Using High-Resolution Cloud Simulations to Explore Variability Unresolved in Large-Scale Models

R. Pincus
National Oceanic and Atmospheric Administration
Cooperative Institute for Research in Environmental Science
Climate Diagnostics Center
Boulder, Colorado

S. A. Klein
National Oceanic and Atmospheric Administration
Geophysical Fluid Dynamics Lab
Princeton, New Jersey

K.-M. Xu
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Fundamentals

Large-scale models represent the atmospheric state as a time-evolving set of values at discrete points, each of which represents the mean within the grid-cell domain, typically 10s to 100s of km. The value at each point changes with time as various dynamic, thermodynamic, and microphysical processes act; the process rate usually depends on the atmospheric state.

In nature every atmospheric property varies at scales from the planetary to the very small. By representing the atmospheric state in terms of mean values, any variability at sub-grid scales is truncated. If the process rates are non-linear, the rate of change of atmospheric properties within a grid cell differs depending on whether it is computed from a single value or for all values.

Unresolved variability is most important in clouds: cloud properties vary dramatically over very small time and space scales, and the processes affecting clouds are strongly non-linear. Biases affect (at least) radiation (the relative albedo bias is of order 15 percent), and microphysical calculations (the bias can be as large as a factor of 2). The size of the bias depends on how non-linear the process is in the neighborhood of the mean value and on the distribution, especially on how wide and how symmetric it is.

If we knew the distribution of cloud properties within the grid cell, we could (at least in principle) compute the correct domain average rate for every process. This isn't a realistic goal in practice, so we ask instead how to most compactly represent the important aspect of variability. Our goal is to inform and evaluate treatments of unresolved variability for stratiform cloud parameterization schemes used in large-scale models.

Representing Variability: Statistical Cloud Schemes and Distribution Moments

Statistical cloud schemes represent unresolved variability in terms of a distribution of some quantity that is conserved under condensation/evaporation and freezing/melting. Conserved quantities include total water mixing ration q_t (vapor, liquid, and ice) or the local perturbation from saturation, denoted s. Distributions are usually modeled with a two-parameter function, (i.e., Gaussian, log-normal, and triangular); the width is either assumed constant or diagnosed, so only one prognostic equation is needed. In principle, more complicated (higher-order) distributions might be used.

Accurate computation of process rates requires, at a minimum, knowing something about the mean value, width, and symmetry of the underlying distribution. Here we use distribution moments—the mean, standard deviation, and skewness of variables within each domain—to characterize the underlying distribution. Parameters for more complicated distributions (e.g., beta distribution) can be obtained from higher-order moments.

Estimates of Variability from Cloud Resolving Model Simulations

We seek a description of the distribution of thermodynamic quantities within large-scale model grid boxes, and to see how physical processes change their character. Obtaining these distributions from observations requires extrapolation from time-height fields to nearly instantaneous three-dimensional fields). We use high-resolution simulations; the underlying calculations may be inaccurate or incomplete in some detail but the interpretation is unambiguous. In Figure 1, we examine simulations of deep convection during July 1997 at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in Oklahoma made using the University of California/Colorado State University (UCLA/CSU) cloud-resolving model (CRM). The CRM has a spatial resolution of 2 km and a domain of 516 km; fields are output every 5 minutes. We partition the domain into stratiform and convective columns at each model time step using established methods based on vertical velocity and surface precipitation rate.

Distributions of Total Water in the Presence of Deep Convection

We use high-resolution CRM fields to examine the relationships between sub-grid scale distributions and physical processes taking place within each cell. In Figure 2, we compute the statistics of total water mixing ratio within each large-scale model grid cell (512 km) and time step (1 hour) from the CRM fields. Convective condensation is treated distinctly from stratiform condensation in most large-scale models; these statistics apply to the stratiform region. We are most interested in the way convection and microphysics affect the higher-order distribution moments.

The absolute amount of variability decreases with height as the saturation mixing ratio decreases, but distribution width changes with time at all levels. Convection affects the stratiform regions through detrainment from moist updrafts and dry downdrafts. Both increase the width of the distribution (above). Convective downdrafts can add dry air to the boundary layer, causing strong negative skewness (at left, especially around 1 km). At weather prediction model scale (32 km, 15 minutes, not shown) unresolved variability is typically smaller, but the assumption that most of the domain is stratiform may fail.

