On the Use of Data Assimilation Methodologies for Examining Cloud system – Environment Interactions

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Convection - Environment Interaction

- Liquid and ice particle size distribution
- Ice particle shape and density
- Aerosol content and chemistry

- Cold pools
- Updraft/downdraft strength
- Thermodynamic environment
- Latent heat release
- Vertical condensate distribution
- Radiative fluxes and heating rates
- Precipitation rate and amount

Posselt et al., 2012 (J. Climate)
Evaluating Cloud System Sensitivity

Assess influence of changes in parameters $x$ on output of model $F(x) = y$

- Which parameters control system evolution?
- Which output is most sensitive to parameter changes?
- Does model output sensitivity change over the range of possible parameter values?

Goal: efficiently and robustly characterize the effects of changes in cloud characteristics

- Map multivariate sensitivity $\frac{\partial F(x)}{\partial x}$
- Allow multiple dimensions, nonlinear relationships
- Maintain consistency with the tropical convective environment (constraint)
Data Assimilation: Quantifying Relationships

- The model maps from one set of state values to another (e.g., evolution of the system) and/or from state to obs space.
- The inverse problem places constraint on the solution.

Inference of
- a previous set of states from a current set or
- a set of states from a set of observations

\[
P(x|y) = \frac{P(y|x)P(x)}{P(y)}
\]
Cloud Sensitivity Analysis via Bayesian Sampling

Goal: estimate $P(y|x)$ or $P(x|y)$

Markov chain Monte Carlo:
- Construct a Markov chain that samples $P(x|y)$
- A random walk guided by information from observations

Application:
- Characterize cloud microphysics (particle size, density, shape) effect
  - Bulk hydrologic cycle and radiative balance
  - Storm-scale dynamics and environment

Convection – Microphysics Interaction: Experiment Configuration

- NASA Goddard cloud system resolving model
- Simulate a single 3D convective system at 2 km horizontal grid spacing, 72 vertical levels
- Perturb cloud microphysical parameters
  - Characterize \textit{parameter sensitivity}
  - Observe bulk hydrologic cycle and radiative flux – \textit{constrain simulation properties}
  - Store ancillary data on dynamics, thermodynamic environment, and radiation – \textit{analyze relationships}
- Generate a sample of $\sim 2 \times 10^6$ realizations
3D Control Simulation, w and cloud

Three Phases:

- **Developing:**
  180-230 minutes

- **Mature:**
  230-280 minutes

- **Dissipating:**
  280-330 minutes

Model Configuration:

- 64 x 24 km domain
- 2 km dx, dy
- 72 vertical levels
## Parameters and Observations

### 10 Microphysics Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow fall speed coefficient ( a_s )</td>
</tr>
<tr>
<td>Snow fall speed exponent ( b_s )</td>
</tr>
<tr>
<td>Graupel fall speed coefficient ( a_g )</td>
</tr>
<tr>
<td>Graupel fall speed exponent ( b_g )</td>
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<tr>
<td>Cloud-rain autoconversion ( q_{c0} )</td>
</tr>
<tr>
<td>Slope intercept Rain ( N_{0r} )</td>
</tr>
<tr>
<td>Slope intercept Snow ( N_{0s} )</td>
</tr>
<tr>
<td>Slope intercept Graupel ( N_{0g} )</td>
</tr>
<tr>
<td>Snow particle density ( \rho_s )</td>
</tr>
<tr>
<td>Graupel particle density ( \rho_g )</td>
</tr>
</tbody>
</table>

### 5 Observations

<table>
<thead>
<tr>
<th>Observations</th>
<th>Obs ( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation Rate</td>
<td>2 mm hr(^{-1})</td>
</tr>
<tr>
<td>Liquid Water Path (LWP)</td>
<td>0.5 kg m(^{-2})</td>
</tr>
<tr>
<td>Ice Water Path (IWP)</td>
<td>1.0 kg m(^{-2})</td>
</tr>
<tr>
<td>Longwave Flux (OLR)</td>
<td>5 W m(^{-2})</td>
</tr>
<tr>
<td>Shortwave Flux (OSR)</td>
<td>5 W m(^{-2})</td>
</tr>
</tbody>
</table>

**Observations taken in 3 intervals**

- Developing
- Mature
- Dissipating

**Defined according to cloud depth and surface rain rate**

D. J. Posselt
Parameter Sensitivity: Posterior Parameter PDFs $P(x|y)$

- Integral effect of parameters on solution
- Degree of sensitivity and inter-parameter relationships
- Possibility of parameter calibration
- Questions:
  - What is the response of model output to changes in cloud microphysical assumptions? $P(y|x)$
  - How do changes in parameters affect convective structure? $P(z|x)$
Hydrologic Cycle / Radiative Flux Response

- Forward observations vs parameters

Warm rain controls the solution

Warm rain and ice processes important

Ice processes control the solution
What of the response of other system variables (Latent heat release, RH, w, radiative heating rates)?

- Liquid and ice particle size distribution
- Ice particle shape and density
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Posselt et al., 2012 (J. Climate)
Storm-Scale Dynamics

- Column integral constraint on microphysical parameters leads to constraint on storm scale dynamics
- Long tail toward stronger storms (stronger updrafts and downdrafts)
Storm-Scale Dynamic – Thermodynamic interactions

- Bimodal solution:
  - Weaker up/downdrafts, near-zero LHR, dry, warm
  - Stronger up/downdrafts, negative LHR, moist, cool
- Rain particle size distribution influence on low-level downdrafts at maturity and on cold pools at dissipation
Warm rain parameters dictate low level latent heating profiles at all times. Note bimodal solution associated with cold pools.
Mid- and Upper-Troposphere Dynamics

- Autoconversion and snow/graupel density determine mid- and upper-level updraft velocity
- Functional relationship differs for mid-level and upper-level updrafts
Summary:

- MCMC-based Bayesian sensitivity experiments identify key control parameters
- Joint PDF of parameters with model states lends information on parameter-state interaction
  
  1. Column integral constraint of microphysics parameters $\rightarrow$ constraint on cloud-scale dynamics and thermodynamic state
  2. Thermodynamics, dynamics, and cloud microphysics are tightly coupled
  
  3. There are multiple stable states in the system; different combinations of parameters produce similar integral observations in very different dynamic and thermodynamic environments
  
  4. Derivative of the response function may change magnitude and sign with changes in parameter value and physical location
Next Steps

- Expansion to other dynamical systems
  - Tropical cyclones (He et al., 2013, J. Climate)
  - Orographic precipitation (in progress)
  - Cloud-aerosol interaction (pending proposal…)
- Use of surrogate models to more efficiently generate large ensembles

References:
- Posselt and Vukicevic (2010, MWR)
- Posselt and Bishop (2012, MWR)
- van Lier-Walqui (2012, 2013, MWR)