Multidecadal trends in tropical convective available potential energy

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[1] Time series of convective available potential energy (CAPE) calculated from 15 tropical radiosonde stations indicate mostly positive trends in CAPE during 1958–1997. Increases in CAPE are associated with increases in near-surface temperature and water vapor, consistent with previous studies. The predominantly positive trends appear mostly as a shift in the middle 1970s, consistent with the time of an apparent shift of the background state of the climate system, as documented by others. A general circulation model of the atmosphere forced by observed sea surface temperatures does not reproduce these overall increases in CAPE, although it does reproduce the temperature trends. The observed changes imply significant changes to the tropical atmosphere over the last 40 years, and potential limitations of climate model simulations. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1610 Global Change: Atmosphere (0315, 0325); 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; *KEYWORDS:* convective available potential energy (CAPE), radiosonde observations, climate change, multidecadal trends, general circulation model (GCM), convective parameterization

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1. Introduction and Motivation

[2] Convective available potential energy (CAPE), which can be calculated from radiosonde observations, is a measure of the conditional stability of the troposphere to a finite vertical displacement, as occurs during moist convection [e.g., *Emanuel*, 1994]. While specific relationships between CAPE and convective triggering, frequency, or intensity are far from clear [*Williams and Renno*, 1993; *Lucas et al.*, 1994; *Emanuel et al.*, 1994; *Brown and Bretherton*, 1997; *Mapes*, 2000], long-term changes in CAPE might be associated with changes in convective activity and the atmospheric energy budget. CAPE is thus a potential indicator of climate change.

[3] Many climate model convective schemes use CAPE as a variable for calculating convective heating [e.g., *Arakawa and Schubert*, 1974]. Thus the fidelity of model-simulated temporal and spatial variations in CAPE may also be an important indicator of model performance, particularly in the tropics. The ability to reproduce long-term observed changes in CAPE in these models would provide important validation for their capacity to simulate future changes in tropical climate.

[4] Although we know of no previous work on observations of long-term trends in CAPE, several previous studies have analyzed multidecadal records of humidity and/or temperature in the tropics. *Gutzler* [1992, 1996] has noted interannual changes in temperature and humidity over the tropical western Pacific with increases in humidity at the surface, and warming increasing with height over the period 1970–1995. *Gaffen et al.* [2000] have noted increases in surface temperature and little change in lower tropospheric temperature between 1979 and 1997 (and an associated increase in lapse rate) throughout the tropics. From 1960 to 1997, *Gaffen et al.* [2000] noted more consistent warming of the surface and lower troposphere. Increasing temperature and relative humidity (RH) throughout the depth of the tropical troposphere has also been observed in the Western Pacific by *Wang et al.* [2001] between 1976 and 1995. Similar changes were also found by *Ross and Elliott* [2001] in the tropical Pacific region, between 1973 and 1995.

[5] Several studies of tropical temperature and humidity using models have also been performed. *Graham* [1995], using a GCM, simulated upward trends in tropospheric temperatures and specific humidities consistent with *Gutzler* [1992]. *Ye et al.* [1998] examined short-term variability of CAPE in a GCM and found that both the CAPE distribution in the tropical western Pacific and the coupling between CAPE and wet-bulb potential temperature resembled observations.

[6] In this study we use radiosonde observations from selected stations in the tropics with long stable records to calculate CAPE. These records are compared to a calculation of CAPE from a climate model simulation forced by observed sea surface temperatures. Details of the CAPE calculation are discussed in section 2. The data and model used are described in section 3. Results from the radiosonde observations and model are discussed in section 4. Compar-

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isons and implications of these trends are discussed in section 5.

2. CAPE Calculation

[7] CAPE is defined as the vertical integral of a lifted air parcel's buoyancy between its level of free convection (LFC) and level of neutral buoyancy (LNB). Expressed in pressure coordinates, CAPE as used in this study is

$$CAPE = \int_{LFC}^{LNB} R_d \left(T_{parcel} - T_{env} \right) d \ln p, \qquad (1)$$

where T_{parcel} is the parcel temperature, T_{env} is the sounding environmental temperature, R_d is the gas constant, and p is pressure. Physically, CAPE provides an indication of the potential energy available for moist convection. The calculation of CAPE, however, involves a number of thermodynamic and microphysical assumptions [e.g., *Williams and Renno*, 1993; *Emanuel*, 1994]. Here we assume that the parcel ascends irreversibly along a standard pseudoadiabat. That is, the parcel is assumed to ascend without mixing with the environment, and condensed water is assumed to be instantaneously precipitated. We also assume there is no freezing, and we ignore the effects of water vapor on the buoyancy, the so-called virtual temperature correction [*Doswell and Rasmussen*, 1994]. Further, we define CAPE to be the integral of the positive portion of the parcel buoyancy only (above the LFC), while the integral of the negative portion below the LFC is called the convective inhibition or CIN. If there is more than one LFC, our procedure is to integrate over all of the multiple positive and negative areas for the CAPE and CIN, respectively. Unless otherwise stated, "near-surface" temperature and humidity used as the initial values for the parcel were taken at 990 hPa, and before the integration, all radiosonde temperature and humidity values were interpolated to a vertical resolution of 10 hPa.

