Reply

KUAN-MAN XU AND DAVID A. RANDALL

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

10 May 2000 and 17 October 2000

1. Introduction

We very much welcome the comments on our paper (Xu and Randall 1999, hereafter XR99) by Tao, Shie, and Simpson (2001, hereafter TSS). TSS comment on some different results and interpretations between XR99 and Tao et al. (1999, hereafter T99).

Using the Goddard cumulus ensemble (GCE) model, T99 produced different statistical equilibrium (SE) states by changing the specifications of domain-averaged wind profiles, which closely correspond to the cold and dry SE state obtained by Sui et al. (1994, hereafter S94) using the GCE model, and the warm and humid SE state obtained by Grabowski et al. (1996a, hereafter G96) with a different model, respectively. T99 concluded that the runs that produce a more humid–warmer climate are always associated with stronger surface evaporation and stronger large-scale forcings.

XR99, on the other hand, imposed the total large-scale advective forcings in their control runs [method 2 in TSS; called ‘‘revealed forcing’’ in Randall and Cripe (1999)] instead of those produced by an imposed large-scale ascent (method 1 in TSS). That is, the horizontal advective tendencies are included. XR99 were able to produce an SE state that is close to a climatological mean, while neither S94 nor G96 were able to do so.

TSS criticize the forcing method used in XR99. We are going to argue that methods 1 and 2 each have merits and flaws. TSS also question an interpretation of the results of S94 offered by XR99, namely, that the weak surface wind (in S94) cannot increase the surface evaporation enough to compensate for the enhanced precipitation (due to larger vertical advection) so that less precipitable water remains in the column. TSS also question the interpretation of the relationship between precipitable water and column temperature simulated by the sensitivity tests in XR99. We think that there is no inconsistency between the results obtained by T99 and XR99.

Corresponding author address: Dr. Kuan-Man Xu, NASA Langley Research Center, Mail Stop 420, Hampton, VA 23681.
E-mail: k.m.xu@larc.nasa.gov

2. Different forcing methods

Neither method 1 nor 2 for specifying the large-scale advective forcings is perfect (Randall and Cripe 1999). The essential differences are (i) the lack of feedbacks of the simulated domain-averaged temperature and moisture profiles on the vertical advective tendencies in method 2; (ii) the omission of the horizontal advective tendencies in method 1; and (iii) the freedom of drifting of the simulated SE state with method 1 if some interactions among cloud dynamics/microphysics, radiation, and surface processes are not properly formulated in the model. Not if the horizontal advective tendencies are added is it impossible to compare all aspects of the simulated SE states with a climatological mean state using method 1. Furthermore, there is a serious deficiency associated with method 1 that should be addressed.

Figure 1 (reproduced from XR99) shows that the levels of the maximum apparent heat source Q_1 and apparent moisture sink Q_2 are well separated in the control simulation (cM) with method 2, but not in a sensitivity test (cW) with method 1. See Yanai et al. (1973) for the definition of Q_1 and Q_2. This leads to 1) an unrealistical separation between the maxima of Q_1 and Q_2 in cW; and 2) smaller differences between $Q_1 - Q_R$ and Q_2 for most heights, where Q_R is the radiative heating rate. Because the local tendency terms are negligible for the SE state, Q_1 and Q_2 are identical to the imposed large-scale advective cooling and moistening rates in the simulations, respectively. Comparing to observations from the Marshall Islands (Yanai et al. 1973), Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) (e.g., Thompson et al. 1979), and midlatitudes (e.g., Kuo and Anthes 1984), method 1 cannot produce realistic simulations of the eddy transport convergences, especially for the moist static energy, which are related to $Q_1 - Q_2 - Q_R$, because the absolute magnitudes of $Q_1 - Q_2 - Q_R$ are

