Using microwave observations in data assimilation, including under conditions of cloud and precipitation

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Thanks to: Bill Bell, Peter Bauer, Fabrizio Baordo, Niels Bormann, Katrin Lonitz and Richard Forbes

ECMWF/EUMETSAT NWP-SAF satellite training course
Last time...

- What is special about the microwave frequency range?
- Sensitivities
- Radiative transfer basics
- Microwave sensors

This time...

- Using AMSU-A sounding radiances in the ECMWF data assimilation system
- More on cloud and precipitation sensitivities, modelling, and screening
- All-sky assimilation
AMSU-A channel 5 radiances:
Metop-A satellite, 9pm 25/4 to 9am 26/4/2012

Observed TB [K] \( y_o \)

First guess TB [K] \( H(M(x_b)) \)

“Clear sky” assumption: no cloud or precipitation radiative transfer
AMSU-A channel 5 radiances

First guess departures $y_o - H(M(x_b))$

Scan bias

General “warm” bias
AMSU-A channel 5 radiances

Bias correction

Scan bias correction

Mean offset

Airmass correction (layer mean temperature)
AMSU-A channel 5 radiances

Bias corrected first guess departures $y_o - b - H(M(x_b))$

- The Andes
- Snow and ice
- Still some scan bias
- Sea ice
- Precipitation and cloud
AMSU-A channel 5 radiances

Bias corrected first guess departures $y_o - b - H(M(x_b))$

After blacklisting

The Andes

Snow and ice

Still some scan bias

Sea ice

Precipitation and cloud

[K]
AMSU-A channel 5 radiances

Bias corrected first guess departures

After blacklisting

\[ y_o - b - H(M(x_b)) \]
AMSU-A channel 5 radiances

Bias corrected first guess departures
After blacklisting
After active thinning and VarQC

$$y_o - b - H(M(x_b))$$
AMSU-A channel 5 radiances

Bias corrected first guess departures
After blacklisting
After active thinning and VarQC

$$y_o - b - H(M(x_b))$$
AMSU-A channel 5 radiances

Departures normalised by observation error, $\sigma_o = 0.28K$

(Absolute values < 0.5 removed here for visual clarity)
AMSU-A channel 5 radiances

Contribution to cost function (as before, low contribution values removed for clarity)

\[
\frac{(y_o - b - H(M(x_b)))^2}{\sigma_o^2}
\]
Now we need to minimise 4D-Var

Feed the minimisation algorithm with…

Cost function

\[ 2J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y_o - b - H(M(x)))^T R^{-1} (y_o - b - H(M(x))) \]

What we just calculated
What did 4D-Var do with AMSU-A channel 5, and all the other observations in the analysis?

Increment [K]
\[ H(M(x_a)) - H(M(x_b)) \]

Just a little nudge in the direction of the observations

1:1 line - if the analysis exactly fitted the observations

FG departure [K] \[ y_o - b - H(M(x_b)) \]
Sensitivities to cloud and precipitation
The microwave gas absorption spectrum

Absorption coefficient $\beta_a [1/km]$

Absorption coefficient $\beta_a [1/km]$

T = 288 K, p = 1000 hpa

Moist

Dry

H$_2$O Rotation lines
+ Water vapour continuum

O$_2$ Rotation Lines
+ Dry air continuum

Temperature sounding:
60 GHz oxygen line

Moisture sounding:
22 GHz and 183 GHz water vapour lines

“Imaging channels” in the windows

Slide 16
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Window channels ("imaging"): surface properties, water vapour, cloud and precipitation (from SSMIS – conical imager)

Increasing frequency [GHz] (h = horizontal polarization)

Observed TB [K]
Window channels ("imaging"): surface properties, water vapour, cloud and precipitation (from SSMIS – conical imager)

Increasing frequency [GHz] (h = horizontal polarization)

19h  37h  91h  150h

Observed TB [K]

Hydrometeor effect: observed TB – Simulated clear-sky TB [K]

Rain (absorption, increases TB)

Cloud (absorption, increases TB)

Snow/graupel/hail (scattering, decreases TB)
Sounding channels: temperature, water vapour, cloud and precipitation
(from SSMIS – conical imager)

Temperature sounding:
- Lower troposphere: 52.8
- Mid troposphere: 53.6

Water vapour sounding:
- Mid troposphere: 183±7
- Upper troposphere: 183±1

Observed TB [K]

Hydrometeor effect: observed TB – Simulated clear-sky TB [K]

Cloud (absorption, increases TB)
Cloud and rain (absorption, pushes up weighting function altitude, decreases TB)
Cloud and snow/ice/graupel (absorption and scattering, decreases TB)
The microwave particle optical property “spectrum”

1.0 g m\(^{-3}\) of hydrometeor at 260 K
The microwave particle optical property “spectrum” 1.0 g m\(^{-3}\) of hydrometeor at 260 K

Rain
Cloud water
Snow
Cloud ice
Radiative transfer for cloud and precipitation
Spherical particles interacting with radiation

- **Rayleigh “scattering”** \((x < 0.2)\):
  - an approximate solution for spherical particles much smaller than the wavelength
  - for \(x < 0.002\) scattering is negligible (but particles still absorb and emit radiation): e.g. at low microwave frequencies, liquid water cloud acts like a gaseous absorber

- **Mie scattering** \((0.2 < x < 2000)\):
  - a complete solution for the interaction of a plane wave with a dielectric sphere
  - valid for all \(x\), but depends on a series expansion in Legendre polynomials - can be slow to compute

- **Geometric optics** \((x > 2000)\):
  - e.g. the rainbow solution for visible light
Non-spherical particles interacting with radiation