[8] As with all calculations of CAPE, the above assumptions may not hold. What is important, however, is that we have calculated a measure of CAPE in a consistent fashion over time, and in a way that is less affected by potential radiosonde measurement problems. The virtual temperature correction was not applied to avoid potential biases in upper level humidity as measured by radiosondes. Interpolation of all soundings to 10 hPa resolution helps avoid time-varying biases associated with an increase in the vertical resolution of the soundings as automated reporting practices are adopted. Sensitivity tests were performed to assess the effect of changes in the vertical resolution on calculated CAPE and CAPE trends. Without vertical interpolation, CAPE calculated using only mandatory level data was generally found to be larger than CAPE calculated using all reported levels. With vertical interpolation, differences between calculations of CAPE using mandatory or all levels (including both reported mandatory and significant levels as the interpolated levels) were generally less than ±10% for any individual sounding, normally distributed around zero.

[9] Finally, some of the stations with data available at 0000 and 1200 UTC suggest diurnal variability in CAPE. We tested whether including a single observation time, or all available times, affected the trends, and found that it did not significantly change the trends, thus we include data at all available times in this analysis.

3. Data

[10] We have calculated CAPE for 15 tropical radiosonde stations for the period 1958–1997. Stations were selected upon consideration of the length and quality of the radiosonde data based on experience gained from *Gaffen* [1996] [see also *Gaffen*, 1994]. Station names and locations are indicated in Figure 3. Data records have been checked for inhomogeneities which correspond to known changes in instrumentation or reporting procedures. The data come from the Comprehensive Aerological Reference Data Set (CARDS) [*Eskridge et al.*, 1995] and the metadata are described by *Gaffen* [1996]. Inhomogeneities were defined based on a change of at least 1 standard deviation, lasting at least 4 years, in annual mean 990-hPa temperature or dew point, which corresponded to a known change in instrument, recording procedure, or station location. If the change occurred within 4 years of the ends of the records, the time constraint was relaxed. Searches for inhomogeneities were performed at other levels as well, and the change points found were generally consistent with those at the 990-hPa level. Using this method, records at five stations (Atuona, Darwin, Koror, Nandi, and Pago Pago) have been truncated. At only one of the stations (Atuona) does this truncation change the sign of the trends. We employ at least 21 years of data at all 15 stations, and 10 stations have 40 years of data. As already stated, the originating level of the parcels was taken as 990 hPa in both the observations and model. Lifting the parcels from 1000 hPa instead did not affect the sign or statistical significance of the trends described here.

[11] The climate model output comes from a simulation conducted with the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3), described by *Kiehl et al.* [1996]. This simulation is forced with observed monthly mean sea surface temperatures for the same period as the radiosonde observations (1958–1997). The model does not have changing greenhouse gas concentrations as observed, although some of the climatic response is probably contained in the SSTs. The model has T42 horizontal resolution (≈2.8°) and 18 vertical levels. The parameterization of convection in the model uses CAPE to determine the convective mass flux which removes CAPE at an adjustment timescale (e-folding time) of 2 hours [*Zhang and McFarlane*, 1995] in the absence of other forcings (CAPE closure).

[12] For the purposes of this study, we calculate CAPE from the model using daily averaged temperature and humidity. This is different than the instantaneous values of CAPE which are used in the convection scheme. Comparisons between CAPE calculated from the simulation and CAPE calculated from radiosondes are performed with the model grid point closest to each station. Because of the averaging in time and different spatial resolution of the model versus point radiosonde measurements, the two calculations of CAPE should not be expected to match. Indeed, as shown in section 4.2, the CAPE from the model is in general lower than that from the radiosondes. In terms of a gross measurement of CAPE variability, however, they

