Experimental assimilation of cloud radar and lidar observations at ECMWF

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• New possibilities for model improvement to be explored through assimilation of data related to clouds from active and passive sensors.

• Observations providing 3D-information on clouds from space-borne active instruments on board of CloudSat & CALIPSO already available and new ones, such as EarthCARE should appear in the near future.

• To study the impact of the new observations on 4D-Var analyses and subsequent forecasts, a 1D+4D-Var technique has been selected.

Methodology:

– 1D-Var + 4D-Var approach built on experience of using such technique for operational assimilation of precipitation related observations. (Bauer et al. 2006 a, b)

– In 2-step 1D-Var + 4D-Var approach used for cloud radar reflectivity (Janisková et al. 2011) or/and lidar backscatter:
  
  ─ 1D-Var retrieval first run on the set of observations to produce pseudo-observations of temperature $T$ and specific humidity $q$ (based on evaluation of $T$ and $q$ increments both variables are modified by the assimilation of cloud related observations),

  ─ modified $T$ and $q$ profiles then assimilated in the ECMWF 4D-Var system.
**1D-Var assimilation of cloud radar and lidar observations**

- **Cloud radar reflectivities or/and lidar backscatter**
- **Observations averaged over model grid box** (T799)
- **Background T,q**
- **Moist physics + reflectivity model + backscatter model**
- **1D-Var (T,q increments)**
- **1D-Var**

Flowchart describing 1D-Var technique:

For a given observation \( y^o \), 1D-Var searches for the model state \( x=(T,q,v) \) that minimizes the cost function:

\[
J(x) = \frac{1}{2} (x - x^b)^T B^{-1} (x - x^b) + \frac{1}{2} (H(x) - y^o)^T R^{-1} (H(x) - y^o)
\]

- **Background term**
- **Observation term**

**Background**
- **Observation**

\( H = \) **nonlinear observation operator (model space \( \rightarrow \) observation space)**

- Moist physics (*cloud and convection scheme*)
- Radar reflectivity operator (*multiple scattering not considered for assimilation studies*)
- Lidar backscatter operator (*simple parametrization for multiple scattering*)

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**Data selection tools**

### Quality control:

- excluding situations when discrepancies between observations and model equivalents are large → based on statistics of first-guess (FG) departures

### Bias correction:

- Statistics based on the comparison of model FG with observations → temperature and altitude used as predictors, separately over seasons and geographical regions
- Applying correction → more Gaussian distribution of FG departures
Observation errors

Observation error = instrument error + forward modelling error + representativity error

**Instrument error:**
- CloudSat instrument random error
  \[ \Delta Z_{dB} = \frac{4.343}{\sqrt{M}} \left( 1 + \frac{1}{SNR} \right) \]
- CALIOP instrument errors evaluated from Level-1 data (background signal power st.dev. and NoiseScaleFactor) according to Liu *et al.* (2006).

**Forward modelling error:**
- Approach: – error expressing uncertainty in microphysical assumption
  – evaluation through differences between perturbed state and reference configuration
- Reflectivity/backscatter standard deviation expressed as percentage of the simulated radar reflectivity/backscatter separately for different ranges of temperature

**Representativity error:**
- Flow dependent error estimated based on statistical approach using the Structure Function Maximum (SFM) defined for different altitudes and geographical regions (Stiller 2010)
1D-Var assimilation experiments

- Assimilating different observations:
  - cloud radar reflectivity \((R)\)
  - cloud lidar backscatter \((L)\)
  - cloud radar reflectivity + lidar backscatter \((C)\)

- Observations averaged in the grid-box using:
  - full error definition
  - quality control and bias correction

- Performance of 1D-Var verified using independent observations:
  - cloud optical depth from MODIS
  - radar reflectivity or lidar backscatter when not assimilated

- Checking increments of system control variables (temperature \(T\) and specific humidity \(q\))
1D-Var of cloud radar reflectivity

