Precipitation assimilation at ECMWF

Alan Geer

Summarising the work of very many people, particularly:

Peter Bauer
Sabatino Di Michele
Chris O’Dell
Philippe Lopez
Validation
Jung et al. 2005 (QJ) show an underestimation of synoptic activity in high latitudes.

Jung et al. 2006 (QJ) show high latitude cyclones are well analysed, but that high horizontal resolution is important for correctly forecasting them, particularly in North Pacific and Arctic.
Land surface modelling is important. There were large wintertime biases over continental areas before improvements to soil freezing and snow albedo.

See Beljaars’ paper from ECMWF polar meteorology seminar, 2006
January, 1986-1995, in ERA-40: 2m temperature increments and snow depth

- 2m temperature analysis increments in ERA-40 reveal model biases in winter. Model is too warm.
- Thought to be linked to parametrized vertical diffusion in the stable air above snow-covered areas.

Beljaars, polar meteorology seminar 2006
Hageman et al. 2005 (ERA 40 project report) – an extensive validation of the ERA-40 hydrological cycle
Most obvious problems are in tropics, not high latitudes
Climatologies disagree in some areas – e.g. NH winter
Figure 10. Several large catchments of the globe. The 6 largest Arctic rivers comprise (from west to east) Mackenzie, Northern Dvina, Ob, Yenisey, Lena, Kolyma.

(Hagemann et al. 2005)
ERA-40 Hydrological Cycle Validation

Figure 11. Precipitation ratio of ERA40 to observations for large river catchments. Observations comprise GPCC data for 1989-2001 and CRU data for the two earlier periods.

Difference between individual ERA-40 periods due to different data sets in data assimilation system

(Hagemann et al. 2005)
Operational assimilation of rain and cloud affected SSM/I observations
Overview

- Clear sky SSM/I radiances are directly assimilated in 4D-Var

- Cloudy and rainy SSM/I radiances have been assimilated operationally at ECMWF since 28th June 2005, over sea only, using a 1D+4D-Var method:
  - 1D-Var minimises T,q profiles and surface windspeed
  - 1D-Var observation operator includes:
    - simplified large-scale and convective cloud schemes
    - Microwave radiative transfer
  - TCWV retrievals are assimilated in 4D-Var
Implementation

SSM/I TBs

Cloudy / rainy TBs

Scan-bias correction

Interpolation to model grid

Air-mass bias correction

Pre-screening

1D-Var

Observation operator:
- Lin. Large-scale condensation
- Lin. Convection
- RTTOV-SCATT

Post-screening

TCWV pseudo-observation

4D-Var

Clear sky TBs
Problems in winter in the Southern ocean

- Rain assimilation was causing deterioration in RMS forecast scores (RH, T and Z) in southern hemisphere
- Large first guess departures in rainy TCWV pseudo-observations at high latitudes in SH:

TCWV FG departures as percentage of FG: RMS, August 2005
Solution

- Eliminate retrievals with too much snow (compared to rain) in the first guess column

Rejected due to excessive frozen precip (260141)

Successful 1D-Var (423457)
1D-Var case study: South Atlantic 12Z 14th August 2005

Pressure at MSL
TCWV

Meteosat visible
1D-Var case study – convective, low TCWV, low freezing level

<table>
<thead>
<tr>
<th>SSMI channel</th>
<th>TCWV /kgm-2</th>
<th>Tb departure /K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19v</td>
<td>19h</td>
</tr>
<tr>
<td>FG</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>analysis</td>
<td>8.8</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Analysis
- First guess
- 3D model
We assimilate channels 19v, 19h, 22v, which have smaller FG biases; little sensitivity to solid precip or cloud ice

Big biases in higher frequency channels
Std. dev. of SSM/I first guess departures (rainy and clear): 1\textsuperscript{st} - 10\textsuperscript{th} February 2007

**Legend:**
- 0
- 5
- 10
- 15
- 20

**Units:** Std. dev. of FG departure [K]
Forecast impact of rainy observations: June, July, August 2006

Vector wind

Relative humidity

RMSE [m s⁻¹]

RMSE [%]

Day

0 1 2 3 4 5 6

0 1 2 3 4 5 6

0 1 2 3 4 5 6

0 1 2 3 4 5 6

0 1 2 3 4 5 6

0 1 2 3 4 5 6

BL Baseline: conventional obs plus one AMSU-A

BL + RAIN

CTRL - RAIN

CTRL Full observing system

Kelly et al., to be submitted
Lessons from assimilation of rainy SSM/I radiances over ocean

- FG biases and standard deviations are much larger in the higher frequency channels:
  - Increased sensitivity to precipitation and cloud reveals moist physics model biases
  - Ice and snow scattering radiative transfer less good
  - Possible surface emissivity biases

- Profiles with more than 30% precipitation in the form of snow are rejected. Low frequency channels give little sensitivity to snow.

