Assimilation of Cloud-Affected Infrared Radiances at Environment-Canada

ECMWF-JCSDA Workshop on Assimilating Satellite Observations of Clouds and Precipitation into NWP models
ECMWF, Reading (UK)
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Tuesday, June 15th, 2010
Outline

• Description of the AIRS and IASI instruments
• Assimilation of cloud unaffected IR radiances at EC
• Comparison of approaches using cloud effective parameters
• Assimilation of cloud affected IR radiances at EC
• A first 4D-Var assimilation cycle
• A second 4D-Var assimilation cycle
• Conclusions
Description of the AIRS and IASI Instruments:

**AIRS Instrument Overview**

- High spectral resolution infrared vertical sounder (grating spectrometer with 2378 channels between 15.5 μm and 3.6 μm) onboard AQUA: provides information on temperature, humidity, ozone, etc…

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**The A-Train**

The A-Train is a constellation of nine Earth-observing satellites that work together to provide a comprehensive view of the Earth’s atmosphere and oceans. The satellites include:

- **Aqua**: Launched in 2002, Aqua carries the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS).
- **CloudSat**: Launched in 2006, CloudSat is a cloud-profiling radar that provides information on the vertical structure of clouds.
- **CALIPSO**: Launched in 2006, CALIPSO carries the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) instrument, which uses laser pulses to measure cloud height and aerosol content.
- **OCO**: Launched in 2014, OCO is designed to measure carbon dioxide concentrations in the atmosphere.
- **PARASOL**: Launched in 2007, PARASOL is a polarimetric and spectropolarimetric instrument that provides information on the polarization properties of aerosols and clouds.
- **Aura**: Launched in 2004, Aura carries the Ozone Monitoring Instrument (OMI) and the Microwave Limb Sounder (MLS).
- **MYDART**: Launched in 2004, MYDART is a cloud and precipitation radar onboard Aqua.
- **CloudSat**: Launched in 2006, CloudSat is a cloud-profiling radar that provides information on the vertical structure of clouds.
- **CALIPSO**: Launched in 2006, CALIPSO carries the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) instrument, which uses laser pulses to measure cloud height and aerosol content.

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**Typical One-Day Scan Pattern**

The A-Train satellites follow a specific scan pattern to ensure coverage of the Earth's surface. The scan pattern is designed to cover all parts of the Earth's surface at least once a day, while also providing detailed data on specific regions.

**AIRS/AMSU FOV**

- **1.1 x 0.6 AIRS**
- **25% Underlap at Nadir**
- **NADIR**
- **3.3 AMSU-A**

**AIRS Scan Geometry**

- **Altitude: 705 km**
- **Scan Period: 2.667 s**
- **Ground Footprints: 90/Scan**

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**Diagram**

The diagram illustrates the relative positions of the A-Train satellites and the typical one-day scan pattern they follow. The scan pattern is designed to ensure comprehensive coverage of the Earth's surface, while also providing detailed data on specific regions.
Description of the AIRS and IASI Instruments:
IASI Instrument overview

- Infrared Atmospheric Sounding Interferometer
- Flying onboard the METOP-A European operational satellite (sun-synchronous polar orbit, mean equator crossing time 09.30, descending node)
- Provides high resolution spectra (apodised resolution of 0.5 cm\(^{-1}\)) of the infrared radiation emitted by earth/atmosphere between 645 cm\(^{-1}\) and 2760 cm\(^{-1}\) in 8461 channels

Typical full resolution spectrum

Radiometric noise characteristics
Description of the AIRS and IASI Instruments:
AIRS and IASI Channels Selected for Assimilation at EC