- Discrete dipole approximation (DDA):
  1. Create a 3D model of a snow or ice particle
  2. Discretise into many small polarisable points (dipoles). Grid spacing << wavelength
  3. Solve computationally – can be slow

- Other solution methods exist or are being developed, e.g. T-matrix, boundary integrals
Cloud and precipitation at 91 GHz
Strong scattering in deep convection

- Rain and snow flux \([\text{g m}^2 \text{s}^{-1}]\)
- Cloud mixing ratio \([0.1 \text{ g kg}^{-1}]\)
- Altitude \([\text{km}]\)
- Single scatter albedo
- Asymmetry
- Extinction coefficient \(\beta_e\) \([\text{km}^{-1}]\)
Cloud and precipitation at 91 GHz
Strong scattering in deep convection

To sensor

SSA [0-1]

Space: 91
Emission: 109
Surface: 0
Scattering: 4025

n=200

No. of emissions
Scattering solvers

- **Reverse Monte-Carlo**
  - Great for understanding and visualisation
  - An easy way to do 3D radiative transfer
  - Much too slow for operational use: many thousands of “photons” are required for convergence to a useful level of accuracy

- **Accurate but too slow for use in assimilation:**
  - DISORT (Discrete ordinates) – a generalisation of the two-stream approach
  - Adding / doubling, SOI (Successive Orders of Interaction)

- **Two-stream and delta-Eddington approaches**
  - What we use operationally at ECMWF (in RTTOV-SCATT)
  - Though quite crude methods, the accuracy is usually more than sufficient: the main R/T error sources in NWP are rarely in the solver
Clear-sky or ‘all-sky’ assimilation?
Clear-sky or all-sky assimilation?

- **Clear-sky assimilation:**
  - Remove any cloud-contaminated observations
  - Do not model the effect of cloud on brightness temperatures
  - Used for temperature sounding channels (e.g. AMSU-A channel 5)
  - Extract small signals of temperature forecast errors (order 0.1K) that would be swamped by errors from displaced clouds and precipitation (10-100K)

- **All-sky assimilation**
  - Model the effect of cloud and precipitation on the observations
  - Assimilate all data, whether clear, cloudy or precipitating
  - Used for water-vapour sounding and imaging channels
  - Use the tracing mechanism of 4D-Var to infer the dynamical state from errors in the location/intensity of water vapour, cloud and precipitation
Cloud screening

- Use clear-sky radiative transfer but remove situations where the observations are cloudy or precipitating

Cloud screening methods:

- FG departures in a window channel

- Simple LWP or cloud retrieval
  - Sounders: Grody et al. (2001, JGR)
  - Imagers: Karstens et al. (1994, Met. Atmos. Phys.)

- Scattering index (SI)
  - Over land, or in sounding channels affected by ice/snow scattering, not cloud absorption: Grody (1991, JGR)

Used for screening AMSU-A channel 5-8 at ECMWF
AMSU-A **clear-sky** nadir weighting functions
these are approximately fixed, in an oxygen line (a well-mixed gas)
AMSU-A channel 3 departures for cloud screening
50.3 GHz observation minus clear-sky first guess (bias corrected), ocean surfaces

Cloud shows up as a warm emitter over a radiatively cold ocean surface
AMSU-A channel 3 departures for cloud screening
50.3 GHz observation minus clear-sky first guess, ocean surfaces

FG departure [K]

20% of observations removed
Warm tail = cloud

3K limit
AMSU-A channel 3 departures for cloud screening
50.3 GHz observation minus clear-sky first guess (bias corrected), ocean surfaces
### Clear-sky assimilation

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<tr>
<th>Model</th>
<th>Observations</th>
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<td><img src="image11" alt="Model Image" /></td>
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- ✓: Correct assimilation
- ×: Incorrect assimilation
- ?: Unclear

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# All-sky assimilation

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✓ ✓ ✓ ✓ ✓ ✓
All-sky assimilation: impact and mechanism
Frontal cloud and precipitation: single-observation example at 190 GHz

Metop-B MHS
190 GHz

GOES
10μm
Dundee receiving station

08Z, 15 Aug 2013
47°N 159°W
Frontal cloud and precipitation – all observations

FG depar

Analysis depar (all obs)

Obs
Frontal cloud and precipitation – single all-sky obs

FG depart

Analysis depart (all obs)

AN dep (single obs, normal obs error)

AN dep (single obs, low obs error, no VarQC or BgQC)

25% error reduction (honest!)

80% error reduction. Locally better than full observing system!
B) Frontal cloud and precipitation – 190 GHz

MSLP and snow column (FG)

Snow column increment

Snow reduction at observation time generated by reduction in strength of low pressure area 1000km away, 11h earlier

MSLP increment
Impact of all-sky microwave humidity sounders and imagers - on top of the otherwise full observing system

2-3% impact on day 4 and 5 dynamical forecasts

Change in RMS error of vector wind
Verified against own analysis

Blue = error reduction (good)

Based on 322 to 360 forecasts

Cross hatching indicates 95% confidence
How observations sensitive to cloud and precipitation benefit global NWP

1. Use more satellite observations, even if there’s no benefit from the cloud and precipitation information itself
   - e.g. try to recover some of the 80% of data lost to cloud in lower-sounding IR channels

2. Directly improve dynamical initial conditions through the observation of cloud and precipitation
   - e.g. infer the strength of a low pressure system from the intensity of its frontal precipitation: the “generalised 4D-var tracer effect”

3. Initialise cloud and precipitation itself

4. Help improve the forecast model – the indirect effect
   - Benefits all forecast ranges, even when initial conditions are lost