- Forecast impact of rainy observations within the full observing system is very small. This is true for most observation types: there is redundancy in the system.

- Forecast impact of moisture, rain, and cloud observations in a low baseline system is large, but principally found in the tropics. Here, wind forecasts are substantially improved, not just moisture.

- Many areas (e.g. moist physics in the model, moisture control variable, background errors, assimilation technique) require improvement before rain- and cloud-affected observations can be used to their full potential.
Precipitation and cloud information content in the microwave spectrum
WP 3110/3120: Information content

Reference profile: 02 Jan 2004, 12:00 UTC 52.50°N - 41.66°W
Observation operator: Hydrometeor Jacobians

Ocean surface

[Graphs of various meteorological phenomena, including Rain, Snow, Cloud, and Ice, with corresponding color scales and vertical and horizontal axes labeled with values.]

Land surface
Observation operator: Profile and surface Jacobians

Ocean surface

\[ V \text{ pol.} \]

Land surface

\[ V \text{ pol. minus } H \text{ pol.} \]

\begin{align*}
\text{Surf Temp} \\
\text{Hum} \\
\text{Surf Emis}
\end{align*}
SSMIS Channel Sensitivity Study - rain

• Take 20,000 profiles
• Output profiles of T, q, cloud water, cloud ice, rain & snow content.
• Use RT model to calculate theoretical TB
• Increase rain (snow) contents by 1% for each profile; calculate TB changes.
• Scale change in TB to a 0.1 kg/m² change in integrated rain (snow) water path, assuming linearity.
SSMIS Channel Sensitivity Study - snow

- Take 20,000 profiles
- Output profiles of T, q, cloud water, cloud ice, rain & snow content.
- Use RT model to calculate theoretical TB
- Increase rain (snow) contents by 1% for each profile; calculate TB changes.
- Scale change in TB to a 0.1 kg/m² change in integrated rain (snow) water path, assuming linearity.

**Graphs:**

- OCEAN
- LAND

**Axes:**

- x-axis: SWP [kg/m²]
- y-axis: ΔTB [K] per 0.1 kg/m² change in SWP
Signal vs. Noise

- **Canadian snowstorm, Area 1:**
  - Heavy frozen precipitation
  - Little liquid precipitation

- **Canadian snowstorm, Area 2:**
  - Moderate frozen precipitation
  - Moderate liquid precipitation

- **North Atlantic frontal system:**
  - Moderate frozen precipitation (above surface)
  - Moderate liquid precipitation

- **Florida convection:**
  - Heavy frozen precipitation (above surface)
  - Moderate liquid precipitation

**Contributions:**
- NE\(\Delta T\) [black]
- Surface emissivity [green]
- Liquid precipitation [blue]
- Solid precipitation [yellow]

(Bauer et al. 2005)
Mission Requirements for a Post-EPS Microwave Radiometer

Peter Bauer, Sabatino Di Michele, Jean Noël Thépaut

European Centre for Medium-range Weather Forecasts (ECMWF)
Objectives

“Derive mission requirements related to the observation of clouds and precipitation with a polar microwave radiometer”

Project:

• Identify those microwave frequencies between 5-200 GHz that are optimally suited for cloud and precipitation remote sensing (and that are protected by International Telecommunication Union, ITU, regulations).

• Consider ocean/land surfaces and all weather conditions.

• Develop framework for the estimation of potential hydrometeor retrieval accuracies given the identified channel selection.

