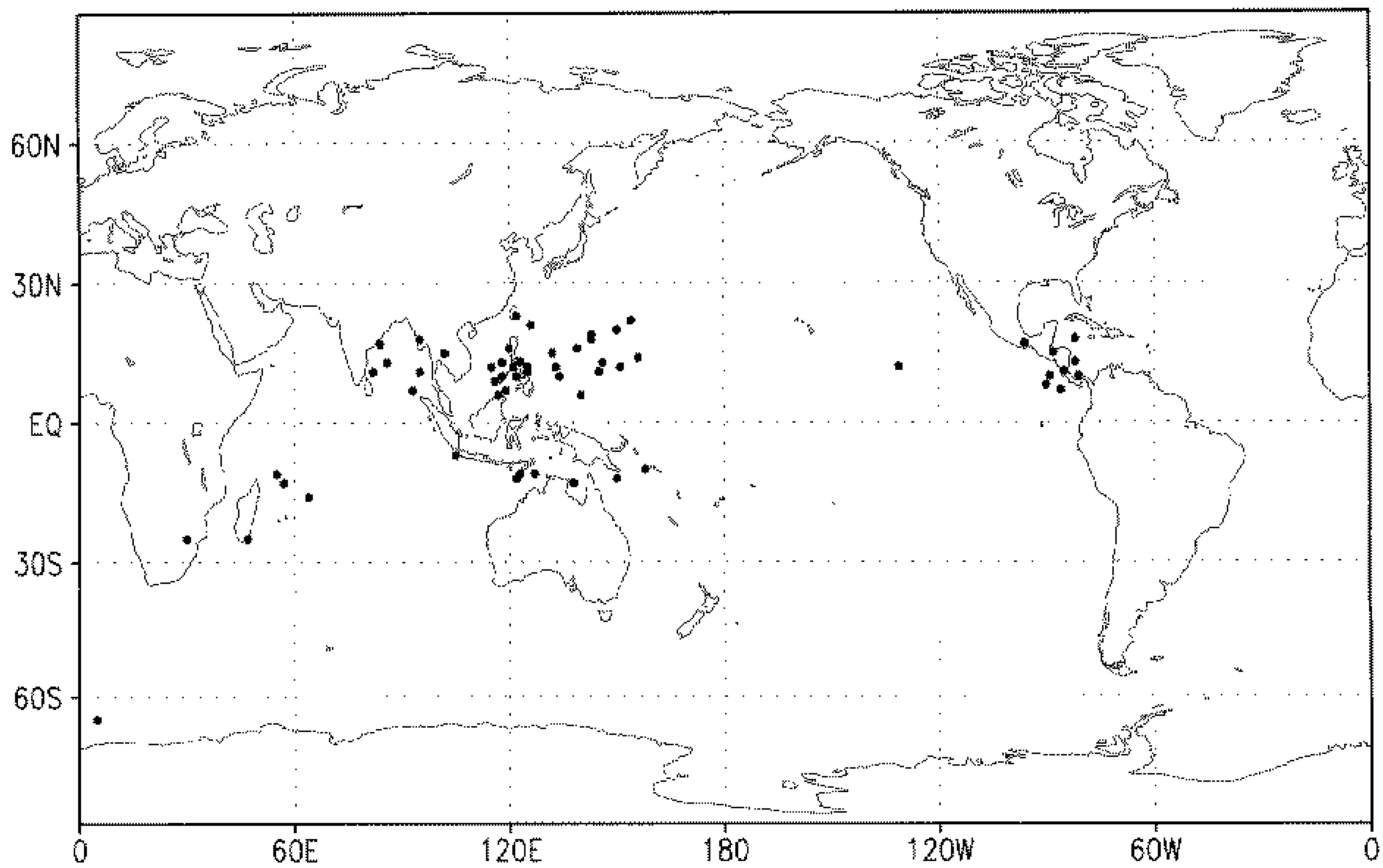


Figure 11. Tropical-storm first location simulated during one year of integration of the NEWRAS+SC (see text) scheme (a) without and (b) with a 60% increase in the convective threshold. Each point represents the first location of one simulated tropical storm in 1979.

