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CUMULUS CONVECTION AND THE TERRESTRIAL WATER–VAPOR DISTRIBUTION; L. J. Donner, National Center for Atmospheric Research, * Boulder, Colorado 80307

1. Introduction

Cumulus convection plays a significant role in determining the structure of the terrestrial water–vapor field. (It also contributes substantially to the momentum and thermal fields.) Cumulus convection acts directly on the moisture field by condensing and precipitating water vapor and by redistributing water vapor through cumulus–induced eddy circulations. Additionally, through its radiative and direct interactions with the thermal field, cumulus convection partially establishes the condensation threshold for water vapor.

The purpose of this paper is to outline the mechanisms by which cumulus convection influences the terrestrial water–vapor distribution. As will readily become apparent, this is a problem of enormous complexity, and several theories for its partial resolution exist. In this paper, calculations using a theory due to Kuo (1) will be used to illustrate the mechanisms by which cumulus convection influences the terrestrial water–vapor distribution.

2. Governing Equations and Closures

Relative to scales resolved by the synoptic meteorological network, cumulus convection occupies a small area. Its effects are represented as a turbulent fluctuation on the large–scale field. The large–scale (spatially averaged) water–vapor mixing ratio ($\overline{q}$) changes locally due to large–scale advection of water vapor, condensation on the large scale ($\overline{c}$), condensation on the scale of cumulus convection ($\overline{c*}$), and convergence of water–vapor fluxes induced by cumulus convection:

$$\frac{\partial \overline{q}}{\partial t} = -\overline{\mathrm{v}} \bullet \vec{\nabla}\overline{q} - \overline{w}\frac{\partial \overline{q}}{\partial p} - \overline{c} - \overline{c^*} - \frac{\partial \overline{w'q'}}{\partial p} - \vec{\nabla} \bullet \overline{\mathrm{v}'q'}. \tag{1}$$

An overbar refers to the large scale, and a prime, to a cumulus deviation from the large scale. The vertical coordinate is pressure p and $w = \frac{dp}{dt}$. The goal of cumulus parameterization is to find a closure for (1) in terms of the large–scale variables. Three major theories of cumulus parameterization are:

(a) Moist adiabatic adjustment (2). The $\overline{q}$ and temperature profiles are constrained so as not to become supersaturated and moist adiabatically unstable.

(b) Arakawa–Schubert parameterization (3). The role of condensation $\overline{c}^*$ in (1) is taken as the maintenance of the vertical mass flux in the cumulus elements and, by continuity, subsidence outside the cumulus elements. The local change in $\overline{q}$ then is due to

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detrainment from cumulus elements and cumulus–induced drying due to subsidence outside the cumulus elements. An ensemble of clouds with varying vertical structures is assumed to exist, and the distribution of mass flux among the members of the ensemble is obtained by assuming buoyancy generated in the cumulus ensemble equilibrates changes in the large scale.

(c) Kuo parameterization (1). The condensation rate $\overline{c^*}$ is assumed to be proportional to large–scale moisture convergence. A cumulus model and an estimate for cumulus fractional area using the large–scale moisture convergence provide closures for the flux–convergence terms in (1).

The validity of the assumptions in all of these cumulus parameterizations is at least restricted in spatial scale, although such limitations have not yet been studied. For the most part, the parameterizations all assume that the forcing of the large scale by cumulus convection depends on the instantaneous large–scale state; the limitations of this approximation are also largely unexplored.

3. Forcing of the Water–Vapor Field by Cumulus Convection

Donner *et al.* (4) and Donner (5) used a Kuo cumulus parameterization in an atmospheric general circulation model to assess the role of cumulus convection in determining the water–vapor distribution and other circulation characteristics. Figure 1 illustrates the time–mean, zonally averaged forcing of the water–vapor field by cumulus convection (July) from the simulation described in (5). Condensation acts as a drying tendency with a maximum of about 1.0 g kg^{-1} day^{-1} in the tropics. The one–dimensional cloud model used in the cumulus parameterization in (5) is characterized by vertical velocities which increase with height in the lower portion of the cloud, while decreasing in the upper portion. This cloud velocity distribution leads to a divergence of moisture flux in the lower troposphere (maximum drying about 2.6 g kg^{-1} day^{-1}) and a convergence in the upper troposphere (maximum moistening about 1.5 g kg^{-1} day^{-1}). The net moisture forcing is the sum of the condensation and eddy–flux processes. The time–mean, zonally averaged water–vapor tendency due to cumulus convection also exhibits a maximum drying in the stormy baroclinic zone of Southern Hemisphere winter.

