New technologies and applications of satellite data assimilation for NWP, including reanalysis

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Outline

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   2. Aeolus
2. NWP and cal/val of satellite data
3. MACC
4. Reanalysis
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1.) New and future observing systems:

**GPSRO**

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**GPS (GNSS) Radio occultation**

- Limb measurement.
- Gradients in refractivity cause bending of a signal path between GPS and LEO satellite (Snell’s law).
- Refractivity is a function of temperature, humidity and pressure.
- Bending angle derived from measures of phase delay.

*Profile information obtained through profiles of bending angles.*
GPS RO characteristics

- **All weather-capability:**
  - Not affected by cloud or rain.

- **Largely bias-free.** Can help “anchor” bias corrections for radiances.

- **Good vertical resolution.** Can see error structures that nadir radiances can’t.

- **But has broad horizontal weighting function!** - Around 70% of the bending occurs over a ~450km section of ray-path, centred on the tangent point (point closest to surface).

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GPS RO vs IASI: 1DVAR simulations

See Healy and Collard 2003, QJRMS:

- **Expected retrieval error:**
  - Mid-Latitude Winter Atmosphere
  - RO
  - RO+IASI
  - Background
  - IASI

- **Power to resolve a peak-shaped error in background:**
  - Input signal
  - Noise PRF
  - Noise at Input
GPS RO data coverage in 6-hour period

Data from GRACE-A, GRAS, COSMIC-1, COSMIC-2, COSMIC-3, COSMIC-4, COSMIC-5, COSMIC-6

Radiosonde comparisons for Antarctica 12h forecasts

Red lines: Without GPSRO
Black: With GPSRO

Structure in the mean fit thought to be caused by inconsistencies in the AIRS and AMSU bias corrections schemes
Impact on ECMWF operational analyses

- We would expect improvements in the stratospheric temperatures. The fit to radiosonde temperatures is improved (e.g., 100 hPa, SH).

GPSRO used in operations since 12th December, 2007.

1.) New and future observing systems:

ADM-Aeolus
Atmospheric Dynamics Mission ADM-Aeolus

- ESA Earth Explorer
- Doppler wind lidar to measure line-of-sight (LOS) wind profiles in the troposphere to lower stratosphere (up to 30 km)
- Vertical resolution from 250 m - 2 km
- Horizontal averages over 50 km every 200 km
- Requirements on random error of horizontal LOS wind:
  - <1 m/s (z=0-2 km, for Δz=0.5 km)
  - <2 m/s (z=2-16 km, for Δz= 1 km)
- First wind lidar in space; will also give information on aerosol/cloud optical properties.
- Launch: not before end of 2012

Doppler wind lidar: Measurement principle

- The wind profiles are derived from the Doppler shifted signals that have been back-scattered by particles and molecules along the lidar line-of-sight.
- The UV lidar (355 nm) operates in burst mode, with spectrometers for both particle and molecular backscatter (Mie channel, Rayleigh channel).
- Vertical resolution is configurable during flight.
ADM-Aeolus: Simulated impact

Expected forecast impact for ADM-Aeolus has been simulated using ensemble methods.

Simulated DWL data adds value at all altitudes and well into longer-range forecasts.

2.) NWP and cal/val of satellite data
Use of NWP systems for characterisation of observations

- NWP systems are increasingly used for the evaluation of (new) satellite data.
- Observation-minus-background-departures provide a comparison against a reference with relatively stable characteristics and allows cross-validation with similar instruments.
- E.g., cal/val for NOAA-19 AMSU-A in April 2009:

![Graphs showing observation-minus-background departures for different instruments](image)

Early identification of data problems

E.g.: increase in noise of channel 7 of METOP-A AMSU-A

![Graphs showing OBS-FG bias and standard deviation over time](image)

FG and AN departures for METOP-A, AMSU-A ch 7 (global, clear data):

- OBS-FG
- OBS-AN
- bc or OBS-FG
- bc or OBS-AN

First email alert sent to EUMETSAT

Channel blacklisted
Evaluation of FY-3A MWTS data

Pass-bands for Microwave Temperature Sounder (MWTS) compared to AMSU-A:

ESA Summer School 2010

Evaluation of FY-3A MWTS data

Brightness Temperatures [K]

ESA Summer School 2010
Evaluation of pass-band shift for FY-3A MWTS data

- FY-3A MWTS channel 4
- Both STD(FG_deps) and Mean(FG_deps) support the hypothesis of a very significant pass-band shift (~80MHz).
- NWP fields are very powerful in diagnosing these effects.
- Importance of accurate pre-launch instrument characterisation.