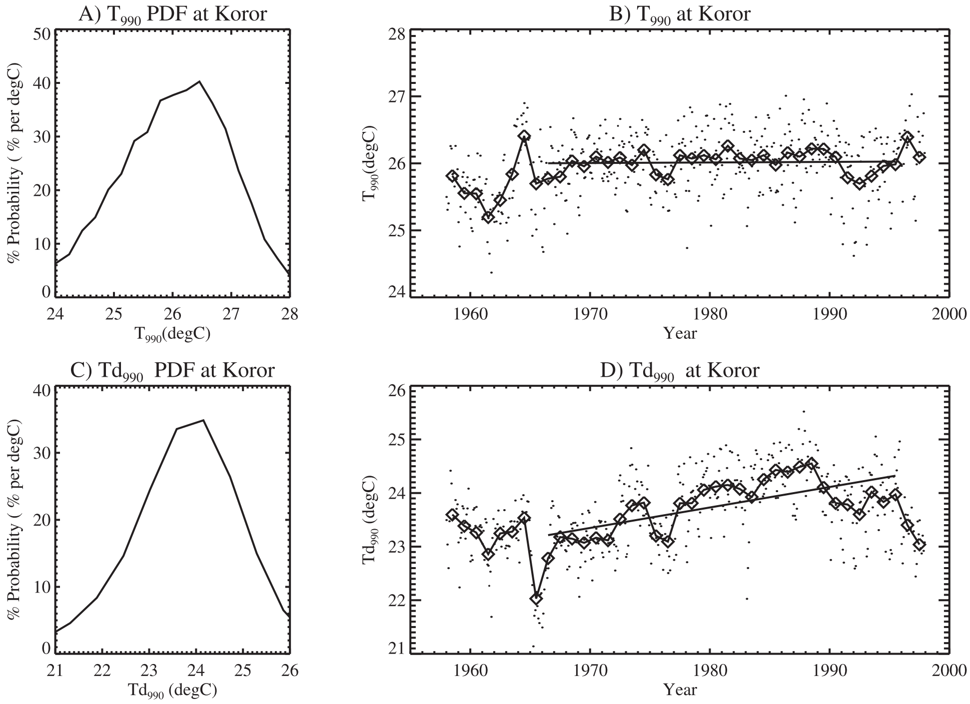

Figure 1. Thermodynamic trends for Koror. (a, b) Temperature at 990 hPa. (c, d) Dew-point temperature at 990 hPa. Left-hand panels are PDFs in percent and right-hand panels are monthly (points) and annual (diamonds) means. Straight line is a linear trend fit to the annual means.

are quite similar, as measured by the standard deviation as a percentage of the mean and the shape of the probability density function at a location. We thus believe that a comparison of trends between the model and observations should still be meaningful.

[13] The trends in CAPE and other quantities are estimated by least-squares linear regression of annual values. Soundings with zero CAPE (about 12% of the ascents) were not included. Statistical significance throughout this study is calculated at the 95% level based a two-sided T-test and an assumption of 1 degree of freedom per year [*Santer et al.*, 2000].

4. Results

4.1. Radiosonde Observations

[14] We begin our discussion of tropical CAPE trends with an example from Koror (7.3°N, 134.5°E). Figure 1 shows time series of annual mean temperature and dew point at 990 hPa. Note that the first 8 and the last 2 years of the record are not included in the trend calculations, because of sudden shifts in temperature corresponding to changes in instrument type at this station in 1965 and 1995. Despite this truncation, some 15,000 soundings are used to generate the statistics going into the calculation of trends at Koror. There is virtually no trend in temperature at 990 hPa observed at Koror, but there is a statistically significant increase in dew-point temperature of 0.4°C decade^{-1}. The distribution of individual values of temperature and dew point from each sounding is represented as a probability distribution function (PDF) in Figures 1a and 1c. Both distributions are nearly normally distributed with mean values of 26.5°C for temperature and 24°C for dew point.

[15] The near-surface values of temperature and dew point, and the environmental temperature soundings, are used to calculate the LFC, the LNB, and the resulting CAPE and CIN in Figure 2. A statistically significant trend in CAPE of 134 J kg^{-1} decade^{-1} (6% decade^{-1}) is present (Figure 2h). Values of CAPE are normally distributed about a mean of approximately 2000 J kg^{-1}, as indicated by the PDF (Figure 2g). The upward CAPE trend is accompanied by statistically significant decreases in the convective inhibition (CIN) of 5 J kg^{-1} decade^{-1} (Figure 2f). CIN values are distributed very close to zero, and the distribution falls off nearly exponentially (Figure 2e). These changes are accompanied by an increase in the pressure (decrease in height) of the LFC (Figure 2b) of 16 hPa decade^{-1} (~110 m decade^{-1}), and a decrease in pressure (increase in height) of the LNB (Figure 2d) of 5 hPa decade^{-1} (~200 m decade^{-1}). Both distributions have a sharp peak followed by a skewed tail. For the LFC (Figure 2a), the tail is toward lower pressure (higher altitudes), while for the LNB (Figure 2c), the tail is toward higher pressure and lower altitudes. These LFC and LNB trends are both significantly different from zero, and they imply that the layer of positive buoyancy is becoming deeper, consistent with the increasing CAPE. In addition, the temperature difference between 990 and 700 hPa (not shown) decreased by a statistically significant 0.2°C decade^{-1} while the temperature difference between 700 and 300 hPa (not shown) decreased by 0.1°C decade^{-1}, which is not significant. These changes imply a slight increase in the static stability of the free troposphere, while the trends in CAPE and CIN suggest more energy available for convection.

