Diagnosing the impact of satellite observations within data assimilation

Peter Bauer

Acknowledgements:
William Bell, Niels Bormann, Carla Cardinali, Andrew Collard, Mohamed Dahoui, Ron Gelaro, Sean Healy, Graeme Kelly, Philippe Lopez, Tony McNally, Carole Peubey, Mark Rodwell, Graeme Stephens, David Tan, Jean-Noël Thépaut

European Centre for Medium-Range Weather Forecasts
Reading, UK
Satellite data usage at ECMWF

Impact of existing satellite data
- Data monitoring
- Observing system experiments
- Advanced diagnostic tools

Impact of future satellite data

Summary
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Summary
**Data sources: Conventional**

**SYNOP/SHIP/METAR:**
- Meteorological/aeronautical land surface weather stations (2m-temperature, dew-point temperature, 10m-wind)
- Ships
  - temperature, dew-point temperature, wind (land: 2m, ships: 25m)

**BUOYS:**
- Moored buoys (TAO, PIRATA)
- Drifters
  - temperature, pressure, wind

**TEMP/TEMPSHIP/DROPSONDES:**
- Radiosondes
- ASAPs (commercial ships replacing stationary weather ships)
- Dropsondes released from aircrafts (NOAA, Met Office, tropical cyclones, experimental field campaigns, e.g., FASTEX, NORPEX)
  - temperature, humidity, pressure, wind profiles

**PROFILERS:**
- UHF/VHF Doppler radars (Europe, US, Japan)
  - wind profiles

**Aircraft:**
- AIREPS (manual reports from pilots)
- AMDARs, ACARs, etc. (automated readings)
  - temperature, pressure, wind profiles
Data sources: Satellites

Radiances (→ brightness temperature = level 1):
- AMSU-A on NOAA-15/18/19, AQUA, Metop
- AMSU-B/MHS on NOAA-17/18, Metop
- SSM/I on F-13/15, AMSR-E on Aqua
- HIRS on NOAA-17/19, Metop
- AIRS on AQUA, IASI on Metop
- MVIRI on Meteosat-7, SEVIRI on Meteosat-9, GOES-11/12, MTSAT-1R imagers

Ozone (→ total column ozone = level 2):
- Total column ozone from SBUV on NOAA-17/18, OMI on Aura

Bending angles (→ bending angle = level 1):
- COSMIC (6 satellites), GRAS on Metop

Atmospheric Motion Vectors (→ wind speed = level 2):
- Meteosat-7/9, GOES-11/12, MTSAT-1R, MODIS on Terra/Aqua

Sea surface parameters (→ wind speed and wave height = level 2):
- Significant wave height from Seawinds on QuikSCAT, AMI on ERS-2, ASCAT on Metop
- Near-surface wind speed from RA-2/ASAR on Envisat, Jason altimeter
Example of satellite data coverage

- LEO Sounders
- Scatterometers
- Satellite Winds (AMVs)
- GPS Radio Occultation
- LEO Imagers
- GEO imagers
Satellite data amounts to 99% in screening and 95% in assimilation.
Radiance data dominates assimilation with 90%.
Relative GPSRO (limb) data amount strongly increases between screening and assimilation while ozone data is largely reduced.
Incremental 4D-Var

Initial model state:
\[ x_o = x_{o,b} + \delta x_o \]

Observation operator at time \( t_i \):
\[ H_i(x_i) = H_i(x_{i,b}) + H_i \delta x_i, \quad \delta x_i = M(x_o, x_i) \delta x_o \]

Cost-function gradient:
\[ \nabla_{\delta x_o} J = B^{-1} \delta x_o + \sum_{i=0}^{n} M^T(t_i, t_o) H_i^T R_i^{-1}(d_i - H_i \delta x_i) \]
\[ d_i = y_{o,i} - H(x_{i,b}) \]

All terms determine analysis impact of observations
⇒ Ideally, impact diagnostics perform evaluation for all terms

(P. Lopez)
How is radiance information used?