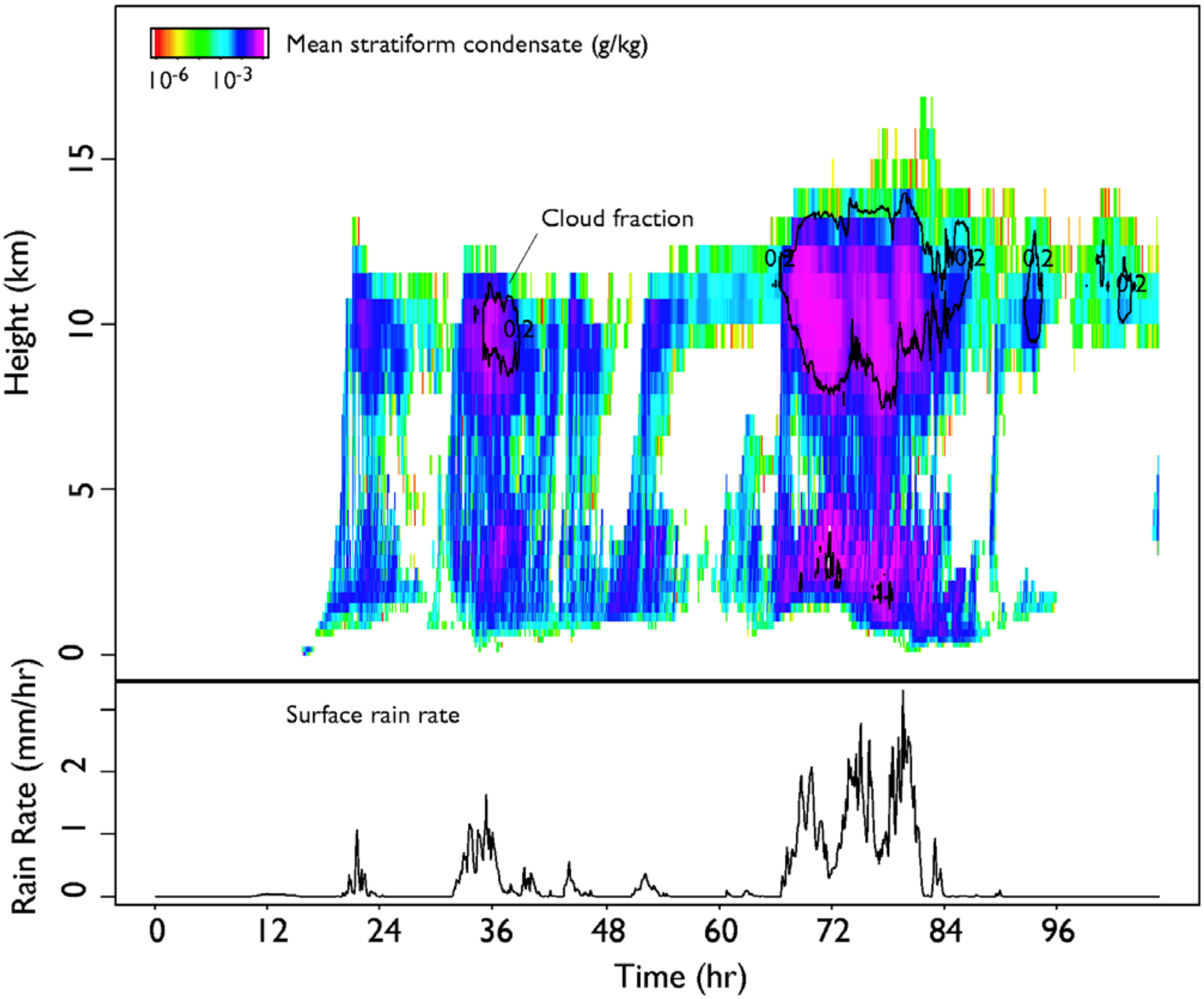

Figure 1. Two-dimensional CRM simulations of convection over the ARM SGP CART site. The UCLA/CSU CRM has been forced by data assimilated for sub-case A of the July 1997 cloud intensive operational period (IOP). Shown are time-height cross sections of mean liquid water content in the stratiform portion of the domain, contours of stratiform cloud fraction, and the surface rain rate.