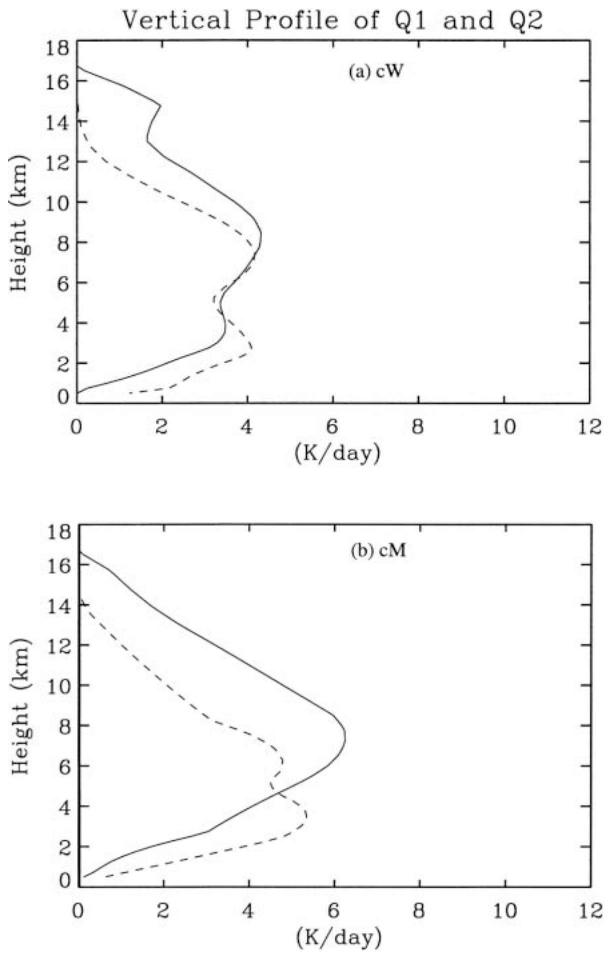

FIG. 1. Vertical profiles of apparent heat source (Q_1; solid line) and apparent moisture sink (Q_2; dashed line) for the statistical-equilibrium states of simulations (a) cW and (b) cM.

much smaller for most heights than those obtained by method 2.

XR99 proposed that an ideal design of numerical simulation is to allow time-varying large-scale vertical motion and horizontal advective effects such that the feedback of the simulated domain-averaged temperature and moisture profiles on the vertical advective effects is present. This method combines the strengths of both methods 1 and 2. Unfortunately, the horizontal advective effects were not separately available from the Marshall Islands experiment (Yanai et al. 1973, 1976). For this reason, such a simulation was not performed by XR99. We agree with TSS that the importance of horizontal advective effects emphasized in XR99 was not completely addressed. On the other hand, the argument on the separation of the maximum Q_1 and Q_2 levels in this reply should lead to utilization of an alternative method (method 3) for imposing large-scale forcing in radiative–convective equilibrium simulations in the near future. Data from more recent field experiments can be used for testing the new forcing method, preferably in

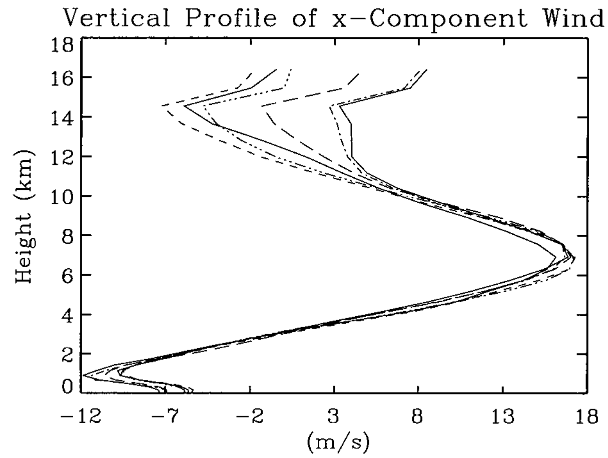

FIG. 2. Vertical profiles of domain-averaged x-component wind at every 10 h of simulation cM.

an intercomparison study participated by several models.

