Data Assimilation of Cloud-Affected Radiances

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Outline

• Motivation

• Methodology

• Results
  - Observation operators
  - Assimilation and verification

• Summary and conclusions
Motivation

4D atmospheric data analysis with clouds

- Initialization of atmospheric state with clouds in NWP
- Validation and advanced development of cloud microphysical parameterizations
- Dynamically consistent cloud and state climatology
Research approach: Evaluate feasibility under best scenario

- Use observations with highest expected information content with respect to clouds, including spatial and temporal variability
- Use cloud resolving model
- Use data assimilation method which allows 4D dynamically consistent analysis
OBSERVATIONS
GOES imager
and
ARM

METHOD
4DVAR data assimilation

MODEL
CRM with bulk explicit cloud microphysics

Collaborators: Tom Greenwald (CIMMS, formerly CIRA), Milija Zupanski (CIRA), Dusanka Zupanski (CIRA), Manajit Sengupta (formerly CIRA), Frank Evans (ATOC/CU) and Rosanne Polkinhorne (ATOC/CU)
### GOES imager

#### GOES Channel Wavelength (µm) Central Wavelength (µm) Detector Resolution (km)

<table>
<thead>
<tr>
<th>GOES Channel</th>
<th>Wavelength (µm)</th>
<th>Central Wavelength (µm)</th>
<th>Detector Resolution (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.52-0.72</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3.78-4.03</td>
<td>3.9</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>6.47-7.02</td>
<td>6.7</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>G12</td>
<td>5.77-7.33</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>10.2-11.2</td>
<td>10.7</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>11.5-12.5</td>
<td>12.0</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>G12</td>
<td>12.9-13.7</td>
<td>8</td>
</tr>
</tbody>
</table>

15 minute data

**Vis**
- Near IR Diff between ice and water clouds
- IR upper water vapor
- IR clouds and surface
- IR clouds, surface and low level vapor
Cloud resolving model representation of cloudy atmosphere

CRTMs have skill

CRTM simulation in 300 x 300 x 17 km

domain starting from a crude 3D analysis

Pristine ice

Mixed phase

Horizontal circulation

Vertical circulation

Liquid cloud

rain
CRTM in this study

RAMS

- Bulk, 2 moment cloud microphysics for ice: pristine ice, aggregates, snow, graupel and hail
- 1 moment for liquid: cloud droplets and rain
- Prognostic mixing ratio and number concentration for ice
- Assumed Gamma distribution with prescribed width
- Nonhydrostatic dynamics
- High resolution regional simulations
Regional Atmospheric Modeling and Data Assimilation System (RAMDAS)

Vukicevic et al, 2004, 2005
Zupanski et al, 2005

**NWP models**
- Mesoscale atmospheric forecast model with explicit cloud microphysics (RAMS)
- Land model coupled to RAMS (LEAF2)

**Observational Operators**
- Satellite observational operator: Cloud property, gas extinction and radiative transfer models
- Station standard and precipitation observational operators (WRF 3DVAR interface)

**4DVAR data assimilation algorithm**
Main features:
- Full physics nonlinear and adjoint models
- Model error (Eta 4dvar)
- Preconditioning (Eta 4dvar)
- Background error (compactly supported, space limited correlations)

**Observations**
- Satellite visible, IR and microwave radiance
- Station surface and upper air
- Precipitation

**Controls include cloud and dynamical variables**

**NWP model adjoints**
- Adjoint of LEAF2
- Adjoint of RAMS

**Observational Operator adjoints**
- Adjoint of satellite observational operator

Adjoint of cloud microphysics and radiative transfer

Arrows show direction of data flow
**Observation operator**

**VIS and IR radiative transfer**

\[ y = H(X^t) + \varepsilon_y \]

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**Version 1**

Greenwald et al. 2003
Gas absorption: OPTRAN (McMillin et al., 1995)
Cloud properties: Anomalous Diffraction
Solar: SHDOM (Evans, 1998)
IR: Eddington two-stream (Deeter and Evans 1998)

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**Version 2**

SHDOMPPDA (Evans, 2007)
SHDOMPPDA operator
Evans (2007, JAS)

- Development was supported by JCSDA and NSF-ATM

- Unpolarized, plane parallel RT model with adjoint and tangent linear models

- Hydrometeor optical properties are determined from lookup tables as function of mass mean radius

- Scattering by look-up tables
  - Mie theory for spherical particles with Gamma or Lognormal size distributions
  - Gamma size distribution of mixture of 6 ice crystal shapes (Yang et al., 2005)
Information content of GOES imager observations
VIS and IR information content analysis
Example of a case with mixed phase clouds

- Vertical and horizontal variability
- Sensitivity to multiple cloud layers

Greenwald et al, 2004
Sensitivity by optical properties and hydrometeor type

0.63 µm
- Extinction coefficient
- Single-scatter albedo
- Asymmetry factor

0.63 µm
- Cloud drops
- Pristine ice
- Aggregates
- Snow
- Graupel
- Hail
- Rain

3.92 µm

3.92 µm

10.7 µm

10.7 µm
Assimilation experiments

• Set 1 (Version 1 observation operator)
  • Case with 100% cloud cover in the model domain
  • Crude estimates of data assimilation parameters
  • GOES IR only
  • Sensitivity to observations

• Set 2 (SHDOMPPDA operator)
  • Estimates of background biases and error correlation length from model validation with observations
  • Use of cloud mask in quality control
  • Cases with mixed clear and cloudy scenes
  • Sensitivity to data assimilation parameters
Set 1 (Vukicevic et al, 2004, 2006)

Assimilation of GOES imager IR multi-layered stratiform case

Model 3D cloud

Optically thin cirrus

ARM central site

Observations every 15 min

End time shown
Large amplitude bias and poor spatial variability are corrected simultaneously.