• Assess retrieval accuracy based on user requirements defined for post-EPS.
Information Content

Signal to noise can be characterized as $x/\sigma$ or $\sigma_x/\sigma$ with:

- $x$ atmospheric/surface variable
- $\sigma_x$ standard deviation of $x$’s variability
- $\sigma$ noise

Information content of a measurement = factor of $x$-knowledge improvement when making observation(s) [often as $\log$ (factor)]

Linear Gaussian case:

$$H_s = S[P(x)] - S[P(x|y)]$$

Entropy reduction

$A$ = Analysis error covariance matrix

$P$ = (joint) pdf of $x(y)$

Iterative method for channel optimization:

$$A^{-1} = B^{-1} + hh^T$$

Improvement of $A$ over $B$ with $H$

$B$ = Background error covariance matrix

$H$ = Jacobian matrix with columns $h$, normalized with $R$

$R$ = Observation+Modelling error covariance matrix

1. calculate $H_s$ for all channels and select highest
2. update $B$ with $A$
3. calculate $H_s$ for remaining channels and select highest
Estimation of $\sigma_B$ vs. $\sigma_{E+F}$ from spatial covariance structure of first-guess departures

Assumptions:
- observation network is rather dense
- observations are spatially uncorrelated (and discrete)

Conclusions:
- at 0-separation distance, the variance is $\sigma_B^2 + \sigma_{E+F}^2$
- at >0-separation distance, the variance is covariance $\sigma_B^2 (d)$

Use SSMIS data over ocean to sample spectrum at SSM/I, AMSU-A, AMSU-B frequencies!

Interpolate between frequencies with HBH$^T$ from simulations
Resulting $\sigma_R$ Spectrum

\begin{align*}
V \text{ polarization} \\
H \text{ polarization}
\end{align*}
Information Content Reduction 1st 10 Iterations

Rain
- vertical polarization
- horizontal polarization

Snow

Cloud
Information Content: Impact of R

Ocean

Rain

Cloud

Ice

Land

Rain

Snow

Cloud

Ice
Global Profile Dataset

<table>
<thead>
<tr>
<th>Type</th>
<th>Zone</th>
<th>Period</th>
<th>Original</th>
<th>Normalized</th>
<th>Representative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Winter</td>
<td>Atlantic O.</td>
<td>January 2004</td>
<td>133829</td>
<td>46766</td>
<td>10000</td>
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<tr>
<td>Ocean Summer</td>
<td>Atlantic O.</td>
<td>July 2004</td>
<td>72992</td>
<td>31420</td>
<td>25000</td>
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<tr>
<td>Land Winter</td>
<td>N. America, Europe</td>
<td>January 2004</td>
<td>85888</td>
<td>25317</td>
<td>20000</td>
</tr>
<tr>
<td>Land Summer</td>
<td>Africa, Amazons</td>
<td>January 2004</td>
<td>156412</td>
<td>63367</td>
<td>45000</td>
</tr>
</tbody>
</table>
Global Profile Characteristics

Ocean

TCWV < 20 kg/m²

20 kg/m² < TCWV < 40 kg/m²

TCWV > 40 kg/m²

Land

TCWV < 20 kg/m²

20 kg/m² < TCWV < 40 kg/m²

TCWV > 40 kg/m²

FL > 4.0 km

1.5 km < FL < 4.0 km

FL < 1.5 km

Rain

Snow

Cloud Water

Cloud Ice
## Channel Selection

### AMSR-E Upgrade

*unprotected 36.5 GHz channels replaced with fully protected 31.4 GHz channels

### Channel Selection Table

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Centre Frequency [GHz]</th>
<th>Bandwidth [MHz]</th>
<th>Polarization</th>
<th>NEATB [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.925</td>
<td>350</td>
<td>v</td>
<td>0.34</td>
</tr>
<tr>
<td>2</td>
<td>6.925</td>
<td>350</td>
<td>h</td>
<td>0.34</td>
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<tr>
<td>3</td>
<td>10.65</td>
<td>100</td>
<td>v</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>10.65</td>
<td>100</td>
<td>h</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>18.7</td>
<td>200</td>
<td>v</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>18.7</td>
<td>200</td>
<td>h</td>
<td>0.7</td>
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<td>7</td>
<td>23.8</td>
<td>400</td>
<td>v</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>23.8</td>
<td>400</td>
<td>h</td>
<td>0.6</td>
</tr>
<tr>
<td>9</td>
<td>31.4</td>
<td>1000</td>
<td>v</td>
<td>0.7</td>
</tr>
<tr>
<td>10</td>
<td>31.4</td>
<td>1000</td>
<td>h</td>
<td>0.7</td>
</tr>
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<td>11</td>
<td>89.0</td>
<td>3000</td>
<td>v</td>
<td>1.2</td>
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<tr>
<td>12</td>
<td>89.0</td>
<td>3000</td>
<td>h</td>
<td>1.2</td>
</tr>
</tbody>
</table>