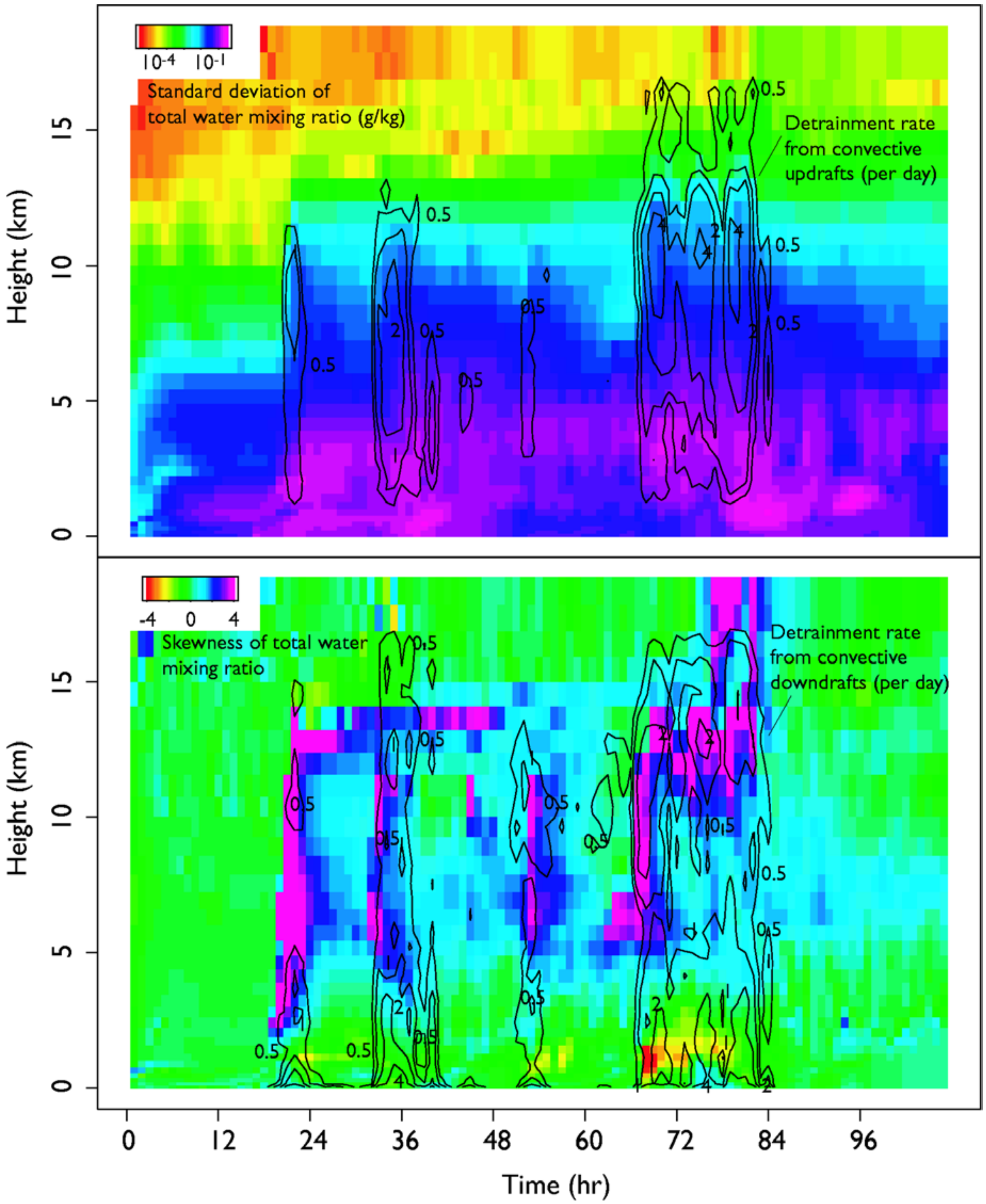

Figure 2. Time-height cross sections of the standard deviation (top panel) and skewness (bottom panel of total water content in non-convective regions in general circulation model-sized domains (512 km, 1 hour) simulated by a two-dimensional CRM with much higher resolution. Also shown are contours of detrainment from convective updrafts (top) and downdrafts (bottom); both tend to increase the variance of total water content, while dry downdrafts detraining into the boundary layer create highly negatively skewed distributions.