[16] CAPE trends in percent per decade for each of the 15 radiosonde stations are illustrated in Figure 3. A statistically

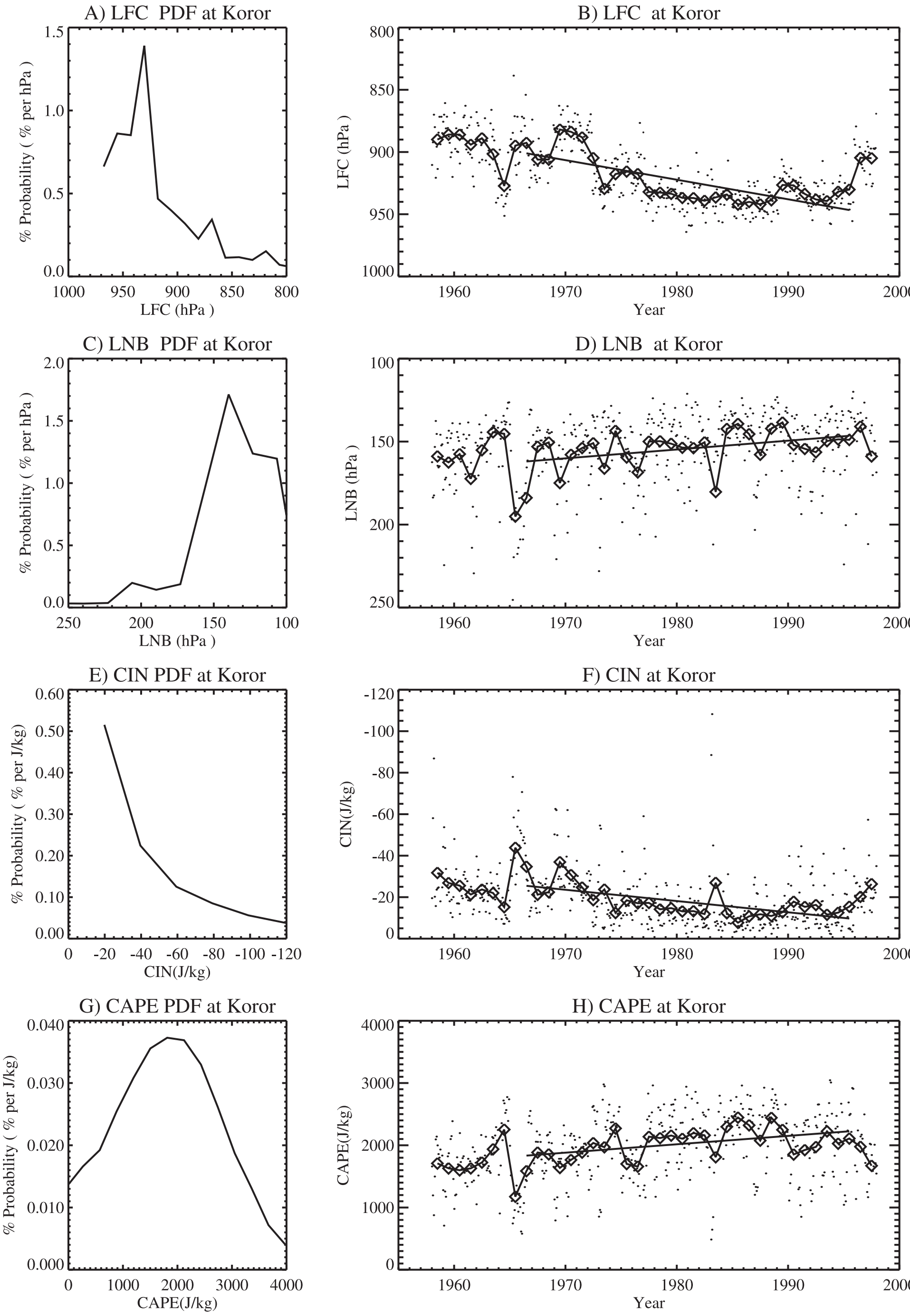

Figure 2. Trends for Koror as in Figure 1 but for (a, b) level of free convection (LFC), (c, d) level of neutral buoyancy (LNB), (e, f) convective inhibition (CIN), and (g, h) CAPE (bottom row). Left-hand panels are PDFs (in percent) and right-hand panels are monthly (points) and annual (diamonds) means. Straight line is a linear trend fit to the annual means.

significant result is indicated by solid triangles, with the direction indicating the sign of the trend. Most stations show evidence of long-term increases in CAPE, particularly in the Western Pacific region. Most of the CAPE increases can be associated with increases in temperature and/or moisture at 990 hPa. At only three stations were decreases in CAPE found, and only one is significantly different from zero.

