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Joint variations of temperature and water vapor over the midlatitude continents

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Abstract. We have used warm-season data from the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains site to investigate the joint variability of the temperature and moisture soundings, and their relationship to the variability of the generalized convective available potential energy (GCAPE). The actual temperature and humidity soundings vary together in such a way as to produce variations of the GCAPE which are far smaller than those which would occur if the relative humidity varied while the temperature sounding was fixed, or vice versa.

1. Introduction

Cumulus convection converts the potential energy of a dry-statically-stable mean state into the kinetic energy of the convection. In order for such a conversion to be possible, a portion of the potential energy of the mean state must be "available," i.e. convective available potential energy (CAPE) must exist; a sounding for which the CAPE is positive is said to be conditionally unstable.

Broadly speaking, conditionally unstable soundings are characterized by high moisture contents, necessarily concentrated at lower levels, and by relatively steep (but dry statically stable) lapse rates. A given sounding can be destabilized, in the sense of conditional instability, by increasing its moisture content, by warming at low levels, or by cooling aloft. Convection feeds back by drying the column through precipitation, warming aloft through latent heat release and upward energy transport, and cooling near the surface as a result of convective-scale, precipitation-driven downdrafts and the attendant evaporation of rainwater. Through these feedbacks, convection tends to reduce the CAPE, by converting it into convective kinetic energy, which is then dissipated and/or radiated away in the form of gravity waves.

Manabe et al, (1965), Arakawa (1969), and Arakawa and Schubert (1974; hereafter AS) proposed that the intensity of convection is approximately that required to consume the CAPE (or more precisely the cloud work functions associated with a spectrum of cloud types) as rapidly as it is generated by non-convective processes (also see Emanuel et al., 1994, and Randall et al., 1997). Many large-scale atmospheric circulation models today use cumulus parameterizations in which the strength of the convective activity is determined by making use of some version of this "CAPE quasiequilibrium" hypothesis, hereafter called the QE hypothesis. Because the QE hypothesis can be used to determine the strength of the convection, it is often described as the "closure" of the convection parameterization.

As explained by AS, the QE closure is expected to be a useful approximation when the statistical properties of the convective cloud field can respond or "adjust" rapidly to variations in the state of the atmosphere. The approximation is useful when the adjustment time scale for the convection is significantly shorter than the time scale on which the atmospheric state is evolving. Obviously QE is favored if the atmospheric state is evolving slowly, and conversely the QE approximation breaks down for rapidly evolving atmospheric states.

As discussed by AS and Randall et al. (1997), a key prediction of the QE hypothesis is that the observed CAPE should be "small" compared to that which would occur if convection could somehow be suppressed so that non-convective processes could have their way with the sounding. The key point is that, according to the QE hypothesis, the convection consumes the CAPE (almost) as rapidly as non-convective processes generate CAPE. Even when there is a steady supply of CAPE through surface heating and evaporation, large-scale lifting, etc., the CAPE actually seen in the sounding never increases very much (according to the QE hypothesis), because the convection responds very quickly and consumes the CAPE as fast as it is generated. It is this predicted "smallness" of the CAPE that is used to test the QE hypothesis in the present study.

The CAPE is a functional of the temperature and water vapor soundings. Broadly speaking, the CAPE can be increased by steepening the lapse rate of temperature, and/or by increasing the water vapor content of the column. According to the QE hypothesis, the temperature and water vapor soundings change with time in such a way that the CAPE is relatively invariant. For example, the QE hypothesis suggests that a steepening of the lapse rate should be accompanied by a drying of the column. It follows that one way to test the QE hypothesis against observations is to assess the extent to which changes in the temperature and moisture soundings produce mutually cancelling changes in the CAPE.