4. The effect of cumulus convection on the mean water–vapor field

The simulation of atmospheric water–vapor fields is fairly sensitive to the parameterization for cumulus convection. Figure 2 shows changes in the humidity field achieved by adding a Kuo cumulus parameterization to the National Center for Atmospheric Research Community Climate Model, which in its control version included a moist adiabatic adjustment. (As discussed in (5), these changes can perhaps plausibly be interpreted as qualitative indications of the effect of cumulus convection on the atmospheric water–vapor distribution.) The specific humidity is reduced significantly, consistent with the moisture tendencies shown in Fig. 1. As discussed in (4) and (5), the Kuo cumulus parameterization cools the atmosphere; as a consequence, changes in relative humidity are less obvious. Still, in the convectively most active areas, significant reductions in relative

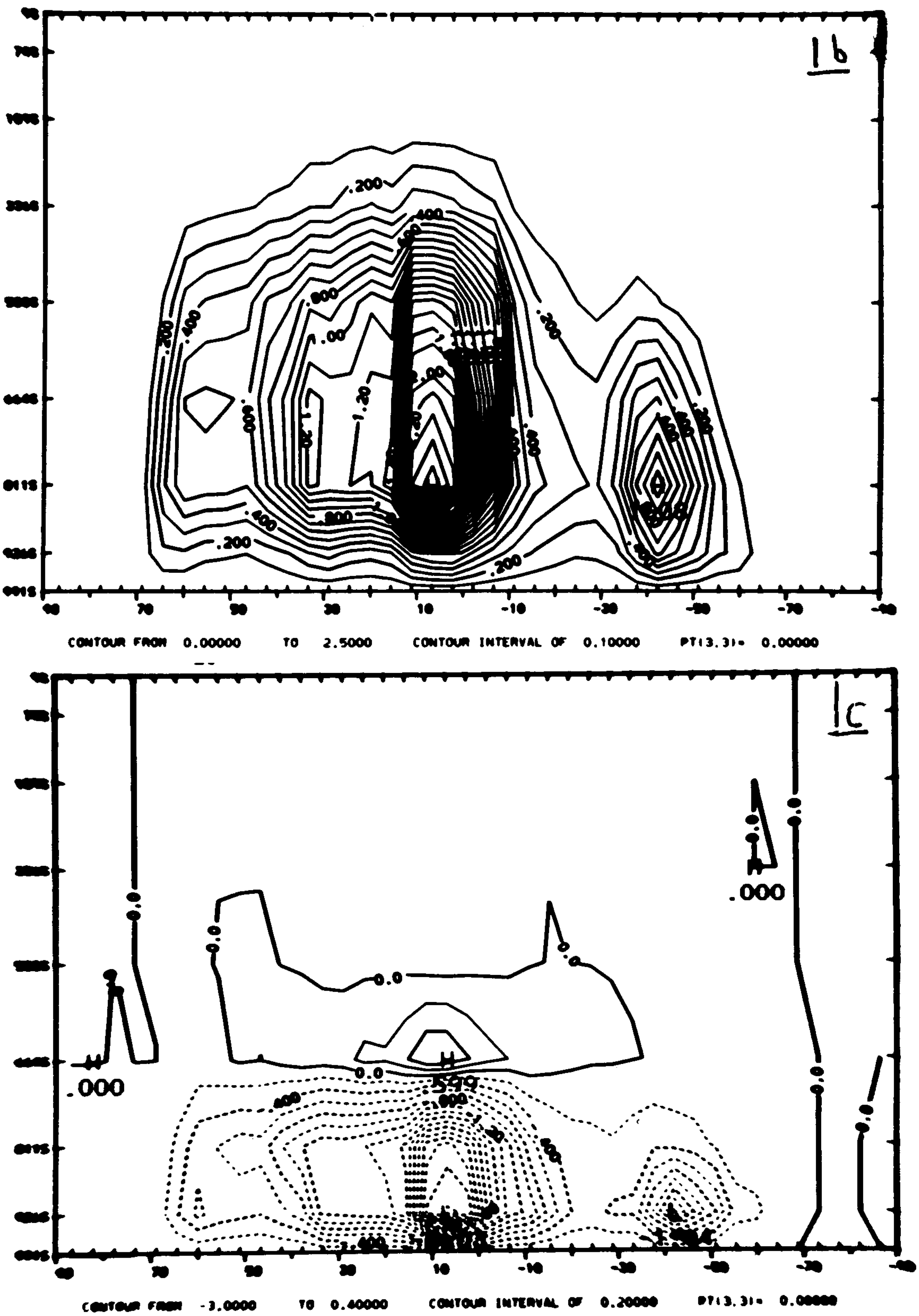

