Using Data Assimilation to Explore Precipitation - Cloud System - Environment Interactions

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Cloud System - Environment Interaction

Controls

• 3D Wind profile
• Land surface properties
• Thermodynamic environment
• Cloud microphysics
• Aerosol content and chemistry

Outcomes

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

Posselt et al., 2012 (J. Climate)
Data Assimilation: Quantifying Relationships

- The model represents the relationship between controls on, and output from, a system (e.g., cloud resolving model)
- Can assess sensitivity of output to changes in input

Can also ask which sets of inputs could have produced a given set of outputs
- Uncertainties represented as probabilities

\[ P(x|y) = \frac{P(y|x)P(x)}{P(y)} \]
Quantifying Response: Brute Force

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

Options:

- Discretize $P(y|x)$ and $P(x)$ and compute $P(x|y)$
  - Specify a range of parameter values
  - Run the model repeatedly in small increments of the control parameters

$$P(x|y) = \frac{P(y|x)P(x)}{P(y)}$$

Thorough, but very computationally expensive
Goal: estimate $P(y|x)$ and/or $P(x|y)$

Options:

- Randomly sample $P(x|y)$
  (traditional Monte Carlo, latin hypercube)
  - Evaluate $P(y|x)$ and $P(x)$
    at points randomly distributed in parameter space
  - Compute sample of $P(x|y)$
  - Fill the response surface using
    - Kernel density estimate
    - Interpolation
    - Function fitting

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

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

Options:

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

Markov chain Monte Carlo:

- Avoids states that provide a poor fit to observations
- Flexible probability distributions

Two Experiments

1. Convection – Microphysics Interaction
   - Sensitivity of convective cloud properties to changes in cloud microphysical parameters
   - Cloud microphysics – dynamics – thermodynamics interaction

2. Multivariate Sensitivity of Orographic Rainfall
   - Sensitivity of mountain rainfall to changes in mountain geometry and upwind sounding
   - Which combinations of geometry and sounding produce heavy upslope precipitation?
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1. Convection – Microphysics Interaction:

64 km (x), 24 km (y), 72 levels, dx=2km
1 x 10^6 simulations

Three phases:
- Developing: 180-230 minutes
- Mature: 230-280 minutes
- Dissipating: 280-330 minutes

Perturb cloud microphysics
- 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}
### Parameters and Observations

#### 10 Microphysics Parameters
- Snow fall speed coefficient ($a_s$)
- Snow fall speed exponent ($b_s$)
- Graupel fall speed coefficient ($a_g$)
- Graupel fall speed exponent ($b_g$)
- Cloud-rain autoconversion ($q_{c0}$)
- Slope intercept Rain ($N_{0r}$)
- Slope intercept Snow ($N_{0s}$)
- Slope intercept Graupel ($N_{0g}$)
- Snow particle density ($\rho_s$)
- Graupel particle density ($\rho_g$)

#### 5 Observations
<table>
<thead>
<tr>
<th></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>

#### Obs taken in 3 time intervals
- Developing (180-230 min)
- Mature (230-280 min)
- Dissipating (280-330 min)

Defined according to **cloud depth** and **surface rain rate**
**Parameter Sensitivity:**
**Posterior Parameter PDFs** \( P(x|y) \)

- Given a set of outcomes (Pcp, LWP, IWP, OLR, OSR)
- Which sets of parameters could have produced them?

**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 early
Warm rain and ice processes important at maturity
Ice processes control the solution late
Storm-Scale Dynamic – Thermodynamic interactions

- Bimodal solution:
  - Weaker up/downdrafts, near-zero LHR, dry, warm
  - Stronger up/downdrafts, negative LHR, moist, cool
Low level latent heating profiles sensitive to warm rain parameters at all times. Note different solutions associated with cold pools.
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2. Orographic Precipitation
(S. Tushaus, Poster 1080)

- CM1 model, stable upslope rainfall
- 2D (x-z) 800 km long, dx = 2 km, 59 levels
- Analytical moist-stable sounding, Gaussian bell mountain, warm rain microphysics
- Observe precipitation in 6 regions

6 Environment Parameters
Wind speed (U)
Moist Brunt Vaisala Freq ($N_m^2$)
Surface potential temperature ($T_s$)
Relative Humidity (RH)
Mountain height
Mountain half-width
Parameter Sensitivity

- Examine functional response of precipitation
- Explore joint parameter PDFs
Parameter Sensitivity

- Tipping point in $T_s$ ...examine change in structure
- Interaction between $T_s$ and stability
- Back-propagating mountain wave
- Strong precipitation response to a small change in profile
Multivariate Precipitation Response

- How does sensitivity change with parameter value?

Change two parameters at a time

Change all parameters simultaneously
Summary:

- MCMC-based Bayesian sensitivity experiments identify key microphysical parameters and their relationship to dynamics and environment.

- Joint PDF of parameters with model states lends information on cloud-environment interaction.

1. There are multiple stable states in each system; different combinations of parameters produce similar integral observations in very different dynamic and thermodynamic environments.

2. Convective cold pools responsive to changes in PSD parameters, but with two distinct preferred states.

3. Tipping point in orographic precipitation system: rapid change in outcome for a small change in input.

4. Strong changes in sensitivity in multivariate orographic case.
Next Steps

- Composite analysis of large ensembles of model states – processes
- Extension to other dynamical systems
  - Tropical and extratropical cyclones (in progress)
  - Cloud-aerosol interaction (in progress)
- Examination of observation information content
  - Dual-polarization radar
  - Combined cloud radar – microwave retrievals

References:
- Posselt and Vukicevic (2010, MWR)
- Posselt and Bishop (2012, MWR)
- van Lier-Walqui et al. (2012, 2014, MWR)
- Posselt, Hodyss, and Bishop (2014, MWR)
- Posselt and Mace (2014, JAMC)
PDF Sampling: Markov Chain Monte Carlo

10^6 Samples

Parameter 2

Parameter 1
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)
PSD – Cold Pool Relationships

- Rain particle size distribution influence on low-level downdrafts at maturity and on cold pools at dissipation
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Model Configuration:
- 64 x 24 km domain
- 2 km dx, dy
- 72 vertical levels
3D Control Simulation, w and cloud

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