Forward problem:
\[ y = H (x_b) \]

Inverse problem:
\[ x_a = H^{-1} (y_o) \]

(G. Stephens)
Forward/inverse modeling

\[ y = H(x_b): \]  Forward (interpolation + radiative transfer)

\[ x_a = H^{-1}(y_o): \]  Inverse (interpolation + radiative transfer + a priori information)
AMSU-A observations

AMSU ch 9 (~T100) OBS_Val, 20090401-20090815, Expver=43, Analyses=DCDA, Time=[00,12]
Microwave brightness temperature, weighting function: 150 to 30 hPa
AMSU-A observation-model

AMSUA ch 9 (-T100) FG_DEP, 20090401-20090815, Expver=43, Analysis=DCDA, Time=[00,12]
Microwave brightness temperature, weighting function: 150 to 30 hPa

(M. Rodwell)
Mean T-increment

Analysis Increments: Mean T100, 20090402-20090815, Expver=35R3 43, Analysis=dcda. Deep colours = 5% significance

Unit = 0.01K

0.8m/s
SSM/I observations

SSM/I ch 3 (~q850) OBS_VAL, 20090401-20090815, Expver=43, Analysis=DCDA, Time=[00,12]
All-sky microwave brightness temperature, +ve correlation with humidity, weighting: surface to 500 hPa

Unit = K

180 210 220 230 240 250 260 270

(M. Rodwell)

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SSM/I observation-model

SSMI ch 3 (~q850) FG_DEP, 20090401-20090815, Expver=43, Analysis=DCDA, Time=[00,12]
All-sky microwave brightness temperature, +ve correlation with humidity, weighting: surface to 500 hPa

Unit = 0.1 K
Mean q-increment

Analysis Increments: Mean q850, 20090402-20090815, Expver=35R3 43, Analysis=dcdca. Deep colours = 5% significance.

(M. Rodwell)
The curious case of degrading MHS channel 5 by adding IASI

exp:ezep /DA (black) v. ezeq/DA 2007080100-2007081612(12)
EUMETSAT TOVS-1C metop-a MHS Tb Tropics
used Tb METOP-A MHS

(A. Collard)
... without assimilating IASI water vapour channels

Water channels added in CY35R2

Water continuum absorption important here

(A. Collard)
IASI window (water vapour) Jacobians

Tropical Atmosphere

Humidity Jacobian ($K/[dq/q]$)

Pressure (hPa)

MHS-3
MHS-4
MHS-5

IASI Window
IASI Water Band

(A. Collard)
... and with assimilating IASI water vapour channels

exp:f010 /DA (black) v. ezeg/DA 2007080100
EUMETSAT TOVS-1C metop-a MHS Tb Tropics
used Tb METOP-A MHS

STD.DEV

Channel Number

exp-ref no exp
-2 3404
+2 4357
4395

IASI: this time with water vapour

No IASI

(A. Collard)
Why is MHS-5 Analysis Degraded?

IASI Improves Fit
MHS Moistens Atmosphere

IASI Degrades Fit
MHS Dries Atmosphere

IASI Degrades Fit
MHS Dries Atmosphere

IASI Improves Fit
MHS Moistens Atmosphere

(A. Collard)
Why is MHS-5 Analysis Degraded?

IASI observations within a 1° gridbox around MHS observations indicate undetected clouds!
AIRS/IASI cloud detection

A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.

This identifies the characteristic signal of cloud in the data and allows contaminated channels to be rejected.
MHS observation statistics/scores

IASI without water vapour and unsafe cloud detection

IASI: this time with water vapour & cloud fix

Cloud changes improve forecast

(A. Collard)

Slide 25
Satellite data usage at ECMWF

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Impact of future satellite data

Summary
Data monitoring – time series

Time evolution of statistics over predefined areas/surfaces/flags

(M. Dahoui)

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Statistics for Radiances from Aqua / AIRS
Channel = 2104, All Data
Area: lon_w = 0.0, lon_e = 360.0, lat_n = 70.0, lat_s = -90.0 (over sea)
EXP = 0001

[Graph showing time evolution of statistics over predefined areas/surfaces/flags]

ECMWF
Data monitoring – overview plots

Time evolution of statistics for several channels

Useful for quick and routine verifications

Can not be used for high spectral resolution sounders

RTTOV version upgrade

(M. Dahoui)
Selected statistics are checked against an expected range.