Most studies of the thermodynamic structure of the convective atmosphere have been based on tropical oceanic soundings. This is understandable, because the widespread convection over the tropical oceans is very important for the general circulation of the atmosphere. Nevertheless, there is much to be gained by investigating the properties of conditionally unstable soundings over the midlatitude continents, and this is especially true for studies aimed at evaluating the QE hypothesis. Both temperature and moisture are much more variable over the midlatitude continents than they are over the tropical oceans, permitting, in principle, much larger variations of the CAPE. The reasons for this are well established. Most obviously, the daytime surface sensible and latent heat fluxes over the continents are much stronger than those over the oceans. In addition, large-scale-dynamical effects strongly limit temperature excursions in the tropics, relative to middle latitudes. In the tropics, the smallness of the Coriolis parameter leads to very flat temperature and surface pressure distributions (Charney, 1963). The larger Coriolis parameter of middle latitudes permits the sharper horizontal pressure gradients associated with more dramatic horizontal temperature gradients. As a result, the horizontal advection of temperature plays a much stronger role in midlatitudes than it does in the tropics, and the

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temporal variability of temperature is much larger in midlatitudes than in the tropics. Moisture fluctuations also tend to be stronger in midlatitudes. Examples of the tendencies of temperature and moisture due to horizontal advection are shown in Fig. 3 of Randall and Cripe (1999), for both midlatitude and tropical cases. The contrast between the tropics and middle latitudes is very apparent in their figure.

In summary, the convective regimes of the midlatitude continents in the warm season provide very useful opportunities for testing the QE hypothesis. These opportunities have rarely been taken advantage of, up to now. Kao and Ogura (1987), Grell et al. (1991), and Wu (1993) reported observational tests of the QE hypothesis with midlatitude continental data. All of these studies provided support for the QE hypothesis, but much further investigation is needed.

In this paper we report the use of warm-season data from the Oklahoma ARM site (ARM is the Atmospheric Radiation Measurements program sponsored by the U.S. Department of Energy) to test the QE hypothesis in a new way. To date, most observational tests of the QE hypothesis, whether in the tropics or midlatitudes, have involved complex analyses of the tendencies of the CAPE due to various processes, notably including the difficult-to-observe large-scale vertical motion. In contrast, the new approach reported here is very simple, and we hope that its simplicity adds to its utility. A preliminary test of this approach was reported by Randall et al. (1997; see their Fig. 2).

Section 2 of this paper provides some background on the version of the CAPE used in our study. Section 3 describes the data used. Section 4 presents our results. Section 5 gives a concluding discussion.

2. GCAPE

A key variable in our analysis is the "generalized CAPE" or GCAPE, which was introduced by Randall and Wang (1992; hereafter RW; also see Wang and Randall, 1994). The GCAPE is defined using Lorenz's (1978, 1979) concept of Moist Available Energy (MAE). Briefly, Lorenz showed that, with a suitably defined moist enthalpy, the sum of the total moist enthalpy of the atmosphere (denoted by H) and the total kinetic energy of the atmosphere (denoted by K) is invariant under both dry adiabatic and moist adiabatic frictionless processes, i.e.

$$H + K = \text{constant}. \tag{1}$$

Suppose that the mass of the atmosphere is reversibly rearranged so as to minimize H, i.e. $H \rightarrow H_{\min}$. The difference between H and $H_{\min}$ represents the maximum possible kinetic energy that can be realized through adiabatic frictionless processes; Lorenz (1978) identified this difference as the MAE. The MAE is a generalization of the concept of available potential energy, which was introduced by Lorenz (1955).

As discussed by RW, the MAE present in a conditionally unstable sounding is the GCAPE of that sounding. The GCAPE is the maximum amount of kinetic energy that can be generated by convection through conversion from the nonkinetic energy of the sounding, via adiabatic frictionless processes. The GCAPE is a more general concept that the conventional CAPE, in two respects. First, the GCAPE can be computed without assuming that the convective updrafts originate at any particular level. This is important for the data used in this study, because it was collected in a regime for which convection is known to originate aloft on some occasions. Second, the GCAPE takes into account the work done in making the dry statically stable environment subside around the moist ascending air. A method to compute the GCAPE is described by RW.