[17] "Overall" tropical trends, based on data at the 15 stations, were computed in three ways. One method involved creating a time series of annual anomaly values based on the median of the anomalies at the 15 stations each year. A second method was similar to the first, but used the mean of the station anomaly values. The third method was to compile the median of the 15 station trend values, computed separately for each station. These methods generally agree to within 20%, except in some cases where an outlier alters the mean. The median is used to mitigate the effect of outliers. Figure 4 shows overall trends, computed

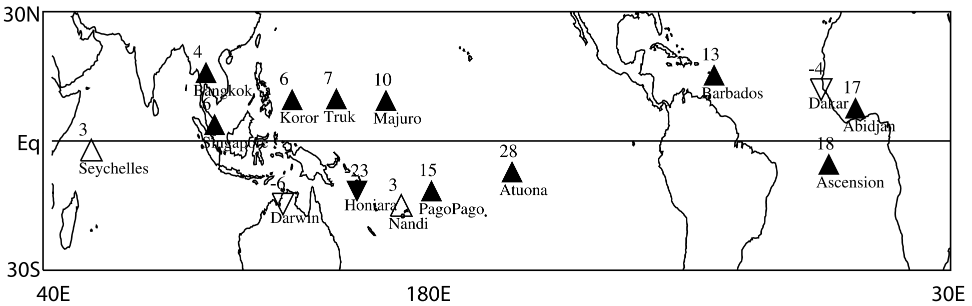

Figure 3. Radiosonde CAPE trends. Triangle direction indicates an increasing (upward) or decreasing (downward) trend. Solid symbols indicate a statistically significant trend at the 95% level. The magnitude of the linear trend in % decade^{-1} is printed above each station, and station names are printed below.

using the first of these three methods, for CAPE, CIN, and the pressure of the LNB and LFC. The collective station records indicate increasing pressure of the LFC and decreasing pressure of the LNB, consistent with the trends at Koror in Figure 2. There is a slight decrease in CIN, and an increase in CAPE of 86 J kg^{-1} decade^{-1} or 6% decade^{-1}.

[18] Examination of temperature and dew-point data yields further insights on these trends. Overall temperature trends near the surface and various levels above are illustrated in Figure 5. Temperature and dew-point generally increased significantly over 1958–1997 at the locations of the radiosonde stations. This change is consistent with the analyses in the western Pacific by *Gutzler* [1996]. The near-surface temperature increases are accompanied by similar or slightly larger increases in the temperature at upper levels, such that the temperature difference between the surface and the lower troposphere and the lower and middle troposphere declines slightly (increasing stability), as illustrated in Figure 5. These changes in lapse rates are consistent with lapse rates over the 1960–1997 period analyzed by *Gaffen et al.* [2000]. Thus the contributions to increasing CAPE on this timescale appear to be increases in temperature and moisture near the surface. This result is consistent with that found for the day-to-day timescale by others [e.g., *Williams and Renno*, 1993; *Ye et al.*, 1998]. The multidecadal trend in stability, on the other hand, would tend to reduce CAPE. Increases in the depth of the layer between the LFC and the LNB could be caused by an increase in temperature near the surface. The decrease in pressure of the LNB is consistent with observations of decreasing tropopause pressures [*Seidel et al.*, 2001] possibly associated with convective overshoots of a higher (lower pressure) LNB.

[19] The median annual anomaly time series from the collective stations for temperature at 990 hPa, dew point at 990 hPa, and CAPE are illustrated in Figure 6, and demonstrate the upward trends discussed above. Clearly, these are not monotonic trends; there appears to be a "shift" in the middle 1970s when observed 990-hPa temperature (Figure 6a) and dew point (Figure 6b) both increase by 0.2–0.5°C. These anomalies are not due to sudden jumps at any particular station (which would have been identified by the quality checking procedure described in section 3), but rather represent slight increases at all the stations. The temperature changes correspond to an increase in median CAPE of about 300 J kg^{-1} (Figure 6c). This shift has been previously documented as a change in the background state of the climate system by *Trenberth and Hurrell* [1994] and

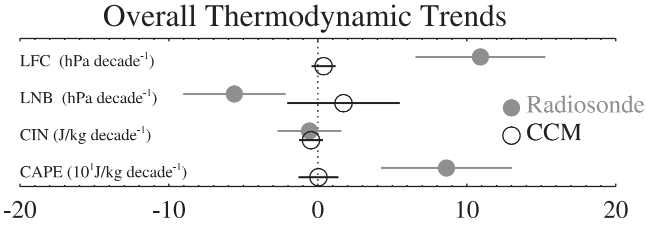

Figure 4. Overall tropical radiosonde (solid circles) and CCM (open circles) trends in LFC (in hPa decade^{-1}), LNB (in hPa decade^{-1}), CIN (in J kg^{-1} decade^{-1}), and CAPE (in 10^1 J kg^{-1} decade^{-1}). Trends are indicated by the circle, and the 95% confidence interval is indicated by the horizontal bar.