In addition, we do not agree with TSS on the statement on footnote 1. None of Soong and Tao (1980), Tao and Soong (1986), and Krueger (1988) compared the simulated convection under observed time-varying large-scale forcings against time-varying observations. Grabowski et al. (1996b) showed substantial model drifting. Xu and Randall (1996) produced better, but not perfect, results. Both studies imposed the time-varying large-scale forcing from the high quality GATE dataset. Li et al. (1999) showed that method 3 is superior to method 2.

The horizontal momentum equation in the model used by XR99 includes the Coriolis acceleration, which restricts the time-averaged wind profile of the SE state closely to the geostrophic wind (Fig. 1 in XR99 and Fig. 2). Figure 2 shows the vertical profiles of domain-averaged x-component winds at the 10-h interval. Both S94 and G96 excluded the Coriolis force in their models. The horizontal momentum during any simulation of XR99 is, however, time varying (Fig. 2). Such a setup resembles closely to the nudging method used in G96, but allows for some temporal fluctuations. We think that the XR99 setup may be more physically realistic than in either S94 or G96.

3. Interpretation of the results of S94

Both T99 and XR99 used the column budgets of heat, moisture, and moist static energy to explain the differences in the SE states among different simulations (Table 1). There is a very important difference between these two studies. In XR99, the temporal averaging for the budgets was taken over a statistical equilibrium subperiod and the temporal change terms were, therefore, negligible. T99, on the other hand, calculated their budgets over the entire integration period, 25 or 40 days, and the temporal change terms are not always negligible.

TABLE 1. Statistical-equilibrium states and their major budget terms (W m^{-2}) for selected simulations in S94, G96, XR99, and T99. Here, P is surface precipitation rate, E is surface evaporation rate, L is latent heat of vaporization, and Q_R is the vertically integrated radiative heating rate. L-S stands for large scale.

Simulation/study	Precipitable water (mm)	Column temperature (K)	LP	LE	Q_R	L-S advective cooling	L-S advective moistening	L-S advective cooling + moistening
S94	51.3	257.6	507	120	−95	−430	387	−43
G96	70.0	263.0	486	94	−40	−405	392	+57
cM, XR99	56.0	259.6	456	145	−104	−368	311	−57
cW, XR99	61.9	261.2	398	118	−109	−303	280	−23
vW, XR99	57.5	261.0	402	133	−117	−299	269	−30
Run 1, T99	57.2	259.6	502	98	−97	−422	411	−11
Run 1W, T99	72.2	262.4	545	105	−93	−454	464	+10

In addition, the averaging procedure in T99 does not guarantee that the values of all individual budget terms are representative of the SE states because these terms also vary greatly with time (see G96), especially the surface evaporation rate, which was the focus of the arguments presented in both T99 and TSS. An ideal approach is to compare two budget analyses: one for a statistically equilibrium subperiod (as in XR99), and the other for an initially nonequilibrium subperiod (as in T99).

First, we would like to examine an interpretation offered by T99. That is, the more humid (drier) climates are *always* associated with stronger (weaker) latent heat flux from the ocean and stronger (weaker) advective moistening. This is correct if one only compares the similar simulations from one group to another. However, comparison between 1W and 2W (members in one of the two groups) in T99 invalidates such a conclusion if their budget component values are representative of the SE states. Second, the surface evaporation in S94 was 120 W m^{-2} (Table 1), which was larger than any run presented in T99 (67 to 110 W m^{-2}), and the advective moistening in S94 was also larger than in runs 1, 2, 3, and 4 of T99 (Table 1). If the T99 interpretation were correct, the SE state in S94 should be more humid than any of runs 1, 2, 3, and 4 presented in T99, but it was only more humid than runs 3 and 4, which had surface evaporation of about 70 W m^{-2}. Last, the surface evaporation in G96 (94 W m^{-2}) should also be higher than in either XR99 (118 W m^{-2}) or S94 (Table 1) if the T99 interpretation were correct. Therefore, the interpretation offered by T99 cannot consistently explain the SE states produced by different simulations and studies.