<table>
<thead>
<tr>
<th></th>
<th>LW T channels (15 μm)</th>
<th>Boundary layer channels (above sea only)</th>
<th>Ozone channels</th>
<th>H₂O channels (6.3 μm)</th>
<th>SW T channels</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational</td>
<td>20</td>
<td>10</td>
<td>33</td>
<td>24</td>
<td></td>
<td>87</td>
</tr>
<tr>
<td>Control 1</td>
<td>20/43</td>
<td>10/19</td>
<td>33/66</td>
<td>24</td>
<td></td>
<td>87/128</td>
</tr>
<tr>
<td>Exp1. when cloud-affected</td>
<td>20/43</td>
<td>10/19</td>
<td>33/66</td>
<td></td>
<td></td>
<td>53/128</td>
</tr>
<tr>
<td>Control 2</td>
<td>55/53</td>
<td>10/19</td>
<td>33/10</td>
<td>24</td>
<td></td>
<td>122/82</td>
</tr>
<tr>
<td>Exp2. when cloud-affected</td>
<td>55/53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55/53</td>
</tr>
</tbody>
</table>
Assimilation of Cloud Unaffected IR Radiances at EC

- Accepted channel
- Rejected channel
- Security margin
- Cloud height from CO₂ slicing
- Height where response becomes significant

\[ \frac{d\tau}{dP} : \text{local response function from RTTOV output} \]
Assimilation of Cloud Unaffected IR Radiances at EC: Severe Limitation in the Number of Assimilated Radiances

87 AIRS channels assimilated in *clear sky* case over ocean

No AIRS channel assimilated for $P_c < 400$ hPa
### Comparison of Approaches Using Effective Parameters (1/2)

<table>
<thead>
<tr>
<th>Background value for cloud parameters</th>
<th>UKMET</th>
<th>Meteo-France</th>
<th>ECMWF</th>
<th>CMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>From 1Dvar initialized by minimum residual (9 channels) method with big background errors</td>
<td>CO\textsubscript{2} slicing (124 pairs with the same reference channel at 979.13 cm\textsuperscript{-1})</td>
<td>Minimum residuals (using 2 or 3 channels)</td>
<td>CO\textsubscript{2} slicing (13 pairs of channels with different reference channels)</td>
<td></td>
</tr>
</tbody>
</table>

| Variable cloud parameters in 4D-Var? | no | no | yes | yes |

<table>
<thead>
<tr>
<th>Cloud parameters</th>
<th>P\textsubscript{c}, N\varepsilon</th>
<th>P\textsubscript{c}, N\varepsilon</th>
<th>P\textsubscript{c}, N\varepsilon</th>
<th>P\textsubscript{c}, \delta, r\textsubscript{e}, D\textsubscript{e}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(only P\textsubscript{c} is variable)</td>
<td>(only the 2 first are variable)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison of Approaches Using Effective Parameters (2/2)

<table>
<thead>
<tr>
<th>Conditions for cloudy assimilation</th>
<th>UKMET</th>
<th>Meteo-France</th>
<th>ECMWF</th>
<th>CMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above sea Radiances weakly affected by clouds</td>
<td>Above sea. 600 hPa&lt;Pc&lt;950 hPa, Nε &gt;0.1</td>
<td>Above sea 100 hPa&lt;Pc&lt;900 hPa, Overcast cloud</td>
<td>Above sea. 250 hPa&lt;Pc&lt;Ps-, 100 hPa, Nε &gt;0.75</td>
<td></td>
</tr>
</tbody>
</table>

| Cloud ε modeling | no | no | no | yes |

| Obs. error for cloud params. | 0 | 0 | 5 hPa for Pc, 0 for Nε | from CO₂ slicing estimates |

| Implemented operationally ? | yes | yes | yes | no |

| Assimilated channels | 92 AIRS for 1D-Var preprocessing In 4D-Var ? | 54 in the CO₂ 15 μm band (AIRS) | Same as cloud unaffected cases except for SW channels | 15 μm CO₂ only |
Assimilation of Cloud Affected IR Radiances at EC: Simplified Cloudy Radiance Modeling With Effective Cloud Parameters (1/2)

- Simplified description of the cloud radiative effect for a cloud located at \( P_c \) with cloud emissivity spectrum \( N\varepsilon(\nu) \):

\[
l_{\text{cld}}(\nu) = N\varepsilon(\nu)l_{\text{ovc}}(\nu, P_c) + (1 - N\varepsilon(\nu))l_{\text{clr}}(\nu)
\]