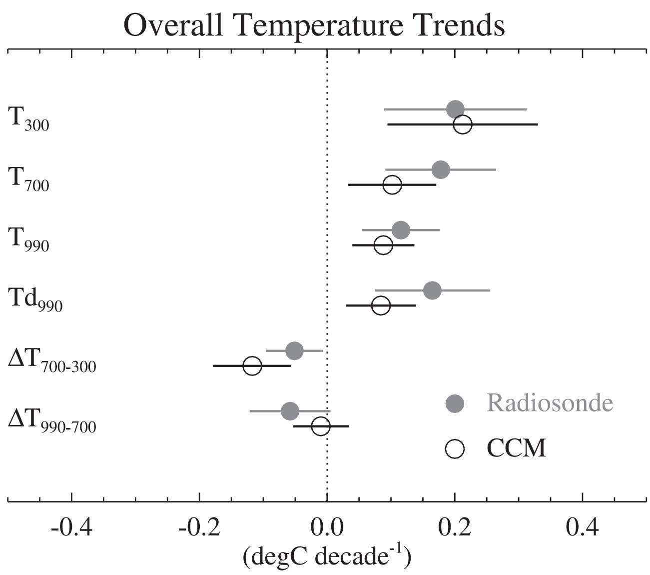

Figure 5. Overall tropical radiosonde (solid circles) and CCM (open circles) trends (in degC decade^{-1}) for temperature at 300 hPa (T_{300}), temperature at 700 hPa (T_{700}), temperature at 990 hPa (T_{990}), dew-point temperature (Td_{990}), temperature difference 700–300 hPa ($T_{700-300}$), and temperature difference 990–700 hPa ($T_{990-700}$). Trends are indicated by the circle, and the 95% confidence interval is indicated by the horizontal bar.

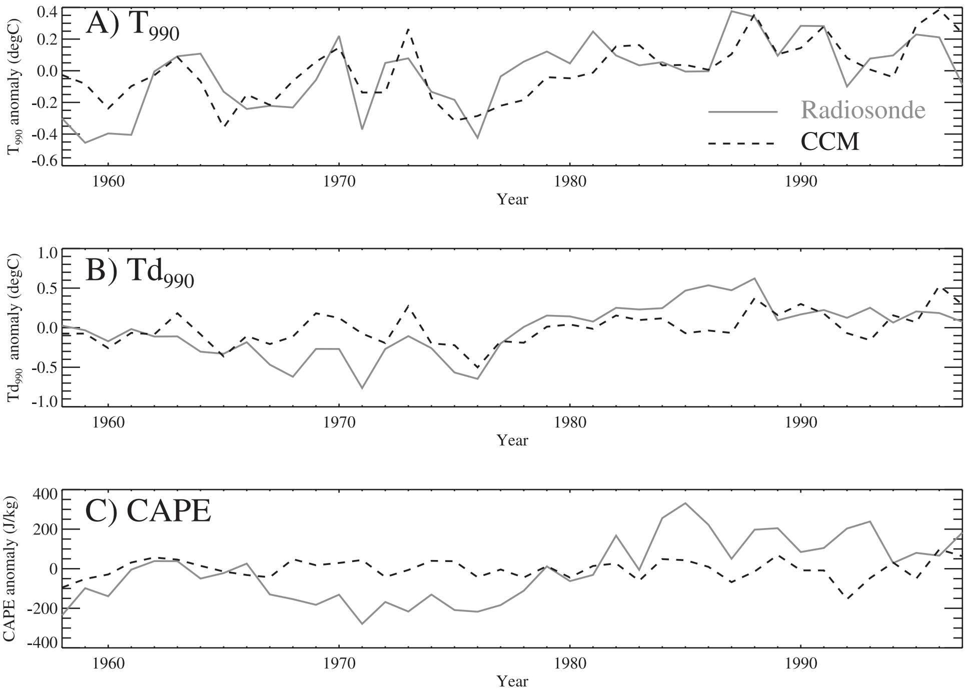

Figure 6. Radiosonde (solid line) and CCM (dashed line) median annual anomalies from the collective 15 station locations for (a) temperature at 990 hPa (T_{990}), (b) dew-point temperature (Td_{990}), and (c) CAPE.

Wang [1995]. The step-like increases in CAPE are also consistent with a step-like increase in precipitable water documented by *Gaffen et al.* [1991].

4.2. GCM Simulations

[20] These observed changes can be compared to CAPE calculated from the CCM simulation. Despite the differences between the observations and the model, as discussed in section 3, the simulated and observed median anomaly time series of temperature (Figure 6a) and near-surface dew-points (Figure 6b) are significantly correlated (correlation coefficients of $\sim$0.7). However, as seen in Figure 6c, modeled and observed CAPE anomalies for all stations show little resemblance (correlation coefficient of 0.12).

[21] As indicated in Figure 5, the model reproduces the overall temperature trends at the station locations, although the magnitudes of the changes are slightly lower than observed. In particular, the simulation indicates increasing 990-hPa temperatures and specific humidity (Figure 5), but with virtually no change in relative humidity (not shown). As shown in Figure 4, however, the simulation does not have significant overall trends in LFC, LNB, or CAPE. Such a result is perhaps to be expected because the model convective parameterization eliminates CAPE at some rate [*Zhang and McFarlane*, 1995] and thus sets some limit on the amount of CAPE which occurs.