3.Data

We have used data from the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site, located in north-central Oklahoma and south-central Kansas. Data are gathered daily at the SGP site by various automated instruments and sensors. In addition, several intensive observation periods (IOPs) are held each year, each lasting three to four weeks. During an IOP, radiosondes are launched every 3 hours, from a location at the center of the site and also from 4 positions around its perimeter (see Figure 1 in the paper of Randall and Cripe, 1999). The soundings used in this study were collected during seven ARM IOPs: April 1995, July 1995, April 1996, July 1996, July 1997, May 1998, and July 1999. Precipitation data for each IOP were obtained from the Oklahoma State University mesonet system. Randall and Cripe (1999) and Ghan et al. (2000) present further discussion of the ARM SGP data.

4. GCAPE variability

During each IOP, both the temperature and water vapor soundings undergo large fluctuations. The GCAPE also varies considerably. As discussed earlier, the QE hypothesis states that the temperature and water-vapor soundings vary together in such a way as to prevent large values of the GCAPE from occurring. In other words, the QE hypothesis states that the temperature and water-vapor profiles evolve together in such a way that the values of the GCAPE which are actually observed are systematically smaller than those which would occur if the given set of temperature profiles (over an IOP, say) were randomly paired with the given set of water-vapor profiles. We decided to pursue this idea as a test of the QE hypothesis.

A practical issue is that random pairings of observed temperature and water vapor soundings can lead to relative humidities which greatly exceed 100%. To avoid this, we can randomly pair observed temperature soundings with observed relative humidity (*RH*) soundings from the same IOP.

A further practical problem is that exhaustively pairing N temperature profiles with N *RH* profiles produces N^2 pairs -- easily reaching tens of thousands of pairs for a typical IOP with between one and two hundred soundings. To avoid this, we modify our strategy by pairing the IOP-averaged *RH* profile with the ensemble of temperature profiles for the IOP; this procedure yields just N pairs of temperature and humidity soundings.

In summary, we carry out the following steps:

1. Acquire N soundings of temperature and water-vapor from an IOP.
2. Compute the time-sequence of N GCAPEs from these N soundings.
3. Compute the observed IOP-averaged *RH* at each level.
4. Using each of the observed N temperature profiles, construct a "hypothetical" water-vapor profile from the observed temperature profile and the IOP-averaged *RH* profile.
5. Compute N "hypothetical" GCAPEs from the observed temperature profiles and the hypothetical water-vapor profiles.
6. Make a scatter diagram by pairing the results of Step 5 with the results of Step 2, for the same observation time. Such a diagram shows the effects of *RH* variations on the GCAPE. If *RH* variations have no effect on the GCAPE, all points will fall along the diagonal. If *RH* variations affect the GCAPE randomly, the hypothetical GCAPE will be larger than the actual GC APE as often as it is smaller. If the scatter diagram shows that the observed GCAPE is *systematically smaller* than the hypothetical GCAPE, this is evidence for GCAPE QE, because it shows that the observed joint variations of the temperature and moisture soundings are correlated in such a way that variations of the