SSMIS Cal/Val

- SSMI/S is a microwave instrument, combining sounding and window channels.
- Conical scanner.
- 3rd instrument launched recently.
Reflector-emission signatures in FG-departures for F-17 SSMI/S

Reflector of F17 SSMI/S is not a perfect reflector, so observations are a combination of Earth’s radiation and reflector emissions.

3.) MACC:
Chemical data assimilation
MACC Project

- **MACC**: Monitoring Atmospheric Composition and Climate
- Current pre-operational atmospheric service of the European GMES programme. Provides:
  - data records on atmospheric composition for recent years,
  - data for monitoring present conditions
  - forecasts of the distribution of key constituents for a few days ahead.
- Combines state-of-the-art atmospheric modelling and data assimilation with Earth observation data to provide information services covering European Air Quality, Global Atmospheric Composition, Climate, and UV and Solar Energy.
- 45 partner institutes in Europe
- ECMWF leads development of a coupled NWP/chemical transport model data assimilation system

ESA Summer School 2010

MACC Daily Service Provision

http://www.gmes-atmosphere.eu/

Air quality
Global Pollution
Biomass burning
Aerosol
UV index
Mean CO from 15 to 30 July 2003 from assimilation of MOPITT total-column data

Comparison with MOZAIC aircraft data over Osaka

Control & Assimilation

Unit: $10^{18}$ molec/cm²

Simulated and analysed aerosol optical depth with MODIS and MISR for July 2003

Aerosol Optical Depth at 550 nm from Unconstrained Model Run July 2003

MISR Terra Aerosol Optical Depth at 557.5 nm [unitless] July 2003

Aerosol Optical Depth at 550 nm for Reanalysis using MODIS AOD July 2003

Radiance assimilation for MACC (AIRS/IASI)

• By sampling the IR spectrum at very high resolution (R=1200) we can measure radiation that is only dependent on temperature and the atmospheric CO$_2$ concentration (small groups of pure lines)

• If we have accurate temperature information (from the ECMWF analysis driven by AMSUA data) we can separate out the CO$_2$ signal.

• Instruments with coarse spectral resolution (e.g. HIRS) sample radiation that is a mixture of absorbing species (e.g. CO$_2$ / N$_2$O / O$_3$ and H$_2$O) and cannot resolve the CO$_2$
Mean column CO$_2$ from assimilation of AIRS radiances: Validation with aircraft

4.) Reanalysis
Reanalysis

What is Re-analysis?

Analysis of past (historical) observational data using a fixed, tried-and-tested, data assimilation system.

What does it produce?

A comprehensive time series of global analyses (i.e. gridded fields of temperature, humidity, wind etc.) and a homogeneous organized / quality controlled data-set of observations.

What is it used for?

Meteorological research – into processes, composition, low-frequency variability, predictability, model development and general climate studies, …

Atmospheric reanalysis: Global products

● Three centres took initiative in mid 1990s: first generation
  - ERA-15 (1979 - 1993) from ECMWF – with significant funding from USA
  - NASA/DAO (1980 - 1993) from USA
  - NCEP/NCAR (1948 - present) from USA

● Second generation of reanalyses followed
  - ERA-40 (1958 - 2001) from ECMWF – with significant funding from EU
  - JRA-25 (1979 - 2004) from Japan
  - NCEP/DOE (1979 - present) from USA

● Now in third generation of comprehensive global reanalysis
  - ERA-Interim (1989 - present) from ECMWF
  - JRA-55 (1958 - 2012) from Japan
  - NASA/GMAO-MERRA (1979 - present) from USA
  - NCEP-CFSRR (1979 - 2008) from USA
Why reanalysis?