### Priority

<table>
<thead>
<tr>
<th>Priority</th>
<th>Ocean</th>
<th>Land</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu$ [GHz]</td>
<td>$\nu$ [GHz]</td>
</tr>
<tr>
<td>1</td>
<td>50.30 (rain, cloud water)</td>
<td>52.61 (rain)</td>
</tr>
<tr>
<td>2</td>
<td>52.61 (rain, snow)</td>
<td>53.24 (rain)</td>
</tr>
<tr>
<td>3</td>
<td>53.24 (rain)</td>
<td>53.75 (rain, snow, cloud water)</td>
</tr>
<tr>
<td>4</td>
<td>100.49 (rain, cloud water)</td>
<td>117.55 (snow)</td>
</tr>
<tr>
<td>5</td>
<td>120.16 (snow)</td>
<td>120.16 (cloud water)</td>
</tr>
<tr>
<td>6</td>
<td>191.70 (snow)</td>
<td>120.91 (snow)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>186.67 (snow)</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>188.17 (snow)</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>189.42 (snow)</td>
</tr>
</tbody>
</table>
1D-Var Retrieval Logic

Applied to:

- 4 test profiles with respect to channels optimized for rain/snow retrieval.
- Bulk of global datasets.

For radiometer options:

- AMSR-E baseline.
- AMSR-E+ upgrade according to IC per profile.
- AMSR-E++ upgrade according to IC from global datasets.
1D-Var Example

Temperature [K]

Specific humidity [kg/kg]

Rain water content [g/m³]

Snow content [g/m³]

Cloud water content [g/m³]

Cloud ice content [g/m³]
1D-Var Test: Rain over ocean

Hydrometeor Profiles

Temperature/moisture profiles

Relative error:

Specific humidity

Rain water

Cloud water

Snow

Cloud ice
1D-Var Test: Snow over land

Hydrometeor Profiles

Relative error:

Temperature

Specific humidity

Rain water

Snow

Cloud water

Cloud ice
1D-Var: Retrieval biases over oceans

- Temperature [%]
- Specific humidity [%]
- Rain water content [%]
- Snow content [%]
- Cloud water content [%]
- Cloud ice content [%]
1D-Var: Retrieval error standard deviations over oceans

- Temperature [%]
- Specific humidity [%]
- Rain water content [%]
- Snow content [%]
- Cloud water content [%]
- Cloud ice content [%]
1D-Var: Retrieval biases over land

Temperature [%]

Specific humidity [%]

Rain water content [%]

Snow content [%]

Cloud water content [%]

Cloud ice content [%]
1D-Var: Retrieval error standard deviations over land

Temperature [%]

Specific humidity [%]

Rain water content [%]

Snow content [%]

Cloud water content [%]

Cloud ice content [%]
Conclusions

Information Content Analysis:
• Channel selection rather sensitive to definition of modelling+observation errors.
• Analysis based on assumption that operator (radiative transfer model) is linear.
• ECMWF model profiles, error statistics, emissivity data, observation operator provide most consistent framework that is available.
• AMSR-E radiometer represents good baseline; significant upgrades possible with AMSU-A – type sounding channels wrt rain and AMSU-B – type sounding channels wrt snow. 118-GHz channels are strong for both rain and snow.
• Recommended radiometer (AMSR-E++) similar to SSMIS with trade-off for sea-surface, snow and ice observation; clear-sky data assimilation in NWP.

1D-Var Retrieval Analysis:
• 1D-Var is more complicated because observation operator also contains moist physics parameterizations; but produces results most comparable to data assimilation framework.
• Error estimates rely on FG-constraint and may be too good wrt off-line retrievals.
• AMSR-E++ significantly better than AMSR-E wrt all variables, in particular for mid-to-upper cloud levels.
• Relative errors (wrt state) well within user requirements.
Assimilation of SSMIS over land
Rain assimilation over land

• Looks like it might be possible, using SSMIS 50.3, 52.8, 91, 150, 183 GHz channels.
• Consistent with findings of di Michele & Bauer (2006) channel selection study for future sensors. However, no 120 GHz on SSMIS.
• Trade-off between sensitivity to clouds/rain and sensitivity to surface.
• SSMIS data available at ECMWF since 2003.
“Raw” SSMIS data stream

150 GHz V-pol
Surface Emissivity Atlas

- Uses SSM/I observations from 1992-2001
- ISCCP co-located observations to screen for only clear obs
- Surface temperature from ISCCP IR
- Temperature/humidity profiles from NCEP-NCAR reanalysis
- One emissivity for each of the 7 SSM/I channels, monthly at 0.25°
Surface emissivity climatology: January mean

Extension to Other Frequencies

1) Fit each monthly averaged, 0.25° grid box observation to Grody (1988) formula. \( P = \{ V, H \} \rightarrow 6 \) parameters.