Fig. 1 Simulated forcing of the water–vapor field for mean July conditions (a) cumulus-induced flux convergence (g kg^{-1} day^{-1}) (b) latent heat release (to convert to a water–vapor tendency in g kg^{-1} day^{-1}, multiply by -.4), (c) net forcing by cumulus convection (g kg^{-1} day^{-1}). Ordinate gives (pressure/surface pressure) X1000.

humidity also occur. These changes in water–vapor distribution interact strongly with the cloud formation and radiative transfer.

5. Summary

Cumulus convection is a dominant mechanism in the transport and removal of atmospheric water vapor in the terrestrial atmosphere. Cumulus parameterizations seek to link the effects of small–scale cumulus convection to the properties of large, synoptic–scale atmospheric flows. Several families of cumulus parameteriztion exist, differing fundamentally in their basic assumptions. The effects of cumulus convection are most evident in the tropics and baroclinic zones of the middle latitudes and consist primarily of a mean drying.

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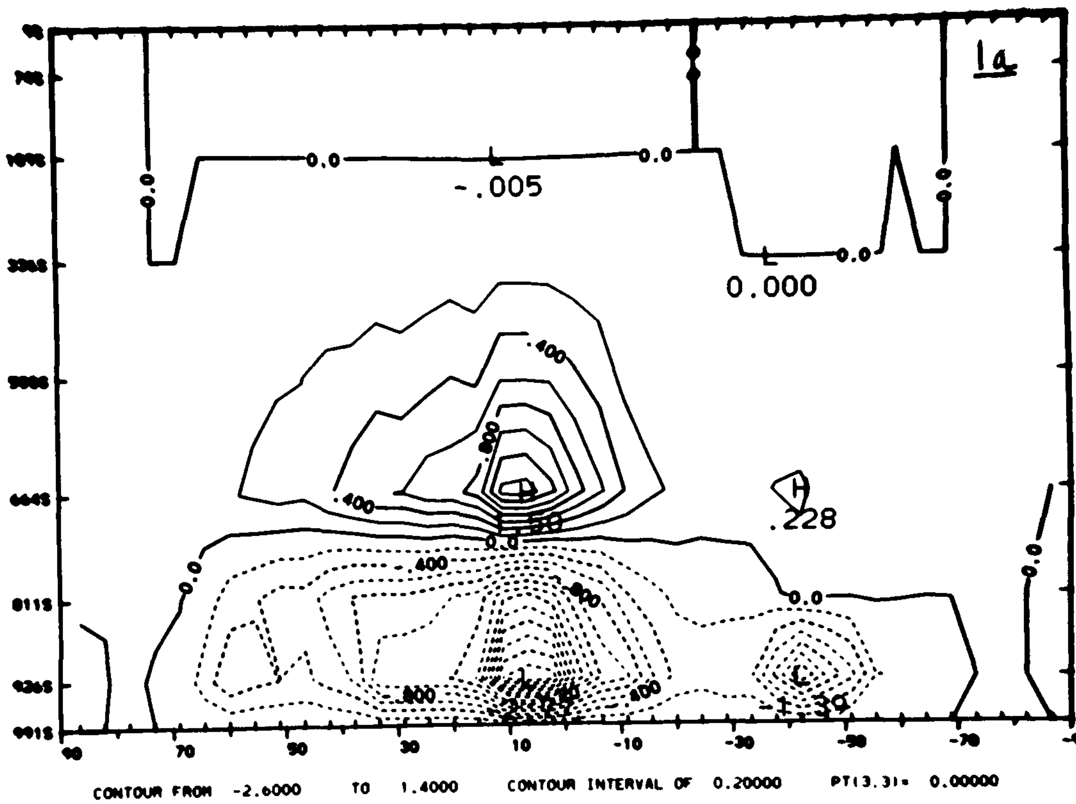

