A New Method for Cloud Model Evaluation Using Satellite Data

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Outline

- Motivation
- New method of satellite data analysis
- Analysis of ECMWF predicted cloud fields
- Comparison of SSF with ECMWF
- Cloud-resolving model simulations
- Possible improvements of CRM simulations
- Future plans
Motivations

- Importance of radiative feedback of clouds in the climate system
- Uncertainties in modeling cloud-radiation interactions in global climate models (GCMs)
- Nonlinearity of cloud processes requiring observations on all relevant modeling scales (in space and in time)
- Existing methods of cloud model evaluation are inadequate
Existing methods for cloud model evaluation

- **Regional field experiments** (DOE ARM, TOGA-COARE, ASTEX, GATE, etc.)
  - Detailed measurements of cloud properties and atmospheric states
  - Limited cases at selected locations for a short period
  - Extrapolate limited cases to global conditions
  - Cloud models may perform well for certain cloud-system types, but not all major types

- **Global and regional monthly mean data** (CERES, ISSC, ERBE, etc.)
  - Large regions and many different cloud-system types
  - Measure only a few variables
  - Impossible to unscramble the nonlinear cloud feedback processes, due to spatial and temporal averaging
  - Cloud models may perform well for the wrong reasons, due to cancellations of errors in GCMs
A new method of satellite data analysis for cloud model evaluation

Ensemble Objective Analysis of Cloud Systems

- EOS Satellite Data
- ECMWF (or NWP model) Meteorological Data
- ECMWF (or NWP Model) Predicted Cloud Fields
- Large-eddy Simulation (LES)
- Cloud-resolving Model (CRM)
- Single-column Model (SCM)

Analyze the statistics of subgrid characteristics of cloud systems, *not* the mean.
Matching the CERES SSF (Single Scanner Footprint ...) cloud and radiative data with ECMWF meteorological data (T, q, u, v and advective tendencies).
Perform cloud model simulations driven by ECMWF advective tendencies.
Also evaluate the ECMWF parameterizations using predicted cloud fields.
Define a cloud system as a contiguous region of the Earth with a single dominant cloud type (e.g. stratocumulus, stratus, and deep convection)

Determine the shapes and sizes of the cloud systems by the satellite data and by the cloud property selection criteria (Wielicki and Welch 1986)
Samples of Cloud Objects in March:

Case: 1998032200  
Case: 1998031722

Outgoing Longwave Radiation (Wm$^{-2}$)
### Analysis of the SSF data set

- March 1998 CERES/TRMM and March 2000 Terra data (> 190 GB/month)
- 29 cases of tropical convective systems with diameters greater than 300 km for March 1998
- Parameters analyzed from CERES SSF data product:

<table>
<thead>
<tr>
<th>Cloud optical depth</th>
<th>Cloud top height</th>
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</thead>
<tbody>
<tr>
<td>Ice water path</td>
<td>Cloud top pressure</td>
</tr>
<tr>
<td>Ice diameter</td>
<td>Cloud top temperature</td>
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<tr>
<td>TOA SW</td>
<td>Liquid water path</td>
</tr>
<tr>
<td>TOA albedo</td>
<td>Water droplet radius</td>
</tr>
<tr>
<td>OLR, Emissivity</td>
<td>Cloud amount</td>
</tr>
</tbody>
</table>
Cloud system selection criteria for tropical deep convective systems

- Cloud top height > 10 km
- Cloud optical depth > 10
- Overcast pixels
- Latitudes between 25 °S and 25 °N
Analysis of ECMWF predicted cloud fields

- ECMWF meteorological data
  - 1/2° x 1/2° gridded, six-hourly analysis from data assimilation
  - temperature, specific humidity, horizontal wind components
- ECMWF predicted cloud fields (prognostic parameterization)
  - 1/2° x 1/2° gridded, six-hour predictions
  - cloud liquid water content
  - cloud ice water content
  - cloud cover
- ECMWF grids are much bigger than some SSF pixels
  (range from 10 x 10 km² to 100 x 100 km²)
- ECMWF does not provide cloud optical properties; we need to use the Fu-Liou radiation code, but it does not treat partially cloudy columns
Analysis of ECMWF predicted cloud fields (cont.)

