Assimilation of all-sky infrared radiance from geostationary satellites

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New Satellites! Himawari-8 AHI & GOES-R ABI

Launch Dates:
- Oct 2014 (Himawari-8, Japan)
- Oct 2016 (GOES-R, USA)

Coverage: Hemispheric
Frequency: 10-15 minutes
Resolution: 2 km

Weighting functions on WV channels

<table>
<thead>
<tr>
<th>Water Vapor Channels</th>
<th>Pressure (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band-8</td>
<td>6.19µm</td>
</tr>
<tr>
<td>Band-9</td>
<td>6.95µm</td>
</tr>
<tr>
<td>Band-10</td>
<td>7.34µm</td>
</tr>
</tbody>
</table>

(Otkin 2012)
EnKF & CRTM
Zhang et al. (2009); Weng and Zhang (2012)

\[ X^a = X^b + K \left( y - h(X^b) \right) \]

Community Radiative Transfer Model
(CRTM; Han et al. 2006)

Ensemble-based data assimilation system
- Ensemble size: 60

Regional convective-permitting model
- Resolution: 27, 9 & 3 km (D1-D3)

Observation error modeling
- Adaptive Observation Error Inflation
  (Zhang, Minamide & Clothiaux, 2016, Minamide & Zhang, in prep)
Truth run: **Hurricane Karl**, 21Z 16 – 00Z 18 SEP 2010
Resolution: **27, 9 & 3 km (D1-D3)**, EnKF only for D3

Synthetic observations:
- Every 10 min: Infrared BT (ch8,9&10)
- Every 1 hour: minSLP

**BT + HPI**

**HPI**
Observing System Simulation Experiments (OSSE)

Truth run: **Hurricane Karl**, 21Z 16 – 00Z 18 SEP 2010
Resolution: **27, 9 & 3 km (D1-D3)**, EnKF only for D3
EnKF Performance on IR Brightness Temperature

Brightness Temperature of GOES-R ABI Ch14 (11.2 µm)

Verifying Truth

EnKF Analysis (BT+HPI)

EnKF Analysis (HPI)

Zhang, Minamide & Clothiaux, 2016, GRL
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EnKF Analysis (BT+HPI)

EnKF Analysis (HPI)

Convective cells
Primary rainband
Eyewall

Zhang, Minamide & Clothiaux, 2016, GRL
- The longer the assimilation, the better the analysis.
- Analysis is capable of capturing the intensity changes.

Zhang, Minamide & Clothiaux, 2016, GRL
EnKF Performance on 10-m wind speeds

Verifying Truth

EnKF Analysis (BT+HPI)

EnKF Analysis (HPI)

Maximum wind & TC size

Secondary horizontal wind maximum

Zhang, Minamidé & Clothiaux, 2016, GRL
EnKF Performances on Hurricane Karl (2010)

Imperfect-model-OSSE

Real-data-GOES-13 assimilation

Verifying Truth

EnKF Analysis

Observation

EnKF Analysis

Zhang, Minamide & Clothiaux, 2016, GRL
- CRTM has been combined to the PSU WRF-EnKF to directly assimilate satellite infrared brightness temperature.

- OSSE and GOES-13 real-data assimilation experiments showed EnKF assimilation of all-sky infrared brightness temperature can well capture detailed structure of tropical cyclones.

- Assimilation of Himawari8-observed real-data is underway.
The CRTM with Microphysics Scheme-Consistent Cloud Optical Properties

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Department of Meteorology and Center for Advanced Data Assimilation and Predictability Techniques (ADAPT), The Pennsylvania State University

This study is supported by NSF GRFP and ONR
Initial goal: to assimilate precipitation-affected microwave imaging channels in regional-scale model (e.g., Zhang et al. 2013), as Masashi is doing for IR
- Good progress at global DA centers (e.g., Bauer et al. 2014, Kazumori et al. 2016)

Had difficulty producing realistic CRTM microwave radiative transfer results in precipitation areas
- Fixed effective radii with values based on literature (~1000 μm) → too much scattering
- Mean particle size as effective radius → too little scattering
Desired cloud scattering in the CRTM to be consistent with our mesoscale NWP model (WRF) output

- Either monodisperse or using generalized gamma particle size distribution (PSD):
  \[ N(r) = N_0 r^\mu \exp(-\lambda r) \]