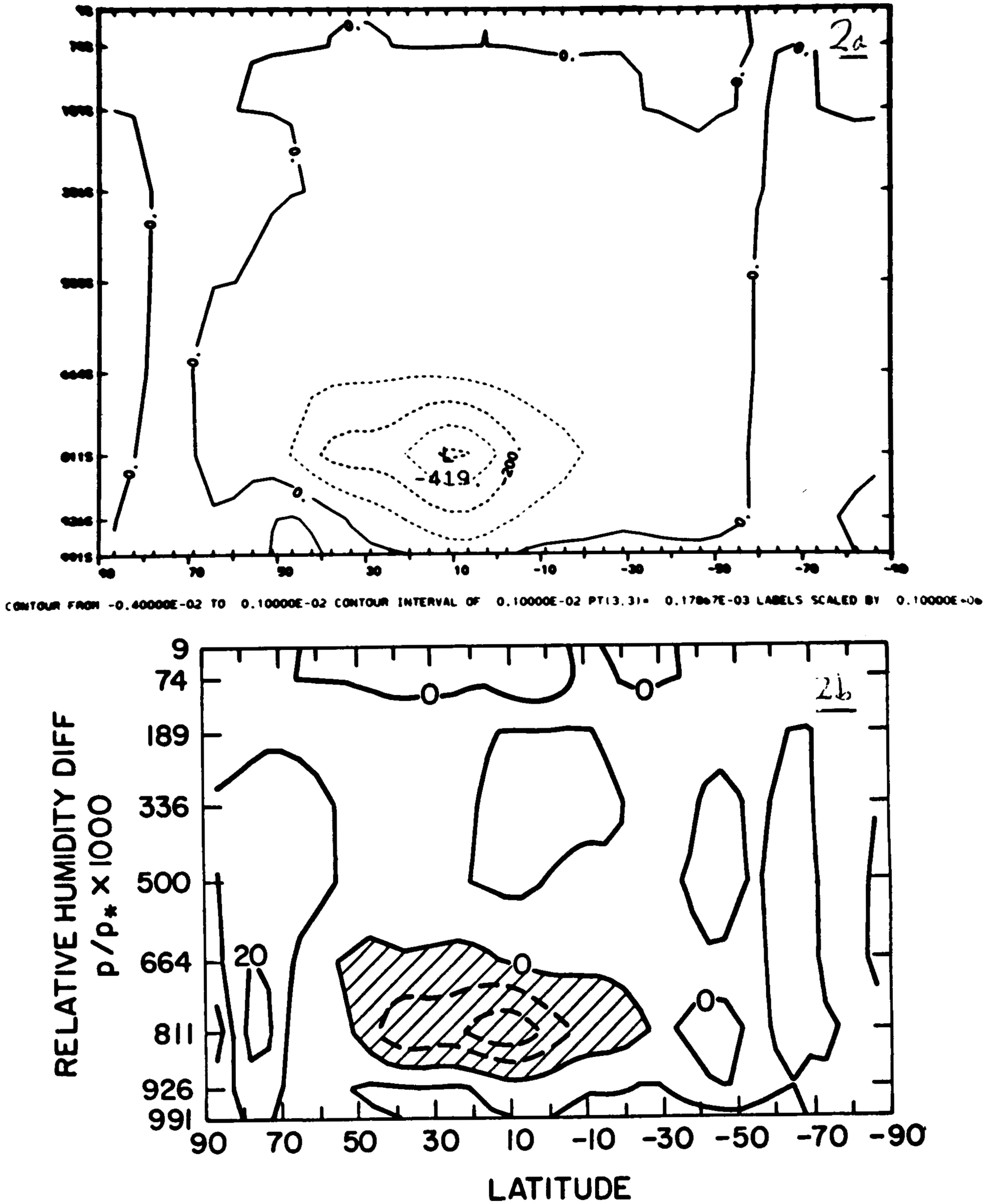

Fig. 2 Changes in (a) specific humidity and (b) relative humidity due to the Kuo cumulus parameterization. Units: (a) g kg^{-1} $\times$ 10^5 (b) %.