E.g., global mean bias correction for GOES-12 (in blue):

Soft limits (mean ± 5 stdev being checked, calculated from past statistics over a period of 20 days, ending 2 days earlier)

Hard limits (fixed)

Email alert:

GOES-12 GOESIMG 2 clear radiances: out of range:

avg(fg_depar) = 1.34775547847879,  expected range: -0.38 0.47
avg(bias_corr) = 4.10498646958382,  expected range: 3.0 3.4

(M. Dahoui & N. Bormann)
Data monitoring – automated warnings

Statistics for Radiances from NOAA-16 / AMSU-A

Channel = 10, Selected data: clear
Area: lon_w - 0.0, lon_e = 360.0, lat_n = 90.0, lat_s = -90.0 (all surface types)

EXP = 0001

OBS-FG   OBS-AN   irrad(OBS-FG)   irrad(OBS-AN)

<table>
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<tr>
<th>Exp</th>
<th>Data Period</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
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<td>0.136874</td>
<td>1.0036</td>
<td>0.362573</td>
</tr>
</tbody>
</table>

M. Dahoui & N. Bormann

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ECMWF
Data monitoring – automated warnings

Statistics for Radiances from NOAA-16 / AMSU-A
Channel = 10, Used Data
Area: lon_w= 0.0, lon_e= 360.0, lat_n= 00.0, lat_s= -90.0 (all surface types)
EXP = 0001

OBS-FG  OBS-AN  bas OBS-FG  base OBS-AN

STATISTICS FOR RADIANCES FROM NOAA-16 / AMSU-A
STDV OF FIRST GUESS DEPARTURES (OBS-FG) [K] (USED)
CHANNEL = 10
EXP = 0001, DATA PERIOD = 2009011300 - 2009033000
Min: 0  Max: 0.667172  Mean: 0.286458

(M. Dahoui & N. Bormann)
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Impact of future satellite data

Summary
Observing System Experiments

‘Continuous’ observation impact assessment:
• Assessment of all individual and combined components of observing system
→ OSEs denying types from operational model/observing system, adding types to baseline system.

Investigating fundamental observation impact:
• Comparison between instruments that constrain similar variables.
• Evaluation of specific operator sensitivity & 4D-Var mechanisms.
→ OSEs with single observation type in addition to poor observing system (e.g. conventional + AMVs + 1 sounder) and operational model version

Adding (improving) a new observation type:
• Introduction of new observation types.
• Improvement of assimilation of existing observations.
→ OSEs with modifications of operational model version and with operational observing system
Observing System Experiments

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Impact of conventional vs satellite data

Observing System Experiments

Anomaly correlation of 500hPa height for Northern hemisphere

Anomaly correlation of 500hPa height for Southern hemisphere

(J.-N. Thépaut & G. Kelly)
Combined impact of all satellite data

EUCOS Observing System Experiments (OSEs):

- 2007 ECMWF forecasting system,
- winter & summer season,
- different baseline systems:
  - no satellite data (NOSAT),
  - NOSAT + AMVs,
  - NOSAT + 1 AMSU-A,
- general impact of satellites,
- impact of individual systems,
- all conventional observations.

← 500 hPa geopotential height anomaly correlation
Individual impact of satellite data

500 hPa *geopotential height* RMS error:

← 2007 ECMWF

2003 Met Office

(J.-N. Thépaut & G. Kelly)

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Impact of microwave sounder data in NWP: Met Office OSEs

2003 OSEs:
- N-15, -16 and -17 AMSU
- N-16 & N-17 HIRS
- AMVs
- Scatterometer winds
- SSM/I ocean surface wind speed
- Conventional observations

2007 OSEs:
- N-16, N-18, MetOp-2 AMSU
- SSMIS
- AIRS & IASI
- Scatterometer winds
- AMVs
- SSM/I ocean surface wind speed
- Conventional observations

(W. Bell)
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Investigating fundamental observation impact: GPSRO

Example: How do GPSRO data (unbiased – not bias corrected) affect variational bias correction of AMSU-A radiance data (at levels where model temperature biases are significant)?