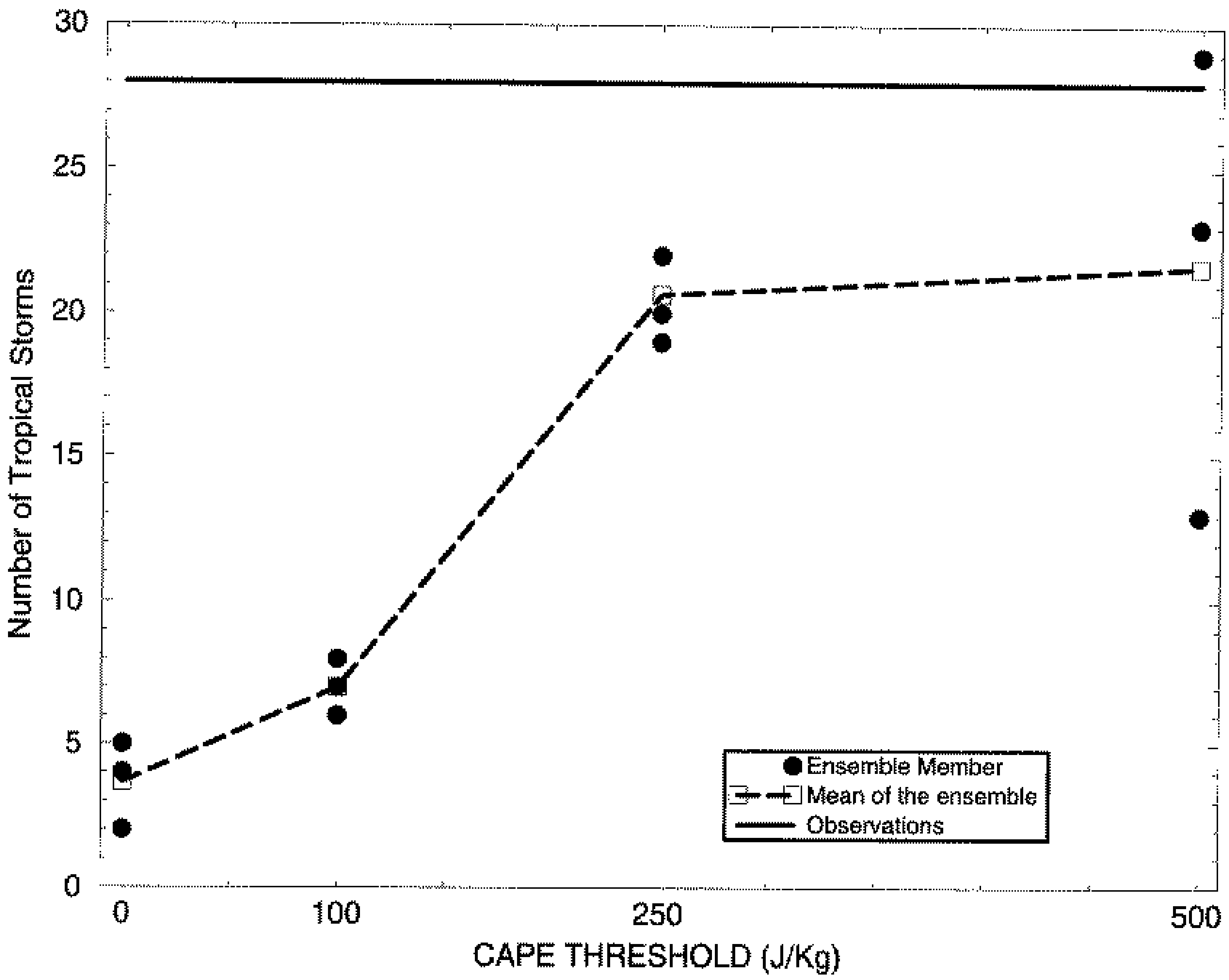


Figure 12. Ensemble distribution of tropical-storm frequency in the European Centre for Medium-Range Weather Forecasts general circulation model for June, July, August and September 1987. Each circle represents one member of the ensemble. The dashed line represents the mean of the ensemble, and the full line the observations.