Ingredients for a reanalysis

- **Observations!**
  - Try using all available (good) observations
  - Observation recovery
  - Reprocessed observations
  - Observations previously unavailable in real-time

- **Advanced data assimilation scheme**
  - State-of-the-art, but tried-and-tested and affordable
  - Unchanged during the reanalysis production
  - Adequate for variable observation coverage over reanalysis period
  - Capable of dealing with changeable observation biases
  - Robust quality control/data selection

- **Advanced NWP forecast model**
  - State-of-the-art, but tried-and-tested and affordable
  - Unchanged during the reanalysis production

- **Constant monitoring** of all aspects during the production!
  - And learn for the next reanalysis…
Observations used in ERA-40 (I)

- Conventional observations
  - Radiosonde and pilot-balloon soundings 1957 - 2002
  - Surface data from land stations and ships 1957 - 2002
  - Flight-level data from commercial aircraft 1973 - 2002
  - Surface data from ocean buoys 1979 - 2002

- Satellite data
  - NOAA VTPR radiances 1973 - 1978
  - NOAA TOVS/ATOVS radiances 1979 - 2002
  - Winds from geostationary orbit 1979 - 2002
  - TOMS/SBUV ozone retrievals 1979 - 2002

Observations used by ERA-40 (II)

The ERA-40 Re-analysis used 41 satellite instruments carried by 15 different NOAA polar satellites
Example of improved data coverage: Reprocessed Atmospheric Motion Vectors from Meteosat

From ERA-40 to ERA-Interim

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<th>ERA-40</th>
<th>ERA-Interim</th>
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<tr>
<td>Period</td>
<td>1957-2002</td>
<td>1989-onwards</td>
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<tr>
<td>Resolution</td>
<td>125 km</td>
<td>80 km</td>
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<td>Radiance biases</td>
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<td>Improved usage and homogenisation of observations based on ERA-40; additional observations for later period</td>
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Benefits of an advanced DA scheme

Analysis of 500 hPa geopotential

15 February 2005 00 UTC

4D-Var CONTROL

All observations (surface, radiosondes, satellite etc…)

3D-Var

Surface pressure observations only

4D-Var

Advances in data assimilation help extract more information from historic data that could ever be thought possible at the time the observations were collected.

Bias correction problems in ERA-40

• ERA-40 used a static bias correction for radiance data, updated manually
• Error-prone, and some effects can be seen in the reanalysis products:

1 hPa global mean temperature:

VTPR bias correction bug NOAA-3
Consistent bias corrections in ERA-Interim: Reference blackbody calibration fluctuations for NOAA-14 MSU

Dee and Uppala, 2009

Effects of observing system changes: GPSRO

(a) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 60-40hPa

(b) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 85-60hPa

(c) Temper. diff. NH land RS minus ERA-Interim (in K), Pressure layer 125-85hPa

Observing System Experiment, in which GPSRO data are *not* assimilated

Introduction of GPSRO COSMIC
Observations assimilated in ERA-Interim

Total number of observations assimilated over 20 years: exceeds $30 \times 10^9$

Reanalyses have to deal with very large numbers of observations, whose quantity vary over time.

Validation: Forecast skill

Anomaly Correlation (%) for the 500 hPa Geopotential Height

100% = perfect forecast
60% = limit of use
Validation: Fit to 2m land temperature anomalies (K)

Differences of monthly values from CRUTEM3

ERA sampled as CRUTEM3 (Brohan et al., 2006) following Simmons et al. (2004)

Progress in time consistency: analysis increments

Zonal mean temperature analysis increments for August 2001
Summary of important reanalysis concepts

- Reanalysis provides past analyses of “all” available observations.
  - Derived within a consistent, state-of-the-art system.

- Reanalysis benefits from a long meteorological research and development chain that includes
  - observation collection (measurement),
  - observation processing,
  - numerical weather prediction modelling, and
  - data assimilation

  → Reanalysis needs repeating from time-to-time as ingredients improve.

- Reanalysis is bridging slowly, but surely, the gap between the “weather datasets” and the “climate datasets”
  - Reanalyses cover longer time periods
  - Helps different communities work together

- Challenges for future reanalysis projects:
  - Additional observations
  - Treatment of model bias
  - Coupling with ocean and land surface
  - Making observations used in reanalysis more accessible to users
  - Uncertainty estimates for the reanalysis products