[22] The shift in the middle 1970s in observed temperature and humidity (Figure 6) is partially captured by the simulation. However, it is clear from Figure 6c that the simulation does not have the same shift in CAPE at the station locations. Also, there is low-frequency variability in the CAPE derived from radiosondes before 1975 in Figure 6c that is not captured by the simulation.

[23] Maps of CAPE trends throughout the tropics in the CCM simulation (Figure 7) confirm this picture. The climatological distribution of CAPE in the simulation is shown in Figure 7a. Highest values are found over the tropical continents and the tropical western Pacific. CAPE trends (Figure 7b) are largest in both percentage or absolute terms where CAPE in the simulation is small, reaching 20% decade^{-1} in the eastern Pacific. The trend patterns in Figure 7b are perhaps somewhat consistent with the limited station data, for instance indicating decreasing CAPE over the northern edge of Australia near the stations of Darwin and Honiara (compared with Figure 3). The overall picture from the radiosondes of generally increasing CAPE is not reproduced, however. Decreases in CAPE are also noted in the subtropics in the simulation. The largest increases in simulated near-surface temperature (Figure 7c) and dew point (not shown) also occur in the eastern Pacific. Relative humidity is nearly constant over the decadal timescale in the simulation.

5. Discussion

[24] We have observed increases in CAPE at 12 of 15 tropical radiosonde stations during 1958–1997. These changes appear to be driven by increases in near-surface temperature and/or humidity, in agreement with previous radiosonde analyses of tropical temperatures and humidity [e.g., *Gutzler*, 1992, 1996; *Gaffen et al.*, 2000]. Some stations show significant changes in relative humidity. On average, the temperature differences between levels do not change much. Observed temperature and CAPE trends also mostly appear as a shift in the middle 1970s, also in agreement with other studies [e.g., *Trenberth and Hurrell*, 1994; *Wang*, 1995].