- Marshall-Palmer (1948) distribution: \( \mu = 0 \)
Our solution: new cloud optical property lookup tables in CRTM

- Method 1, “Distribution-Specific”: scheme-specific cloud scattering property lookup tables

- Method 2, “Generalized-Bin”: particle scattering property lookup tables
  - Scheme information and integration of particle size distributions within CRTM

■ Mie theory single-particle scattering by soft spheres as specified by schemes
Use model forecast output from Hurricane Karl EnKF analysis (3-hour forecast, 3 km grid spacing domain):

- **Modified CRTM, Distribution-Specific (Method 1)**
- **Modified CRTM, Generalized-Bin (Method 2)**
  - 32, 64 or 128 bins spaced log-linearly between 1 μm and 10000 μm
- **Unmodified CRTM (effective radii)**
  - Mean particle size: \( r_{eff} = (\mu + 1)\lambda^{-1} \)
  - Mean radius for scattering (Hansen and Travis 1974):
    \( r_{eff} = (\mu + 3)\lambda^{-1} \)
  - Prescribed for each species, uniform in space
    - Values chosen to produce simulations matching well to observations and be physically reasonable
Results, WSM6 Scheme

SSMI/S Observations

scheme-consistent mean size effective radius Hansen and Travis (1974) effective radius

CRTM

37.0 GHz

91.66 GHz

36.5 GHz

89.0 GHz

36.5 GHz

89.0 GHz

36.5 GHz

89.0 GHz

90

120

150

180

210

240

270

300

Brightness Temperature (K)
Results, Morrison and Goddard Schemes

Goddard (Lang et al. 2007)

SSMI/S

Morrison (Morrison et al. 2014)

fixed and tuned effective radii

scheme-consistent

Brightness Temperature (K)
Generalized-Bin Results (WSM6)

SSMIS 91.66H

Generalized-Bin 128
89.0H

Generalized-Bin 64
89.0H

Generalized-Bin 32
89.0H

Distribution-Specific
89.0H

Difference using
128 Bins

Difference using
64 Bins

Difference using
32 Bins

Brightness Temperature Difference (K)
Concluding Remarks

- Successful scheme-consistent cloud radiative properties in the CRTM
  - Simulation bias to observations (too much scattering) consistent with other radar and passive microwave studies

- Brightness temperatures more similar to observations are possible with unmodified CRTM
  - Apparently compensating for errors in CRTM and microphysics

- Scheme-consistent cloud scattering necessary for model evaluation/constraining with observations
References


Assimilation of precipitation information can be productive with cloud scattering inconsistent with microphysics schemes
- Particle shape and bulk density is first priority; it will be a

Constraining microphysics schemes with remote sensing data?
- Will require accurate radiative transfer in all components. Can it be fast enough for operations?
- Can microphysics be sufficiently accurate and complex? (Field et al. 2007)
- Constrain both physical attributes and processes?

As microphysics improve, scheme-consistent cloud scattering should provide optimal data assimilation
- Particle size distributions is first priority
- Habit prediction is probably necessary, has potential (citations)
<table>
<thead>
<tr>
<th></th>
<th>Brightness Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a1)</strong> Consistent Clouds</td>
<td>10.65H</td>
</tr>
<tr>
<td><strong>b1)</strong> Consistent Clouds</td>
<td>18.7H</td>
</tr>
<tr>
<td><strong>c1)</strong> Consistent Clouds</td>
<td>23.8V</td>
</tr>
<tr>
<td><strong>d1)</strong> Consistent Clouds</td>
<td>165.5H</td>
</tr>
<tr>
<td><strong>a2)</strong> Fixed Radius</td>
<td>10.65H</td>
</tr>
<tr>
<td><strong>b2)</strong> Fixed Radius</td>
<td>18.7H</td>
</tr>
<tr>
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</tr>
<tr>
<td><strong>d2)</strong> Fixed Radius</td>
<td>165.5H</td>
</tr>
<tr>
<td><strong>a3)</strong> Mean Scattering Radius</td>
<td>10.65H</td>
</tr>
<tr>
<td><strong>b3)</strong> Mean Scattering Radius</td>
<td>18.7H</td>
</tr>
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</table>
Rain and cloud liquid net add to low water surface emission

Some scattering by precipitation ice

Scattering by precipitation ice dominates the signal
Rain and cloud liquid net add to low emission by water