- \( l_{\text{cld}}(\nu) \): Cloudy radiance
- \( N\varepsilon(\nu) \): Cloud effective emissivity
- \( l_{\text{ovc}}(\nu, P_c) \): Cloudy overcast radiance
- \( l_{\text{clr}}(\nu) \): Clear radiance
Assimilation of Cloud Affected IR Radiances at EC: Simplified Cloudy Radiance Modeling With Effective Cloud Parameters (2/2)

• Cloud emissivity model:

\[ N\varepsilon(\nu) = 1 - \exp\left(-k_{cld}(\nu, r_e, D_e)\delta \right) \]

- \( r_e \): effective radius for liquid phase (set to 12 \( \mu \)m)
- \( D_e \): effective diameter for ice phase (set to 55 \( \mu \)m)
- \( \delta \): effective cloud water path

• Up to date optical properties of liquid and solid (ice) water are used

• Scattering is accounted for approximately

• **It is implicitly assumed that the cloud covers the whole field of view**

• First guess and background values determined from CO\(_2\) slicing for \( \delta \) (via retrieved \( N\varepsilon \)) and \( P_c \)
Assimilation of Cloud Affected IR Radiances at EC: Proposed 3D/4D-Var Assimilation

- Addition to the state vector $\mathbf{x}$ of a local estimate of the 4 cloud parameters at each AIRS observation location

$\mathbf{x}$: model fields

$\mathbf{z}$: vector of local effective parameters:

$\mathbf{z} = (P_{c1}, \delta_{1}, r_{e1}, D_{e1}, \ldots, P_{ci}, \delta_{i}, r_{ei}, D_{ei}, \ldots, P_{cn}, \delta_{n}, r_{en}, D_{en})$

$\mathbf{x} \rightarrow \tilde{\mathbf{x}} = (\mathbf{x}, \mathbf{z})$ State augmentation

$\dim(\mathbf{x}) \sim 10^6 - 10^7$

$\dim(\mathbf{z}) = 4N_{\text{obs}} \sim 10^4$

$J_c(\tilde{\mathbf{x}}) = \begin{cases} (\mathbf{x} - \mathbf{x}_b)^\top B^{-1}(\mathbf{x} - \mathbf{x}_b) & \text{Background term} \\ (\mathbf{z} - \mathbf{z}_b)^\top C^{-1}(\mathbf{z} - \mathbf{z}_b) & \text{Cloudy background term} \\ (H_c(\tilde{\mathbf{x}}) - \mathbf{y})^\top O^{-1}(H_c(\tilde{\mathbf{x}}) - \mathbf{y}) & \text{Observation term with cloud} \end{cases}$

$\mathbf{z}_b$: cloud background state from CO$_2$ slicing and climatology

$H_c$ cloudy observation operator combining RTTOV 8.7 and the cloud emissivity model
Minimization of the cost function is more difficult in 4D-Var mode than it was in 3D-Var mode.

→ Need for a preconditioning with the diagonal of the hessian Matrix for cloud parameters

\[ z \rightarrow Z = C(z - z_b) \]

Where \( z \) is a cloud parameter

\[
C = \sqrt{\frac{1}{\sigma_c^2} + \sum_{\text{channels } i} \left( \frac{1}{\sigma_{oi}} \frac{\partial H_i}{\partial z} \right)^2}
\]

Instead of

\[
C = \frac{1}{\sigma_c}
\]

\( \sigma_c \) represents the error associated with the cloud parameter \( z \)

\( \sigma_{oi} \) represents the observation error of channel \( i \)

\( H \) is the radiative transfer operator
A First 4D-Var Assimilation Cycle : Description of the 4D-Var Experiments

- Background error for cloud parameters :

\[
\sigma_{bP_c} = \frac{2.0}{\partial BT_{window} / \partial P_c}
\]

\[
\sigma_{b\delta} = \frac{2.0}{\partial BT_{window} / \partial \delta}
\]