**Prior**

**Observations**

1 h window, every 15 min end time shown

**Posterior**
GOES imager IR error statistics (model - observation)

prior

Brightness Temperature

mean = 33 K
sd = 8.2 K

posterior

Brightness Temperature

mean = 0.3 K
sd = 5.9 K
Verification with independent cloud observations

ARM Cloud Radar reflectivity

Observations

Posterior

Prior

Time

Ice cloud

Liquid cloud
Complementary information from IR channels

Sensitivity of Tb in 10.7nm and 12.0 nm to clouds is very similar.

Model - Observations
brightness temperature
Sensitivity to observation frequency

Tb errors

Worst

10.7 \mu m

12.0 \mu m

Guess

Single channel assimilations, 30 min frequency

2-channel assimilation, 30 min frequency

2-channel assimilation, 15 min frequency
Set 2

- Estimate of background biases and error correlation length from model validation with observations
- Use of cloud mask in quality control
- Cases with mixed clear and cloudy scenes
- Assimilation of visible and ground-based ARM observations
- Sensitivity to data assimilation parameters
  - QC
  - Background error decorrelation length
  - Spatial smoothing in RAMS adjoint
  - Length of assimilation window
Estimates of background statistics using GOES imager and ARM data (Polkinghorne et al., 2008)

- 280 verification times
- Domain centered on ARM central facility
- Grid \( dx=4\text{km} \)

**Clear sky**: emphasis on surface temperature bias
Biases in cloudy conditions

Average residuals - low cloud - overall

Low clouds

Average residuals - high cloud - overall

High clouds
Large biases in cloudy condition motivate design of cloud mask for QC

Figure 4: A flowchart representing the cloud mask algorithm. $T_b$ is brightness temperature, $T_{b4}$ is GOES channel 4 brightness temperature, $T_{b5}$ is GOES channel 5 brightness temperature, $R$ is GOES channel 1 reflectivity.
Background error correlation for cloud variables
Experiments with mixed clear and cloudy scenes
(Polkinghorne and Vukicevic, 2010)

Observed and background IR

Figure 2: a) observed and b) simulated GOES channel 4 on Mar 21, 2000 at 1109, 1139, and 1210 UTC.

Figure 3: a) observed and b) simulated GOES channel 4 on Mar 28, 2000 at 1818, 2039, and 2110 UTC.
### Sensitivity experiments to data assimilation parameters

<table>
<thead>
<tr>
<th>Exp #</th>
<th>Sensitivity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Simple QC mask, residuals greater than 50 K excluded</td>
</tr>
<tr>
<td>1a</td>
<td>Cloud mask applied, hh residuals greater than 20 K excluded</td>
</tr>
<tr>
<td>1b</td>
<td>Cloud mask applied, hh residuals greater than 30 K excluded</td>
</tr>
<tr>
<td>1c</td>
<td>Cloud mask applied, hh residuals greater than 40 K excluded</td>
</tr>
<tr>
<td>1d</td>
<td>Cloud mask applied, hh residuals greater than 50 K excluded</td>
</tr>
<tr>
<td>2a</td>
<td>Experiment 1d with smoother applied to the adjoint solution, span=1</td>
</tr>
<tr>
<td>2b</td>
<td>Experiment 1d with smoother applied to the adjoint solution, span=2</td>
</tr>
<tr>
<td>3</td>
<td>Experiment 1d with background decorrelation length=100 km</td>
</tr>
<tr>
<td>4</td>
<td>Experiment 1d with longer assimilation window</td>
</tr>
<tr>
<td>5a</td>
<td>Experiment 1d with ground-based data assimilated at satellite assimilation times</td>
</tr>
<tr>
<td>5b</td>
<td>Experiment 1d with ground-based data assimilated every 5 minutes</td>
</tr>
<tr>
<td>5c</td>
<td>Experiment 5b with the background decorrelation length=100 km</td>
</tr>
<tr>
<td>6</td>
<td>Experiment 3 with assimilation of GOES channels 1 and 2</td>
</tr>
</tbody>
</table>
Application of cloud mask in QC

- Black contours mark boundary of regions within which the observations are used in assimilation.
- Color shows impact of observations in the experiment with 2 h assimilation window.
Bulk results: convergence and global fit to observations

- Different convergence rate
- Similar final global fit to observations

See additional slides for description of experiments.
Quality of analysis

• Despite small differences in the global fit to observations there are significant differences in quality of analysis between different experiments

• Best analysis is produced in the experiments that include the cloud mask in QC together with large allowed maximum residual, observation based decorrelation length and longer assimilation window

• Small but positive impact of VIS and ground-based remote sensing observations
Example of best analysis

Background
Resulting 4D cloud analysis

Example vertical cross-section

R_PICE at lat=37.03 - exp4 i10-i01
Impact of longer assimilation window
less noise/more balance
Summary

• 4D, dynamically consistent analysis of cloudy atmosphere by assimilation of GOES imager observations is feasible
• The assimilation benefits from the use of cloud-mask based QC with large maximum residuals
• Balanced analysis requires sufficiently long assimilation window
• More frequent observations improve the analysis
• Window IR channels have complementary information
• Assimilation of visible observations has small impact in the studied cases that are dominated by ice clouds
• Assimilation of ground based remote sensing has small but positive local impact