Can the T99 explanation be applied to the results in XR99? The budget difference between cW and vW (identical to cW except with time-varying large-scale ascent or descent), or between cW and cM, in XR99 cannot be explained because the cold–dry SE state in vW (cM) corresponds to the higher surface evaporation rate (Table 1). As explained in XR99, the difference between vW and cW is attributed to the accumulation of moisture and hydrometeor in cW. Through interactions with radiation, the budget partitioning among radiation, surface fluxes, and large-scale advective effects is slightly changed. In particular, the ratio of large-scale advective cooling rate to advective moistening rate is slightly changed. The increase of surface evaporation in vW is the response to the drier boundary layer, *not* the cause of a warmer–more humid SE state as in T99.

TSS simply reinterpret the XR99 interpretation of S94 results as a proportional relationship between the SE state (i.e., precipitable water) and the large-scale advective moistening rate. This contradicts one of the major conclusions in XR99; that is, the SE state is not sensitive to the magnitudes of large-scale advective forcings. The advective moistening rate is equal to the difference between surface precipitation and evaporation rates for an SE state. The full XR99 interpretation also includes the relationship between the stability of the SE state and surface precipitation rate (see section 5 of XR99). TSS then contrast the differences of cW and vW simulations of XR99 to invalidate the XR99 interpretation. They then go on using the small differences in the large-scale advective moistening rates between S94 and G96 (Table 1) to argue against the TSS version of the XR99 interpretation.

Is the XR99 explanation applicable to the T99 results? Because the budget numbers were not given in T99 for the SE states, we cannot draw a firm conclusion. It is likely that the answer is no. However, the XR99 explanation is applicable to the comparison between cW, S94, and G96, as explained in XR99. On the other hand, one noticeable feature in the budget analyses among different simulations/studies (last column in Table 1) is that the large-scale moist static energy advection changes sign from one group of simulations (colder–drier; S94, cM, cW, vW, runs 1–4 of T99) to the other (warmer–more humid; G96 and 1W–4W of T99); that is, the ratio of large-scale destabilization to large-scale moisture supply is slightly different. This small difference in the ratio could be the fundamental reason why the simulated SE states between the two groups are so different in T99. Xu and Randall (1998) found that the quasi-equilibrium states are very sensitive to the ratio (their Fig. 7).

TSS also question the ratios of surface evaporation to surface precipitation (REP for short) in XR99, implying for a weaker response of precipitation processes to the imposed large-scale advective forcing in XR99 than in T99. The ratios are 30%–33% in XR99, but only 15%–21% in T99. The observed ratio was 22% (Yanai et al. 1973, 1976). However, Yanai et al. (1976) mentioned that the estimated surface evaporation rates were too low partly because of the use of the surface wind at island stations in the bulk aerodynamic formula. Yanai et al. (1973) gave an uncertainty of 20%; a 20% increase would increase the ratio to 26%, which is higher than those obtained by T99 but lower than those obtained by XR99. Yanai et al. (1973) also gave a mean evaporation rate based upon ship data, which was 38% higher. This would effectively increase the observed REP to 33%. For the depressed periods, the observed REP was 37%. The highest REP in XR99 (30%) was obtained for a simulation with time-varying advective forcing (vW), which allows for large-scale descent. Such a result is consistent with observations.