2) Average fits to 1° grid boxes and over all 10 years. Typically 50-100 contributing fits.

3) Obtain error covariance matrix

\[
S_p(j,k) = \frac{1}{N-1} \sum_{i=1}^{N} \left( p_j(i) - \langle \tilde{p}_j \rangle \right) \left( p_k(i) - \langle \tilde{p}_k \rangle \right)
\]

\( j,k = 1..6 \)
Central Canada, March
1D-Var Methodology Changes over land

\[
\begin{align*}
\mathbf{x}_\text{Ocean} &= \begin{pmatrix} \vec{t} \\ \vec{q} \\ u_{10} \\ v_{10} \end{pmatrix} \\
\mathbf{x}_\text{Land} &= \begin{pmatrix} \vec{t} \\ \vec{q} \\ T_{\text{skin}} \\ \vec{e} \end{pmatrix}
\end{align*}
\]

May be actual emissivities or Grody formula parameters
First-Guess Statistics, Map-View

Obs – FG Chan 8 [K]

Mean = 1.56  Std = 15.1

150 GHz H-pol
First-Guess Statistics, Map-View

Obs - FG Chan 10 [K]

Mean = 0.259  Std = 6.98

183±3 GHz H-pol
Experiment: OLDEMIS:

- surface emissivity retrieved individually for each channel
- 50, 52, 150±1, 183±3,6, 91 Ghz channels used
Experiment: ALL:

- retrieve the parameters of the surface emissivity model
- much larger errors assigned to the first guess of these parameters
- 19, 37, 50, 52, 150±1, 183±1,3,6, 91 Ghz channels used
Conclusions after first tests over land

- Basic assimilation seems to be working as desired for precipitating regions.
- TCWV error reduction much less than that of over-ocean SSM/I assimilation
- Can still have a significant impact on the 4D-Var analysis
- Land emissivity can have spurious effects and is likely leading to the general drying trends seen in clear-sky areas.
Channel selection studies:
- For snow: 118+/-(around the oxygen line) and 183+/-(around the water vapour line) on top of a baseline ASMR-E configuration
- NWP gives very large database of profiles, so good statistics

From operational rain assimilation:
- Biases and standard deviations are higher in higher frequency window channels – many things become more difficult
- Current rain assimilation system has mainly tropical impact
- Much work still to be done to get the best out of this kind of observation.
- Direct 4D-Var in testing and should make significant improvements

Experiments with assimilation of rainy SSMIS over land:
- For snow retrievals, would prefer 183GHz channels to 90 or 150GHz, as less/no surface contribution, and more linear radiative transfer due to the sensitivity to atmospheric humidity
- Rainy microwave assimilation is more difficult over land, but certainly possible. Crucially, must retrieve surface emissivity model parameters and skin temperature.

Gaps:
- For a focused snow mission may need focused study of microwave information content over snow and sea ice.
- Surface emissivity models over land, snow and ice
- Validation of model rain, snow, and cloud at high latitudes
References

Information content:

- Bauer and DiMichele: Study on definition of mission requirements for a post-EPS microwave radiometer for cloud and precipitation observation, EUMETSAT contract report EUM/CO/06/1510/PS, 2007. Need permission from EUMETSAT to release this, but should be fine.

Operational rain assimilation:

- Geer, Bauer and Lopez: Lessons learnt from the 1D+4D-Var assimilation of rain and cloud affected SSM/I radiances at ECMWF, ECMWF tech. memo, in preparation
- Kelly, Bauer, Geer, Lopez, and Thépaut: Impact of SSM/I observations related to moisture, clouds and precipitation on global NWP forecast skill, to be submitted, 2007
- O’Dell and Bauer: Assimilation of precipitation affected SSMIS radiances over land in the ECMWF data assimilation system. Report for EUMETSAT hydrology SAF, 2007
Microwave Spectrum: Sampled/Protected Frequencies