- OSE: only conventional + Metop AMSU-A, MHS, initialized with operational analysis:
  - control
  - control + COSMIC GPSRO
- Variational bias correction active.

→ AMSU-A channel 8-11 bias correction smaller when GPSRO data present (better constraint)

→ AMSU-A channel 12-13 bias correction larger when GPSRO data present (model bias too large?)

(AMSU-A channel 14 bias frozen)

(S. Healy)
Investigating fundamental observation impact: GPSRO

Metop AMSU-A channel 9 departure & bias correction evolution

(S. Healy)
Investigating fundamental observation impact: CSRs from geostationary satellite radiometers

Objective: What is impact of CSRs on wind analysis?

- CSRs: Meteosat-9 only, 2 water vapour channels (300 and 500 hPa)
- AMVs: Meteosat-9 only, all AMVs assimilated in operations (infrared, water vapour and visible)

\[
\epsilon_{\text{base}} - \epsilon_{\text{csr}} > 0 \Rightarrow \text{positive impact}
\]

(C. Peubey & T. McNally)

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Investigating fundamental observation impact: CSRs from geostationary satellite radiometers

\[ \nabla_{\tilde{x}_o} J = B^{-1}\delta_{x_o} + \sum_{i=0}^{n} M^T(t_i, t_o)H^T_i R^{-1}_i (d_i - H_i \delta x_i) \]

Experiments:
- Baseline + “4D-Var” CSRs
- Baseline + “T tracer effect” CSRs (i.e. no q sensitivity)
- Baseline + “q tracer effect” CSRs (i.e. no T sensitivity)

(C. Peubey & T. McNally)
300 hPa wind increments 1st analysis cycle

4D-Var

"q effect"

"T effect"

No q-tracing due to missing model integration

(C. Peubey & T. McNally)
Analysis error reduction

WIND SPEED: Base + 4D-Var CSRs + “no 4D-Var” CSRs + “q eff.” CSRs + no 4D-Var CSRs+AMVs

Æ With cycling alone (no 4D-Var), CSRs do not have a significant impact on winds.
Æ Most of the CSR impact on wind seem to come from the 4D-Var tracer effect of humidity.
Æ Not shown: humidity and temperature also better with 4D-Var wind increment, so there is a feedback between wind and temperature/moisture:

better wind ↔ better q and T

(C. Peubey & T. McNally)

Seminar on diagnosis of forecasting and data assimilation systems  P. Bauer 09/2009
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Adding a new observation type

Technical implementation:
• BUFR conversion of received format (if necessary)
• BUFR conversion to observational database (ODB) that is used in analysis system
• Management of satellite/instrument IDs in system
• Generation of radiative transfer model coefficients
• Screening (q/c for data problems, clouds, surfaces)
• Management of satellite/instrument in variational bias correction

Monitoring:
• Blacklisting of observations (i.e. data active in screening but not in minimization)
• Monitoring experiments to evaluate data quality and spin up biases

Analysis impact evaluation:
• Assimilation experiments with data active and evolved biases (plus control)
• Impact on short-range forecast/analysis fit to other observations
• Impact on mean analysis state

Forecast impact evaluation:
• Assimilation experiments with data active and evolved biases (plus control)
• Impact on short-to-medium-range forecasts (statistical significance)

Evaluation for operational implementation with a new cycle:
• Repeat previous two steps with other modifications
Example – Advanced IR sounders

- AIRS CO$_2$ and H$_2$O channels assimilated since October 2003.
- IASI CO$_2$/H$_2$O channels assimilated since June 2007/March 2009.
- Assimilated in clear-sky areas and above clouds; since March 2009 in fully overcast situations, AIRS (not IASI) over land surfaces/sea-ice.
- Continuous revision of channel usage, quality control.
Adding 10 IASI water vapour channels

Best value at ~1.5K

Normalised to unity here
The addition of the IASI water band improves the analysis fit to radiosondes.
Forecast skill: Verified with operational analysis

Relative humidity at 500 hPa
1st Aug.-9th Sept. 2007

N.Hemis.