Description of the model

- GEM global model
- 800x600 grid
- 80 vertical hybrid levels with a top at 0.1 hPa
A First 4D-Var Assimilation Cycle:
Quality Control Criteria for Cloud-affected Radiances
Experiment 1

- Assimilation of cloudy radiances above sea only
- No assimilation of AIRS shortwave channels
- \(250 \text{ hPa} < P_c < P_s - 100 \text{ hPa}\)
- Restriction to near overcast situations \((N_\varepsilon > 0.9)\)
- Exclusion of situations with temperature inversion leading to an ambiguous solution for the CO\(_2\) slicing algorithm
- Restriction to situation where the solution of the CO\(_2\) slicing is well defined \((\sigma_{Pc} < 50 \text{ hPa}, \sigma_{N_\varepsilon} < 0.1)\)
- To limit the impact of uncertainty on cloud phase:

\[
\left| \left( \varepsilon_{ice} - \varepsilon_{liquid} \right) \frac{\partial T_B}{\partial \varepsilon} \frac{1}{\sigma_{obs}} \right| \leq \frac{1}{4}
\]
A First 4D-Var Assimilation Cycle: Description of the 4d-var Experiment 1

From 12/15/2008 to 01/08/2009 (25 days).

• **Control 1 experiment:**
  - Conventional data (radiosondes, etc…).
  - Quickscat winds.
  - AMSU-A and AMSU-B microwave radiances.
  - SSM-I and SSM-I-S microwave radiances.
  - **GEORAD radiances.**
  - AIRS infrared radiances (87 channels).
  - **IASI infrared radiances (128 channels).**
  - GPS radio-occultation (refractivity profiles).
  - **Humidity from planes.**

• **Cloudy 1 test experiment:** same as above + AIRS and IASI in cloudy mode with bias correction represented by a constant (instead of A*BT+B in the control run).
A First 4D-Var Assimilation Cycle: IASI Obs-first Guess Statistics 6h Period

- Residual bias for cloudy radiances not negligible
- Cloudy standard deviation lower for water vapor sensitive channels
- Very similar standard deviation for temperature channels

<table>
<thead>
<tr>
<th></th>
<th>CONTROL1</th>
<th>CLOUDY1</th>
<th>INCREASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS</td>
<td>2997 FOVS</td>
<td>3185 FOVS</td>
<td>+6% FOVS</td>
</tr>
<tr>
<td></td>
<td>66189 rad.</td>
<td>71939 rad.</td>
<td>+8% RAD.</td>
</tr>
<tr>
<td>IASI</td>
<td>3958 FOVS</td>
<td>4258 FOVS</td>
<td>+7% FOVS</td>
</tr>
<tr>
<td></td>
<td>155696 rad.</td>
<td>183042 rad.</td>
<td>+17% RAD.</td>
</tr>
</tbody>
</table>

- BIAS IASI
  - Residual bias for cloudy radiances not negligible
- STD IASI
  - Cloudy standard deviation lower for water vapor sensitive channels
  - Very similar standard deviation for temperature channels
A First 4D-Var Assimilation Cycle: IASI Obs-analysis Statistics 6h Period

- Persistant residual bias for cloudy radiances
- Similar standard deviation after assimilation except for channels close to 2000 cm\(^{-1}\)
A First 4D-Var Assimilation Cycle:
Validation of Forecasts Against Radiosondes: North America 72 H

Legend:
- Control is better
- Test is better
A First 4D-Var Assimilation Cycle:
Validation Against Analyses North America
Temperature Anomaly Correlation

Control Experiment

200 hPa
500 hPa
850 hPa

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A First 4D-Var Assimilation Cycle
Validation Against Analyses Tropics
Temperature Anomaly Correlation

Control Experiment

200 hPa 500 hPa 850 hPa
A First 4D-Var Assimilation Cycle: Lessons Learned From First 4dvar Experiment (and Others)