Observations

First guess

Analysis_R

2007012400 over Pacific
1D-Var of cloud lidar backscatter

Observations

First guess

Analysis_L

2007012400 over Pacific
PDF of first-guess vs. analysis departures

Cloud radar reflectivity

- **FG**
- **AN: R**
- $\rightarrow 36.6$
- $\rightarrow 53.0$

- **FG**
- **AN: L**
- $\rightarrow 41.3$
- $\rightarrow 42.3$

- **FG**
- **AN: C**
- $\rightarrow 37.9$
- $\rightarrow 53.3$

Cloud lidar backscatter

- **FG**
- **AN: R**
- **R assimilated**
- **L independent**

- **FG**
- **AN: L**
- **L assimilated**

- **FG**
- **AN: C**
- **R assimilated**
- **L assimilated**
Improvement from assimilation of cloud radar and lidar observations

**RMS (OBS – FG) – RMS (OBS – AN)**

**Cloud radar reflectivity**

- Reflectivity: RMS_(obs-fg) – RMS_(obs-an) [mm⁻³ m⁻³]
- AN – radar (R)
- AN – lidar (L)
- AN – combi (C)

**Cloud lidar backscatter**

- Backscatter: RMS_(obs-fg) – RMS_(obs-an) [1000 km⁻¹ s⁻¹]
- AN – radar (R)
- AN – lidar (L)
- AN – combi (C)

Comparison for:
FG, AN against MODIS OBS ≤ 50
Cloud optical depth (independent OBS)
Increments of T and q from 1D-Var

Specific humidity [g/kg]
1D-Var - radar
1D-Var - lidar

Temperature [K]
1D-Var - radar
1D-Var - lidar
1D+4D-Var for CloudSat and CALIPSO observations

Flowchart describing 1D+4D-Var technique:

cloud radar reflectivities or/and lidar backscatter

y: observations averaged over model grid box (T799)

x_b: background T, q

H(x): moist physics + reflectivity model + backscatter model

1D-Var (T,q increments)  1D-Var

pseudo T, q observations

1D-Var

4D-Var

Observations:
- modified profiles of T and q from 1D-Var retrievals used as pseudo-observations in 4D-Var

Observation errors:
- Observation errors for T and q pseudo-observations:
  - derived from 1D-Var analysis error covariance matrix

\[ A = \mathbf{B}^{-1} + \mathbf{K}^T \mathbf{R}^{-1} \mathbf{K} \mathbf{x}^{-1} \]

where

\[ \mathbf{K} = \left[ \frac{\partial H(x)}{\partial x} \right] \]

- or twice (2err) as large as computed (i.e. closer to the errors for radiosonde T and q)
PDF of FG vs. AN departures
T,q pseudo-obs from 1D-Var of radar

RMS (OBS – FG) – RMS (OBS – AN)

Improvement from assimilation of radar/lidar obs

Temperature [K]

Specific humidity [g/kg]
Verification of assimilation runs against other assimilated observations

4D-Var assimilating $T$, $q$
pseudo-obs retrieved from 1D-Var with radar and lidar

area NSEW = 65/-65/-130/-180
2007012400

SYNOP – Ps (Pa)
Summary and perspectives

• 1D-Var assimilation experiments performed using observations:
  – cloud radar reflectivity
  – lidar backscatter
  – combination of cloud radar reflectivity and lidar backscatter

• information on T and q retrieved from 1D-Var of cloud radar and/or lidar data used as pseudo-observations in the 4D-Var system

• Obtained results indicate:
  – 1D-Var analysis gets closer to assimilated and also independent observations
  – impact of cloud radar reflectivity larger than of lidar backscatter
  – 1D+4D-Var analysis reduces analysis departures for T, q pseudo observations
  – small impact observed in FG and AN departure statistics when verified against other observation types assimilated in 4D-Var
  – getting more impact from the new data would require to carefully tune their usage in the assimilation system

• More experiments to be performed:
  – for different situations
  – for refining data control and error definition usage