In T99, runs 1W, 2W, 3W, and 4W all produced much warmer–more humid SE states while nudging the observed wind ($\sim$10 m s^{-1}). This suggests that the boundary layers in these runs were also much warmer and more humid, which reduced the surface evaporation rate. So, the REPs were expected to be smaller than the observed. This is also the case in G96. On the other hand, the surface wind speeds of the SE states in runs 1, 2, 3, and 4 of T99 were much smaller than observed, that is, nearly zero (see Fig. 4 in T99). The gustiness factors (1 or 4 m s^{-1}), thus, played a more important role than in runs 1W, 2W, 3W, and 4W. Consequently, the surface evaporation was expected to be much smaller than the observed if the simulated boundary layers in Runs 1, 2, 3, and 4 of T99 were not much drier than the observed. That is, only if the surface wind speed and the near-surface specific humidity are both close to the observed, we can justify the realism of the evaporation algorithm in the model. We do not think that the precipitation processes in XR99 are much weaker than the observed. Further evidence on the realism of the evaporation formula in the XR99 model can be found in Xu and Randall (1996), which simulated cumulus convection observed during GATE Phase III.

4. Stability of the SE states

The results related to the stability of the SE states are totally consistent between XR99 and T99 (see Fig. 2a of TSS). Comparison between cW and vW of XR99 supports TSS regarding the relationship between the SE states and the magnitudes of advective forcings (Table 1). That is, the warmer and more humid SE state is associated with larger advective cooling and advective moistening. This does not imply that the lapse rate is larger for the entire troposphere. XR99 shows that the lapse rate is smaller in the lower troposphere but larger in the upper troposphere for the warmer and more humid SE state (Fig. 5 in XR99).

What TSS suggest is that 1) the warmer and more humid SE state is more unstable in terms of the equivalent potential temperature and 2) the large-scale advective cooling rate is thus larger. However, the advective cooling rate is related to the vertical gradient of potential temperature, not that of the equivalent potential temperature. Thus, TSS's argument fails to link the (moist convective) stability with the magnitude of the large-scale advective cooling rate. Therefore, there is no disagreement between TSS and XR99 in interpreting the stability of the SE states, which results from the relationship between column temperature and precipitable water of the SE states.

5. Summary

The three comments by TSS are not directed toward the major conclusions in XR99. They are related to some explanations offered in XR99. We do not agree with TSS on the first two comments. There is no disagreement between the results of T99 and those of XR99 regarding the stability of the SE states. Our reply can be summarized as follows:

1) The forcing methods used by XR99 and T99 each have merits and flaws. The argument on the realism of the eddy transport convergences leads to adopting a third method in the future (Randall and Cripe 1999), which imposes not only the large-scale vertical motion, but also the horizontal advective tendencies.
2) The interpretation of S94 results by XR99 is physically sound. TSS suggest cause-and-effect relationships between an individual budget component and the SE state to explain the SE state. A comparison between two sensitivity simulations (cW and vW) is consistent with the interpretation in XR99; that is, the colder–drier SE state is associated with stronger surface evaporation due to a drier boundary layer. This conclusion is different from that obtained by T99. A possible explanation for the results in T99 is that the ratio of large-scale destabilization to large-scale moisture supply is different from one group of simulations to another (Xu and Randall 1998). The interpretation offered by T99 could not explain the drier–colder SE state obtained by S94 because surface evaporation in S94 is higher than that of any simulation in T99. In addition, we do not think that the precipitation processes in XR99 are much weaker than the observed.
3) TSS link the vertical gradient of equivalent potential temperature to the magnitude of large-scale advective cooling, where in fact it is related to the vertical gradient of potential temperature. The results in XR99 also show that the warmer–more humid SE state is associated with larger advective cooling and moistening rates, as in T99, using the large-scale ascent as the forcing. This result is consistent between T99 and XR99.

Finally, we thank Tao, Shie, and Simpson for the fruitful exchanges. We think that cloud-resolving models can be used to further improve the understanding of radiative–convective equilibrium and climate sensitivity. The Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) Working Group 4 (Moncrieff et al. 1997) can play an important role in this regard.

Acknowledgments. This research was supported by the Environmental Sciences Division of the U.S. Department of Energy under Grant DE-FG03-95ER61968 as part of the Atmospheric Radiation Measurement Program and by the NASA Earth Observing System Interdisciplinary Science Program. The computations were performed at the National Energy Research Supercomputer Center, Berkely, California.