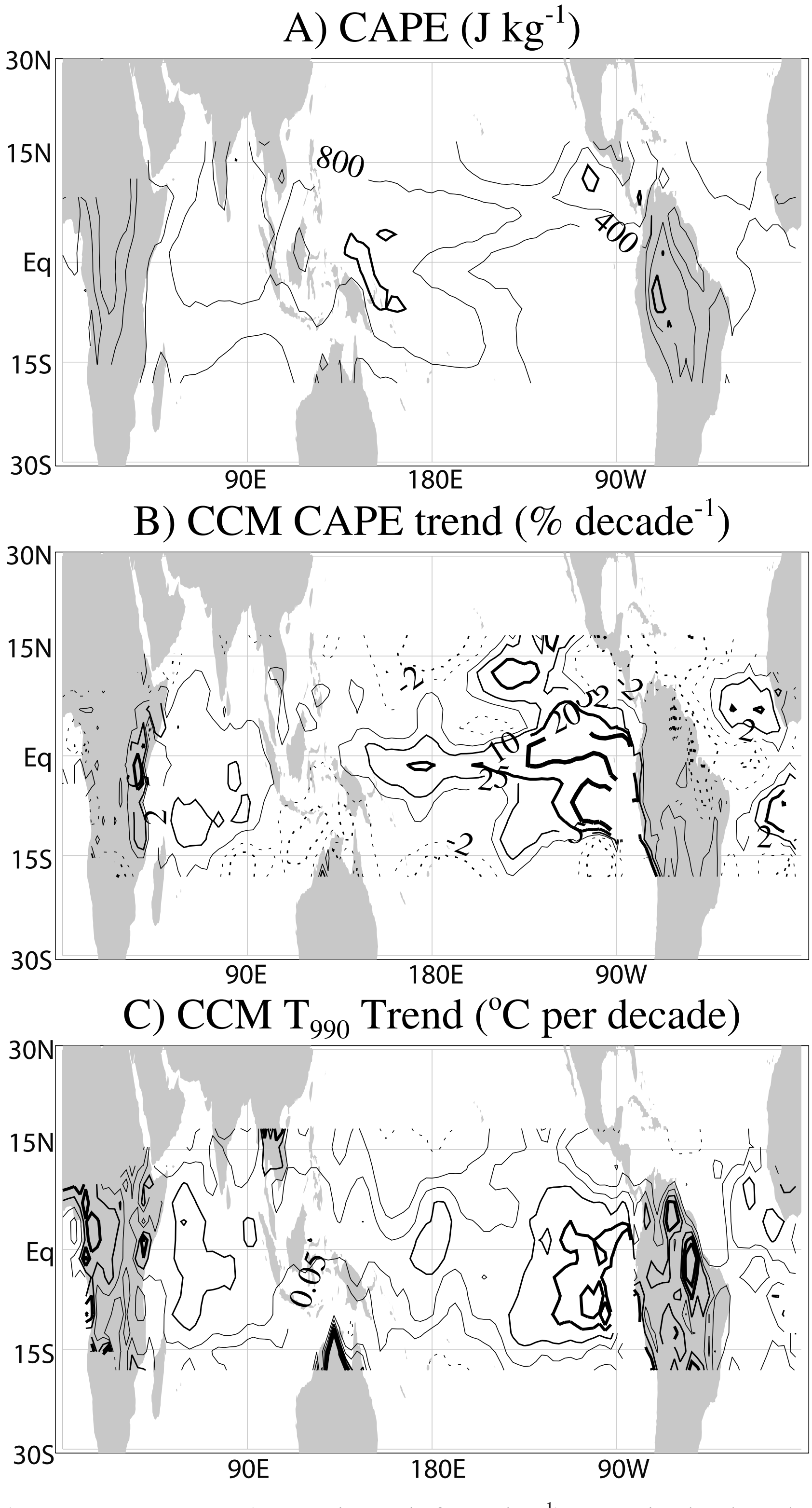

Figure 7. (a) Average CCM CAPE (contour interval of 400 J kg^{-1}). CCM simulated trends (1958–1998) in (b) CAPE (contours at ±20, 10, 5, and 2% $decade^{-1}$; negative contours are dashed), and (c) temperature at 990 hPa (contour interval of 0.05°C $decade^{-1}$ with no zero line; negative contours are dashed).

[25] Sensitivity studies conducted on the CAPE calculation indicate that the trends are not strongly sensitive to the way the calculation is performed, or to the changing number of levels in the sounding data. In addition, data records were checked for abrupt jumps that coincided with changes in station location, type of radiosonde, or reporting practice. The records of five stations were truncated to avoid those artificial changes in the records. However, we have not

eliminated possible time dependent biases, perhaps the most serious being possible changes in near-surface temperature due to increased human activity near the stations (an "urban heat island" effect).

[26] A model forced by observed changes in sea surface temperatures over the same period does not reproduce an increasing CAPE at the majority of the station locations. The simulation does, however, reproduce overall increases in temperature and dew points in the tropics, consistent with other GCM simulations by *Graham* [1995]. The simulation also reproduces observed shifts in temperature and humidity near the surface in the middle 1970's. *Wang* [1995] attributes this shift to changes in SSTs, so it is not surprising that the model (forced by observed SSTs) is able to reproduce this change.

[27] The lack of an overall increase in tropical CAPE in the simulation is also perhaps not surprising: The model is designed to eliminate CAPE when it appears by lifting parcels from below the cloud layer with a constant relaxation timescale. More CAPE is destroyed if more is present. A complication for the interpretation of the model trends, however, is that we diagnose CAPE in the model from daily average temperature and moisture values, after the simulation has undergone its convective adjustment. Like the CAPE, the model relative humidity is also essentially constant on the timescale of the trends. Simulated temperature trends are slightly lower than observed trends at 990 and 700 hPa, but larger at 300 hPa than observed. Trends in modeled near-surface temperature and humidity are largest in the eastern Pacific.

[28] The magnitudes of the observed trends in CAPE indicate that there have been significant changes to the convective stability, at least by this measure, of the tropical atmosphere over the 40-year period examined. One may speculate that radiative forcing due to greenhouse gases may be the ultimate cause of these changes in CAPE. However, we also examined the variations in CAPE in a simulation of the NCAR Climate System Model (the same atmospheric GCM discussed in section 3 but coupled to an ocean model) and forced with changing greenhouse gases and aerosols in the twentieth century. Like the atmospheric GCM, the coupled model did not reproduce the observed trends in CAPE over the period examined (1958–1997), either. As in the CCM3 simulation, relative humidity in the coupled model also remained essentially constant. Thus there are observed trends in CAPE that appear to be unable to be captured by climate models that use CAPE closure in their convective schemes. Diagnosed CAPE from such simulations does not appear to respond to climate shifts, even when these are imposed through the SST field.

[29] In summary, CAPE is perhaps a sensitive diagnostic of changes to the atmosphere. CAPE may be a useful diagnostic for climate model simulations, and an indicator of model skill at reproducing observed climate changes. Here, we have shown that observed CAPE has mostly statistically significant positive trends over the period of 1958–1997 in the tropics, yet a modern climate model is not able to reproduce these trends. Ensuring future models can faithfully reproduce such trends is perhaps quite important for enhancing confidence in model predictions of future climate changes.

[30] **Acknowledgments.** We would like to thank the staff of the Climate and Global Dynamics division at NCAR for supplying the model simulations used in this study. We would also like to thank C. S. Bretherton, E. D. Maloney, J. K. Angell, S. K. LeDuc, and three anonymous reviewers for comments.

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