- A positive impact was demonstrated locally in North America.
- Some channels selected in both control and test experiments (extra stratospheric channels and IASI water vapor channels) are problematic and could be responsible for some of the observed problems.
- The constant bias correction used in the cloudy experiment 1 is sub-optimal. Furthermore a air mass predictor based bias correction was shown to improve our clear radiance assimilation and is also suitable for cloudy radiances.
- Some channels far (spectrally) from the 15 μm CO₂ band seem to be problematic from their O-F and O-A statistics.
- The extra data volume was relatively small and could be increased by decreasing our threshold on cloud effective fraction from 0.9 to 0.75.
A Second 4D-Var Assimilation Cycle: Quality Control Criteria for Cloud-affected Radiances Assimilation Experiment 2

- Assimilation of cloudy radiances above sea only (slightly revised criteria)
- **Restriction of the assimilation of cloud-affected radiances to the 15 μm longwave temperature sounding channels**
- \( P_s - 100 \text{ hPa} < P_c < 250 \text{ hPa} \)
- **Restriction to close to overcast situations \((N_\varepsilon > 0.75)\)**
- Exclusion of situations with temperature inversion leading to an ambiguous solution for the CO\(_2\) slicing algorithm
- Restriction to situation where the solution of the CO\(_2\) slicing is well defined \((\sigma_{P_c} < 50 \text{ hPa}, \sigma_{N_\varepsilon} < 0.1)\)
- Criteria on cloud phase related to emissivity model is longer necessary if cloudy assimilation is restricted 15 μm channels
A Second 4D-Var assimilation cycle: Description

Winter 2008/2009

- Bias correction from A*BT+B to air mass predictors
- **Reduced Spatial thinning (250 km → 150 km)**
- **Control 2 experiment** ad before except for:
  - AIRS infrared radiances (122 channels)
  - **IASI infrared radiances (82 channels)**
- **Test 2 experiment**: same but with assimilation of AIRS and IASI in cloudy mode
Conclusions

• EC assimilation system is extended to assimilate cloudy radiances in 4D-Var mode
• The assimilation is robust and the additional computational cost is modest
• The system takes into account the spectral variation of cloud optical properties
• Results of first 4D-Var assimilation experiments (3 weeks) indicate a mix of slightly positive and negative impacts
• New assimilation experiments currently running
SPARE SLIDES
### Details of AIRS and IASI Channels Selected for Assimilation

<table>
<thead>
<tr>
<th>cm$^{-1}$</th>
<th>Spectral bands</th>
<th>AIRS</th>
<th>IASI</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 – 770</td>
<td>Temperature Sounding (CO2 Band)</td>
<td>20 + 37</td>
<td>65</td>
</tr>
<tr>
<td>770 – 980</td>
<td>Surface and cloud properties</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>1000 – 1070</td>
<td>Ozone sounding</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1070 – 1150</td>
<td>Surface and cloud properties</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>1210 – 1650</td>
<td>Water vapor temperature sounding</td>
<td>33</td>
<td>55</td>
</tr>
<tr>
<td>1650 – 2100</td>
<td>Water vapor temperature sounding</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>2100 – 2150</td>
<td>CO column amount</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2150 – 2250</td>
<td>Temperature sounding</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>2350 – 2420</td>
<td>Temperature sounding (CO2 Band)</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>2420 – 2700</td>
<td>Surface and cloud properties</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Examples of Cloud Emissivity Spectra

\[ \mu \]

Wavelength (\( \mu m \))

\[ \delta \]

Emissivity

Wavenumber (cm\(^{-1}\))

\( r_c = 8.0 \ \mu m \)

\( r_c = 10.0 \ \mu m \)

\( r_c = 13.0 \ \mu m \)

\( r_c = 18.0 \ \mu m \)

No AIRS channel

Environment Canada

Environment Canada

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Examples of Cloud Emissivity Spectra

![Graph showing examples of cloud emissivity spectra. The graph plots emissivity against wave number (cm⁻¹) for different values of De (diameter of cloud droplets). The graph includes data for De = 25.0 μm, De = 50.0 μm, De = 75.0 μm, and De = 100.0 μm. The graph also indicates that there is no AIRS channel at certain wavelengths.]