REFERENCES

Grabowski, W. W., M. W. Moncrieff, and J. T. Kiehl, 1996a: Long-term behavior of precipitating tropical cloud systems: A numerical study. *Quart. J. Roy. Meteor. Soc.,* **122,** 1019–1041.

——, X. Wu, and M. W. Moncrieff, 1996b: Cloud-resolving modeling of tropical cloud systems during Phase III of GATE. Part I: Two-dimensional experiments. *J. Atmos. Sci.,* **53,** 3684–3709.

Krueger, S. K., 1988: Numerical simulation of tropical cumulus clouds and their interaction with the subcloud layer. *J. Atmos. Sci.,* **45,** 2221–2250.

Kuo, Y.-H., and R. A. Anthes, 1984: Mesoscale budgets of heat and moisture in a convective system over the central United States. *Mon. Wea. Rev.,* **112,** 1482–1497.

Li, X., C.-H. Sui, K.-M. Lau, and M.-D. Chou, 1999: Large-scale forcing and cloud–radiation interaction in the tropical deep convective regime. *J. Atmos. Sci.,* **56,** 3028–3042.

Moncrieff, M. W., S. K. Krueger, D. Gregory, J.-L. Redelsperger, and W.-K. Tao, 1997: GEWEX Cloud System Study (GCSS) Working Group 4: Precipitating convective cloud systems. *Bull. Amer. Meteor. Soc.,* **78,** 831–845.

Randall, D. A., and D. G. Cripe, 1999: Alternative methods for specification of observed forcing in single-column models and cloud system models. *J. Geophys. Res.,* **104,** 24 527–24 545.

Soong, S.-T., and W.-K. Tao, 1980: Response of deep tropical cumulus clouds to mesoscale processes. *J. Atmos. Sci.,* **37,** 2016–2034.

Sui, C.-H., K.-M. Lau, W.-K. Tao, and J. Simpson, 1994: The tropical water and energy cycles in a cumulus ensemble model. Part I: Equilibrium climate. *J. Atmos. Sci.,* **51,** 711–728.

Tao, W.-K., and S.-T. Soong, 1986: A study of the response of deep tropical clouds to mesoscale processes: Three-dimensional numerical experiments. *J. Atmos. Sci.,* **43,** 2653–2676.

——, J. Simpson, C.-H. Sui, C.-L. Shie, B. Zhou, K. M. Lau, and M. Moncrieff, 1999: Equilibrium states simulated by cloud-resolving models. *J. Atmos. Sci.,* **56,** 3128–3139.

——, C.-L. Shie, and J. Simpson, 2001: Comments on ''A sensitivity study of radiative–convective equilibrium in the Tropics with a convection-resolving model.'' *J. Atmos. Sci.,* **58,** 1328–1333.

Thompson, R. M., Jr., S. W. Payne, E. E. Recker, and R. J. Reed, 1979: Structure and properties of synoptic-scale wave disturbances in the Intertropical Convergence Zone of the eastern Atlantic. *J. Atmos. Sci.,* **36,** 53–72.

Xu, K.-M., and D. A. Randall, 1996: Explicit simulation of cumulus ensembles with the GATE Phase III data: Comparison with observations. *J. Atmos. Sci.,* **53,** 3710–3736.

——, and ——, 1998: Influence of large-scale advective cooling and moistening effects on the quasi-equilibrium behavior of explicitly simulated cumulus ensembles. *J. Atmos. Sci.,* **55,** 896–909.

——, and ——, 1999: A sensitivity study of radiative–convective equilibrium in the Tropics with a convection-resolving model. *J. Atmos. Sci.,* **56,** 3385–3399; Corrigendum, **57,** 1958.

Yanai, M., S. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.,* **30,** 611–627.

——, J.-H. Chu, T. E. Stark, and T. Nitta, 1976: Response of deep and shallow tropical maritime cumuli to large-scale processes. *J. Atmos. Sci.,* **33,** 976–991.