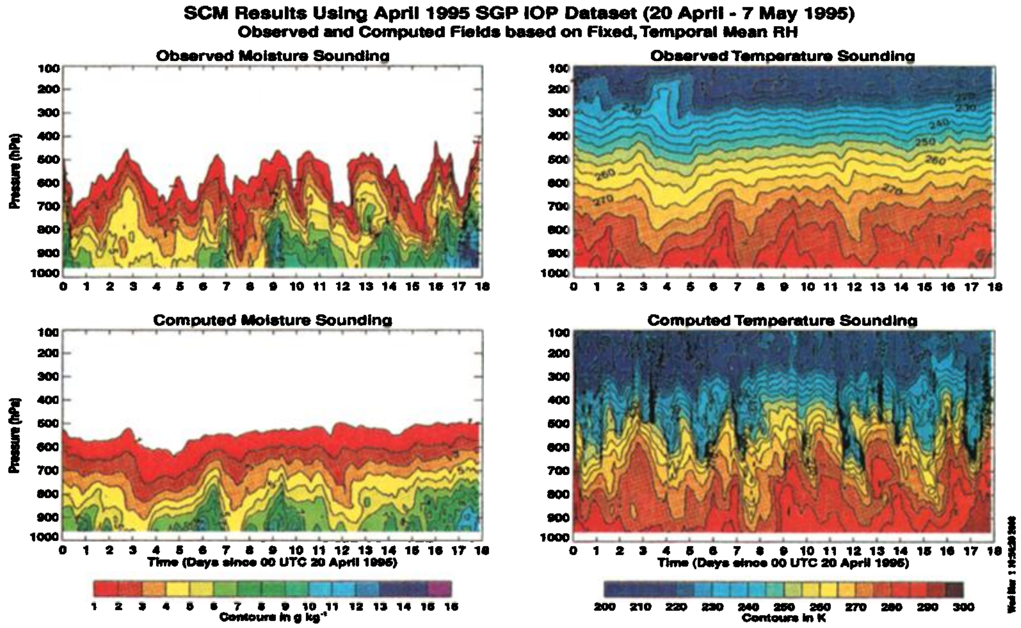

Plate 1. The top panels show the observed time-pressure distributions of the water vapor mixing ratio (left) and the temperature (right). The bottom left panel shows the time-pressure distribution of the water vapor mixing ratio computed by using the observed time-varying temperature and the time-averaged relative humidity at each level. The bottom right panel shows the time-pressure distribution of temperature computed by using the observed time-varying water vapor mixing ratio and the time-averaged relative humidity at each level.

GCAPE are suppressed relative to those which would occur if the *RH* remained constant at each level. Conversely, if the observed values of the GCAPE are on the whole comparable to or larger than the hypothetical ones, this is evidence against GCAPE QE.

Note, however, that Step 4 is arbitrary in the sense that we could just as well use the observed water-vapor profiles together with the IOP-average *RH* profiles to compute *N* hypothetical temperature profiles.[1] We could then pair the *N* hypothetical temperature profiles with the corresponding observed water-vapor profiles to compute a second set of hypothetical GCAPEs, in analogy to Step 5 above, and of course we could then make a second scatter diagram by pairing the observed GCAPEs of Step 2 with the second set of hypothetical GCAPEs. We have actually followed both approaches, as discussed below.

Plate 1 shows an example of the observed and hypothetical temperature and water-vapor profiles, as functions of time, for one particular IOP (April 1995). In the lower troposphere, the hypothetical moisture plot bears a resemblance to the observed temperature plot, and vice versa.

Fig. 1 shows the scatter diagrams (see Step 6 above) for all seven IOPs combined. The GCAPE obtained from the observed soundings is plotted along the ordinate. The abscissas represent the GCAPEs obtained from the observed water-vapor profiles paired with the hypothetical temperature profiles (the top pair of panels) and those obtained from the observed temperature profiles paired with the hypothetical moisture soundings (the bottom pair of panels). Results for all data are shown on the left-hand side of Fig. 1. On the right-hand side we show the results for only those soundings obtained at the ends of three-hour periods with an observed precipitation rate of at least 1 mm day^{-1}. We refer to these as the precipitation-constrained soundings. For the precipitation-constrained results, we averaged the *RH* over only the precipitation-constrained soundings. The results obtained with the precipitation-constrained soundings focus on the effects of *RH* variations on the GCAPE during times when convection is (presumably) active and thus capable of affecting the state of the atmosphere.

The results presented in Fig. 1 show that both sets of hypothetical soundings yield GCAPEs larger than those observed in the vast majority of cases, and smaller than those observed in very few cases. This means that the observed variations of the *RH* profile overwhelmingly tend to reduce the GCAPE below the values that it would take if the *RH* profile were fixed to the IOP-averaged profile. Our results show much more than that the observed variations in the *RH* profile affect the CAPE; they show that the observed variations in the *RH* profile systematically reduce the CAPE.