60%. Fifty-seven tropical storms are detected when using this modified version of the NEWRAS+SC scheme, while only 25 were detected in the control run (Fig. 11). Additional yearly integrations would be needed to evaluate the significance of this difference over a complete year. However, the factor of two difference in the annual number of tropical storms is likely to be significant since all previous ensemble integrations (MCA, MCA+SC, RAS, and RAS+SC) display a spread in the annual number of tropical storms smaller than 25%. Increasing the convective threshold by 60% increases the CAPE over the western North Pacific by an average of 620 J kg^{-1}.

A similar experiment was performed using a model developed at the ECMWF. The atmospheric model is a T63, 31-level version of the ECMWF forecast model known as cycle 19r1. The cumulus parametrization is a mass-flux scheme from Tiedtke (1989). The model forced by prescribed varying SSTs was integrated for 4 months starting on 1 June 1987 with three different initial states and the objective procedure for tracking model tropical storms was applied. In addition to the control run (no CAPE threshold), the atmospheric model was integrated with modifications to force the deep convection to occur only if the CAPE exceeds 100 J kg^{-1}, 250 J kg^{-1} or 500 J kg^{-1}. As was the case for the GFDL model, the number of simulated tropical storms increases as the CAPE threshold increases (Fig. 12). However, the increase may not be as linear as with the GFDL model. There appears to be a value of the CAPE threshold, between 100 J kg^{-1} and 250 J kg^{-1}, above which the model produces a much larger number of tropical storms, although additional experiments would be needed to strengthen this conclusion. In the ECMWF control run, the frequency of simulated tropical storms is well below that observed (Fig. 12), but it gets closer to the observed frequency as the CAPE threshold is increased.

Values of CAPE are significantly higher with MCA+SC than with RAS+SC (Fig. 7(a)). This may explain the larger number of tropical storms with MCA+SC than with RAS+SC (section 3(a)), although the difference is not significant. These results, from both the GFDL and ECMWF models, support the hypothesis that a critical background value of CAPE is necessary in order to simulate realistic numbers of tropical storms in a low-resolution GCM. If the convective parametrization acts to keep the background CAPE small, the number of simulated tropical storms is greatly reduced. However, this result may not be valid for very-high-resolution GCMs nor for the real world. It is possible that high values of CAPE are necessary in coarse resolution GCMs to produce reasonable numbers of cyclones, as a compensation for deficient resolution, poor convection schemes, and potential intensities that are too small.

5. Discussion

Simulations of tropical storms in a GCM with a variety of convective parametrizations were examined. Parametrizations included MCA, two variants of RAS, and two variants of the Arakawa–Schubert scheme; a shallow-convection scheme was also added to MCA (MCA+SC) and RAS (RAS+SC). The sensitivity of tropical-storm frequency (both global and regional), intensity, structure, and interannual variability were documented. Global frequency was found to be relatively insensitive to changes in convective parametrization, unless those changes impacted on the CAPE of the tropical background atmosphere. Variants of RAS with modifications leading to increased background CAPE produce larger numbers of tropical storms while the original RAS version, which produces small background CAPE, produced far too few storms. The original Arakawa–Schubert parametrization also produces a low background CAPE and far too few tropical storms. However, a modification to the Arakawa–Schubert scheme (Tokioka *et al.* 1995), originally introduced to produce a stronger Madden–Julian oscillation (MJO), simulates a more realistic frequency of tropical storms along with a higher background CAPE. In either case, the background stability of the tropical atmosphere, as measured by CAPE here, appears to be a crucial factor in the simulation of transient convective features like the MJO and tropical storms in a low-resolution GCM.

The intensity and structure of the simulated tropical storms are much more sensitive than the frequency. Significant differences exist between the MCA, MCA+SC, RAS, and RAS+SC GCMs (Figs. 3 and 4). Most notable is that the RAS GCMs produce tropical storms that are weaker than the already unrealistically weak MCA storms and that have an unrealistically low warm core (for a comparison with observations see, for example, Frank (1977)), about 150 mb below that simulated by the MCA GCMs (Fig. 3).

Despite these clear deficiencies in the simulation of the details of tropical-storm structure, some variants of the RAS GCMs produce the proper number of storms globally (as noted above) and produce significantly more realistic simulations of interannual variability of tropical-storm frequency over most ocean basins. This suggests that the accuracy of the simulation of the interannual variability of the large-scale circulation is more important than the accuracy of the simulation of the tropical storms themselves. This may explain why very-low-resolution models like R15 or T42 can produce good simulations of the interannual variability of tropical storms although their resolution is clearly too coarse to capture properly the tropical-storm physics.