- Divide an ECMWF grid box into 100 subgrid boxes (~30 km$^2$)
- Use the maximum/random overlap assumption (Klein & Jacob 1999)
- Use the Fu-Liou radiation codes to obtain cloud optical properties and radiative fluxes for each subgrid box
Comparison of SSF with ECMWF

- Only subgrid boxes with cloud top height > 10 and cloud optical depth > 10 are selected for statistical analysis.
- Cloud top is defined for thick anvil with optical depth > 2.
- Clouds within the vicinity of the observed cloud systems are also included.
Comparison of SSF with ECMWF

Cloud optical depth (29 cases combined)
Comparison of SSF with ECMWF
Ice (total, for ECMWF) water path

Ice Water Path PDF: ECMWF (blk), SSF (grn)
Comparison of SSF with ECMWF
TOA solar radiation
Comparison of SSF with ECMWF
TOA Albedo
Comparison of SSF with ECMWF

Cloud ice diameter

Cloud Ice Diameter PDFs: ECMWF (blk), SSF (grn)
Comparison of SSF with ECMWF

Outgoing longwave radiation
Comparison of SSF with ECMWF
Cloud top height
Comparison of SSF with ECMWF

Summary

- The probability density functions (PDFs) of ECMWF predicted cloud fields basically agree with satellite observations.
- The PDFs of most parameters are close to the Gaussian distribution, except for optical depth and total (ice) water path, which are exponentially distributed.
- The ECMWF predicted clouds tend to be deeper and colder than those observed with the SSF.
Cloud resolving model simulation:

What is a cloud-resolving model (CRM)?

- Sufficient spatial and temporal resolution to resolve individual cloud elements (~ 1 km)
- Sufficient large domain and long time scale for statistical analyses of cloud systems
- Explicitly resolve cloud-scale and mesoscale dynamical processes
- Need to parameterize turbulence, cloud microphysics and radiative transfer
- Often used as a tool for cloud parameterization development for GCMs
- Will probably be used as a “super parameterization” in future GCMs
Cloud-resolving model simulation

Description of the models

LaRC2d CRM (UCLA/CSU; Krueger 1988; Xu and Randall 1995)

- Two-dimensional, anelastic dynamics (no sound waves)
- Third-moment turbulence closures (35 prognostic equations and one diagnostic equation)
- Three-phase cloud microphysics parameterization (Lin et al. 1983; Krueger et al. 1995)
- Harshvardhan et al. (1987) radiative transfer parameterization

LaRC3d CRM (Advanced Regional Prediction System; Xue et al. 2000)

- 2-D or 3-D fully compressible dynamics
- Prognostic turbulent kinetic energy (TKE) closure
- Three-phase cloud microphysics parameterization (Lin et al. 1983)
- Chou (1990, 1992) and Chou and Suarez (1994) radiative transfer parameterization
Cloud resolving model simulation:

Design of simulation

- 2-D (x-z), horizontal grid size is 2 km
- Prescribe large-scale advective tendencies that are calculated from ECMWF data and averaged over an area three times as great as the satellite observed cloud system
- The advective tendencies are assumed to be quasi-steady
- Simulation lasts for 24 h
- Only the last 12 h is analyzed
Comparison of CRMs with SSF

Cloud optical depth – LaRC2d
Comparison of CRMs with SSF:
Ice water path - LaRC2d
Comparison of CRMs with SSF
TOA SW – LaRC2d
Comparison of CRMs with SSF

TOA albedo – LaRC2d

TOA Albedo PDFS: CRM (black), SSF (green)
Comparison of CRMs with SSF

Outgoing LW – LaRC2d
Comparison of CRMs with SSF:

Cloud top height - LaRC2d
Simulations with LaRC3d CRM: Sensitivity to ice microphysics

Radar reflectivities from LaRC3d CRM simulations and observations
Control (left), modified ice microphysics (center), observation (right)

Williams et al. (1995)
Comparison of CRMs with SSF

Cloud optical depth – LaRC3d
SSF (solid), control (dotted), modified microphysics (dashed)
Comparison of CRMs with SSF

Outgoing LW – LaRC3d

SSF (solid), control (dotted), modified microphysics (dashed)
Comparison of CRMs with SSF

Cloud top height – LaRC3d

SSF (solid), control (dotted), modified microphysics (dashed)
Comparison of CRMs with SSF

Summary

- Most of our CRM results agree with satellite observations well.
- The CRM clouds tend to be shallower and warmer than those observed with the SSF for both LaRC2d and LaRC3d models, unlike those predicted by the ECMWF model.
- Inadequate ice-phase microphysics and the forcing method (single profile) are two possible causes for the CRM results.
Possible improvements of CRM simulations

- Sensitivity tests to the advective forcings, eliminating those cases with inconsistent advective forcings
- Two-column advective forcings, instead of single-column ones
- Improvements to model physics [ice microphysics, radiation and turbulence closure (LaRC3d CRM)]
Future plan

- Statistical analysis of all cloud systems identified by SSF data for the March 1998 and March 2000 periods
- CRM simulations of these two periods
- Analysis of SSF data for other major cloud types such as stratus and stratocumulus
- CRM simulations of these shallow cloud types
- Comparison of CRM simulations with single-column model (SCM) simulations