Some scattering by precipitation ice

Scattering by precipitation ice dominates the signal
Experiments

Use model output from same Hurricane Karl EnKF analysis (3-hour forecast, 3 km grid spacing domain):

- Modified CRTM, Distribution-Specific (Method 1)
- Modified CRTM, Generalized-Bin (Method 2)
  - 32, 64 or 128 bins spaced log-linearly between 1 μm and 10000 μm
- CRTM with effective radii
  - Mean particle size; for generalized gamma particle size distribution,
    \[ r_{eff} = (\mu + 1)\lambda^{-1} \]  \( (\mu = 0 \text{ for Marshall and Palmer (1948)}) \)
  - Mean radius for scattering assuming \( r^2 \) relationship of particle size to scattering (Hansen and Travis 1974)
    \[ r_{eff} = \frac{\int r^3 N(r)dr}{\int r^2 N(r)dr} \]  ; for generalized gamma, \( r_{eff} = (\mu + 3)\lambda^{-1} \).
  - Prescribed for each species, uniform in space
    - Values chosen to produce simulations matching well to observations and be physically reasonable
Strong dependence of particle size to scattering: $r^6$ for 3D particles much smaller than the wavelength

- Many passive microwave radiometer wavelengths are close to the size of a significant mass of hydrometeors

Mass scattering (solid) and absorption (dashed) coefficients ($m^2 \text{ kg}^{-1}$) and sample particle mass distribution (dot-dashed; kg m$^{-3}$ µm$^{-1}$) of graupel-like ice spheres. Wavelength (blue) and one-sixth the wavelength (red) shown for reference.
Concluding Remarks

- Sufficiently accurate radiative transfer would pin the discrepancy to observations onto the NWP model
  - Not there yet with CRTM

- Sufficiently accurate and complex microphysics scheme required for scheme-consistent radiative transfer results to well-resemble observations
  - Probably not there yet with microphysics available in WRF
  - Habit prediction (Morrison et al. 2015), 1-moment bin (Khain et al. 2010), 2-moment bin
Most bulk species are assumed either monodisperse, or having a generalized gamma particle size distribution (PSD):

\[ N(r) = N_0 r^\mu \exp(-\lambda r), \]

- Common is Marshall-Palmer (1948) distribution: \( \mu = 0 \)

Most frozen species assumed to be homogeneous “soft spheres”

- Mie theory well-represents scattering and absorption

Schemes differ by some PSD parameter values and particle properties
WRF output provides cloud species and mass, but no particle size information for assigning effective radii (must obtain from literature and source code)

- Most bulk species are assumed monodisperse, or having a generalized gamma particle size distribution (PSD):
  \[ N(r) = N_0 r^\mu \exp(-\lambda r), \]
  - Common is Marshall-Palmer (1948) distribution: \( \mu = 0 \)

Did not know how to best interface microphysics schemes to the CRTM via effective radius

- There is little CRTM documentation on effective radius
- Assume it relates in some way to a generalized gamma particle size distribution (perhaps monodisperse for cloud water and ice)
Even when using the most appropriate effective radius, cloud scattering may be inconsistent

- Differences in particle shapes, bulk densities and size distributions are relevant (e.g., Geer and Baordo 2014, Mitchel 2001)

- e.g, WSM6: graupel bulk density, snow particle size distribution

Our solution: new cloud optical property lookup tables in CRTM

Mass scattering (solid) and absorption (dashed) coefficients (m² kg⁻¹) and sample particle mass distribution (dot-dashed; kg m⁻³ μm⁻¹) of graupel-like ice spheres.

Wavelength (blue) and one-sixth the wavelength (red) shown for reference.
Problem: erroneous analysis increments

If Model (clear / cloudy) ≠ Observation (cloudy / clear)

In updating SLP, \( \frac{12.5 \times hPa \times K}{3^2 + 5^2[K^2]} \times 40[K] \approx 15[hPa] \)

AOEI: inflating observation error variance

\[
\sigma_{o-AOEI}^2 = \max \left\{ \sigma_o^2, [y_o - h(x_b)]^2 - \sigma_h^2(x_b) \right\}
\]

With AOEI, \( \frac{12.5 \times hPa \times K}{40^2[K^2]} \times 40[K] \approx 0.3[hPa] \)

AOEI suppresses erroneous analysis increments, relieves the issues of representativeness & sampling, & contributes to maintaining balance.