Despite this, it could still be argued that the deficiencies of simulated tropical storms in the GFDL or ECMWF model are primarily a result of insufficient resolution. To check this hypothesis, a three-member ensemble of 4-month integrations starting on 1

TABLE 3. TROPICAL-STORM FREQUENCY OVER THE SOUTHERN HEMISPHERE. DECEMBER 1987 TO MARCH 1988. ECMWF MODEL. RESOLUTION IS T63

CAPE threshold	Tropical-storm number
0	6
100	16
250	31
500	34

See text for further explanation.

TABLE 4. TROPICAL-STORM FREQUENCY OVER THE SOUTHERN HEMISPHERE. DECEMBER 1987 TO MARCH 1988. ECMWF MODEL WITH NO CAPE THRESHOLD

	Resolution		
	T63	T159	T319
EXP 1	1	8	11
EXP 2	10	10	7
EXP 3	4	13	12
Mean	5	10.33	10

See text for further explanation.

TABLE 5. SENSITIVITY OF SIMULATED TROPICAL STORMS

	Increase in CAPE threshold	RAS instead of MCA	Shallow convection	Increase in resolution
Global frequency	Significant increase	No significant impact	No significant impact	Small increase
Intensity	No significant impact	Significantly weaker	Significantly stronger (MCA) weaker (RAS)	Significantly stronger
Vertical position of the warm core	No significant impact	Significantly lower	No significant impact	No significant impact

See text for further explanation.

November 1987 was performed with three different resolutions (T63, T159 and T319) of the ECMWF atmospheric model discussed in section 4(b)(iii). The number of tropical storms does increase with resolution, but the increase is much more moderate than when modifying the CAPE threshold (Tables 3 and 4), and even at T319, the simulated tropical-storm frequency is only half that observed (21 tropical storms were observed). This further supports the contention that simulated tropical-storm frequency is much more sensitive to changes in cumulus parametrization than to changes in the resolution of the GCM. A summary of the sensitivity of the model tropical-storm statistics to changes in convective parametrization or model resolution is presented in Table 5.

A further clarification of the role of the large-scale thermodynamic background on tropical-storm intensity was presented using the GFDL regional hurricane model and MPI calculations. The initial background state of the hurricane model was specified directly from climatological means of the RAS+SC and MCA+SC GCM integrations. Identical initial hurricane vortices were then superimposed on the GCM background and the hurricane model integrated. The MCA+SC background state consistently led to a much stronger predicted hurricane. Furthermore, the MPI calculations qualitatively supported the conclusion that the background state can have a significant impact on storm intensity. This is in agreement with the earlier GCM results of Fig. 2.

The present study highlights the importance of the general background structure of the tropical atmosphere on the tropical storms simulated by a low-resolution GCM. Improving the details of the general structure of the tropical atmosphere can improve significantly the simulation of model tropical storms. This can also be the case for other transient phenomena in the tropics (like the MJO). However a good mean state does not necessarily guarantee a good simulation of the transients (Slingo *et al.* 1994). Further research is needed to see if convective parametrizations that support both better simulations of tropical-storm details and of the tropical background state can be developed.

Conclusions from the present study concerning the impact of background CAPE on tropical-storm frequency can only be drawn for *low-resolution* GCMs. So far, no observational evidence of the sensitivity of tropical-storm frequency to CAPE has been documented. It is possible that the sensitivity to CAPE is directly linked to the coarse resolution of the GCM. Low-resolution GCMs may not represent correctly the cyclogenesis process, which, according to observations, occurs on a 100 km scale. Future research will investigate the impact of increased CAPE in a very-high-resolution GCM.

ACKNOWLEDGEMENTS

The authors would like to thank Dr L. Donner and T. Knutson for their stimulating discussions and help, and Dr Christian Jakob and Dr David Gregory for providing experiments involving model resolution and parametrization. The authors would also like to thank the two anonymous reviewers and Kenneth R. Sperber whose comments proved invaluable in improving the present paper.

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