The results could easily have come out differently, such that the hypothetical GCAPE was smaller than the observed as often as it was larger. This did not happen, and a physical explanation is needed. The QE hypothesis provides such an explanation. We therefore interpret our results as strongly supporting the QE hypothesis.

We have checked the influence of the diurnal cycle on our results in two ways. First, we have repeated our calculations for each of eight local times of day. In these calculations, the average relative humidities were computed separately for each local time. In addition, we have repeated our calculations using daily mean soundings. The figures are omitted here due to space limitations, but all cases, the results obtained are consistent with the discussion and conclusions given above.

5. Summary and conclusions

We have used midlatitude temperature and water vapor soundings to investigate the variability of the GCAPE. The test requires only a time series of temperature and moisture soundings and precipitation rate. Our results show that the observed GCAPE is often smaller than and rarely larger than hypothetical GCAPEs obtained by fixing the relative humidity at its observed time-averaged value, at each level, and using either the observed temperature sounding or the observed water vapor sounding. We interpret

1. An iterative procedure must be used to determine these hypothetical temperature profiles

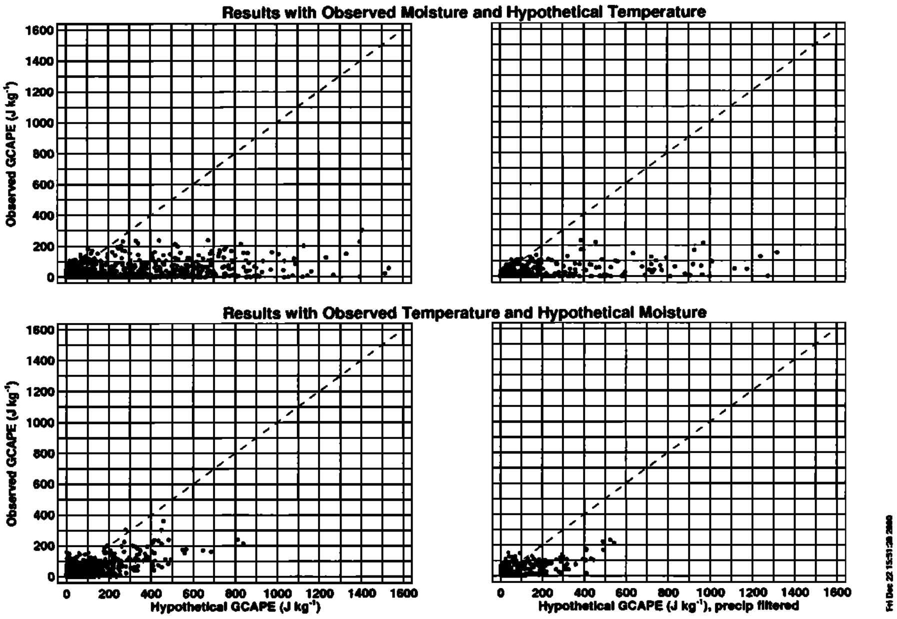

Figure 1. Scatter diagrams for all seven IOPs combined. The GCAPE computed from the observed soundings is plotted along the ordinate in each panel. The abscissas represent the GCAPEs computed from the hypothetical temperature profiles and observed water-vapor profiles (the top pair of panels) and those computed from the hypothetical moisture and observed temperature soundings (the bottom pair of panels). All results are shown on the left-hand side. On the right-hand side we show the results for only those "precipitation-constrained" soundings obtained at the ends of three-hour periods with an observed precipitation rate of at least 1 mm day^{-1}. For the calculations shown on the right, we averaged the *RH* over only the precipitation-constrained soundings.

these results as strongly supporting the hypothesis of GCAPE quasi-equilibrium, which is closely related to closure assumptions used in cumulus parameterizations.

Our QE test has been performed using midlatitude data. The test would be difficult to perform using tropical data because the observed tropical temperature variations are so small.

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