S.Hemis.

(A. Collard)
Forecast skill: Verified with own analysis

Relative humidity at 500 hPa
1st Aug.-9th Sept. 2007

(A. Collard)
Forecast skill: Verified with experiment’s analysis

Relative humidity at 500 hPa
1st Aug.-9th Sept. 2007

(A. Collard)
The IASI observations act to dry the NOSAT (and OPS) system which has run to an excessively moist state → is consistent with the observed climate bias of the forecast model 700hPa. → observations that draw analysis away from model climate will score negatively unless when both experiment and control are verified with improved analysis.
Satellite data usage at ECMWF

Impact of existing satellite data

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Impact of future satellite data

Summary
Adjoint diagnostics - OSEs

Remarks on ADJ-OSE by Ron Gelaro (NASA GMAO):

**ADJ**: measures the impacts of observations in the context of all other observations present in the assimilation system

**OSE**: removal of observations changes or degrades the system… differs for each member

**ADJ**: measures the impact of observations in each analysis cycle separately and against the control background

**OSE**: measures the impact of removing information from both the background and analysis in a cumulative manner

**ADJ**: measures the response of a single forecast metric to all perturbations of the observing system

**OSE**: measures the effect of a single perturbation on all forecast metrics
Adjoint diagnostics - OSEs

% Contributions to 24hr Forecast Error Reduction
July 2005

(R. Gelaro)
(Y. Zhu & R. Gelaro 2009)
Investigating fundamental observation impact: TCWV

Forecast sensitivity to observations in analysis

SSM/I clear-sky, winter
SSM/I clouds/rain, winter

Mean 36-12h precipitation forecast initialized at 12 UTC

(C. Cardinali)
IASI – channel 212 (250 hPa)

First-guess departure standard deviation (K; 7 days)
Assimilation over sea-ice but not over land

⇒ Information available for analysis from observations (= innovation)

(G. Radnoti)
IASI – channel 212 (250 hPa)

Mean analysis sensitivity to observations* (7 days)
Assimilation over sea-ice but not over land

⇒ Sensitivity of the analysis to those observations
(* or self-sensitivity, see Cardinali et al. (2004))
IASI – channel 212 (250 hPa)

Mean analysis increment (K; 7 days)
Assimilation over sea-ice but not over land

⇒ Work performed by the analysis in observation space

(G. Radnoti)
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Summary
OSEs and OSSEs

OSE

<table>
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<th>Reference</th>
<th>Observations</th>
<th>NWP-System</th>
<th>Verification</th>
<th>Result</th>
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<td>Real atmosphere</td>
<td>Assimilation/ forecast</td>
<td>Compare to reference</td>
<td>Impact assessment</td>
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OSSE

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(D.Tan)
Data assimilation ensembles

(D. Tan)
Data assimilation ensembles

12-hour forecast impact
Southern hemisphere

Ensemble spread in zonal wind (u, m/s) $\approx$ forecast error
Scaling factor $\sim$2 for wind error:

- Performance similar in Tropics, Northern and Southern hemisphere
- Simulated DWL adds value at all altitudes and in longer-range forecasts (t+48h, t+120h)
- Differences significant (T-test)
- Supported by information content diagnostics

(D. Tan)
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Summary
Concluding remarks

- OSEs are continuously performed for:
  - assessment of new (revised) observation impact along model updates;
  - study of basic impact features (poor observing system);
  - assessment of ensemble of observing system components.

- Impact is currently evaluated using:
  - fit to short-range forecast/analysis model fields (consistency, reference observations);
  - model forecast skill using standard scores.

- Shortcomings of current observation impact assessment:
  - evaluation of individual observation type impact on fit of model fields to other observation types is only available for analyses *not* forecasts;
  - diagnostics for tuning/optimization of observing system is not available (thinning, channel selection, observation errors);
  - overview diagnostics require large and costly set of OSEs, no continuous built-in evaluation yet;
  - standard forecast scores can contradict analysis evaluation (new observations add noise and may increase root-mean-square ‘error’).