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

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ECMWF

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):

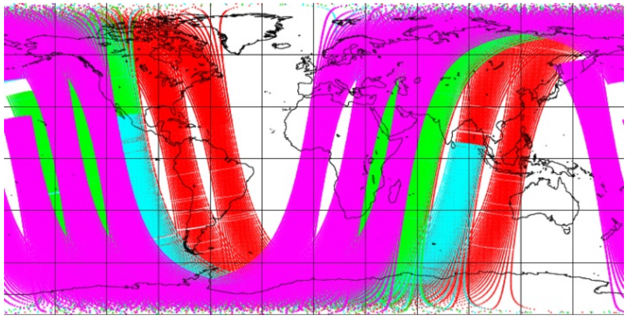
- Meteosat-7/9, GOES-11/12, MTSAT-1R, MODIS on Terra/Aqua

Sea surface parameters (→ wind speed and wave height = level 2):

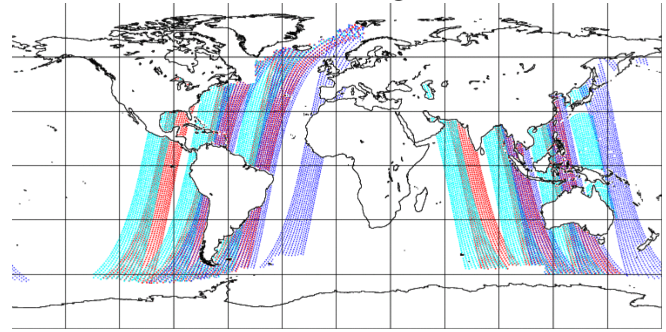
- Significant wave height from Seawinds on QuikSCAT, AMI on ERS-2, ASCAT on Metop
- Near-surface wind speed from RA-2/ASAR on Envisat, Jason altimeter

Example of satellite data coverage

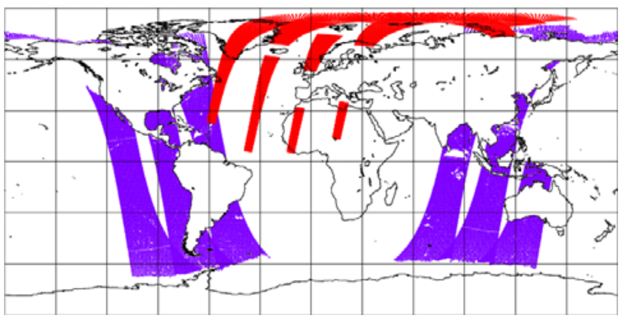
LEO Sounders



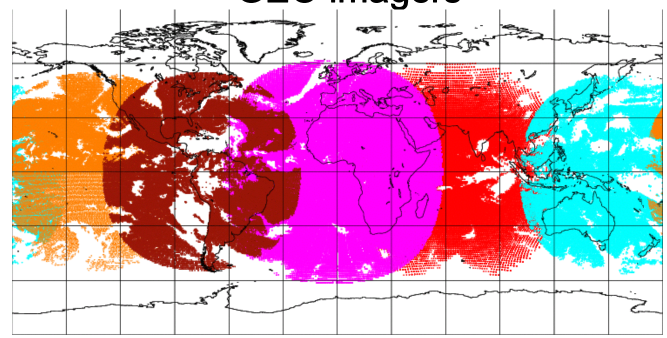
LEO Imagers



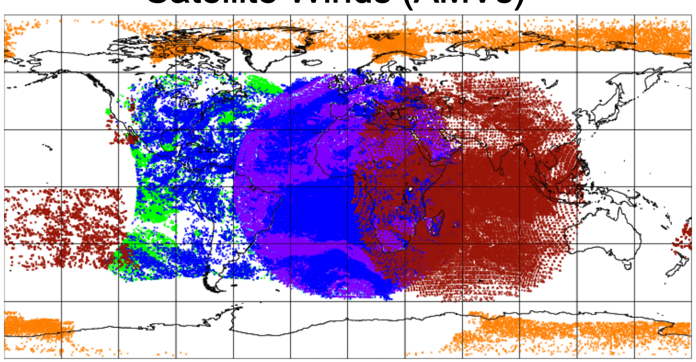
Scatterometers



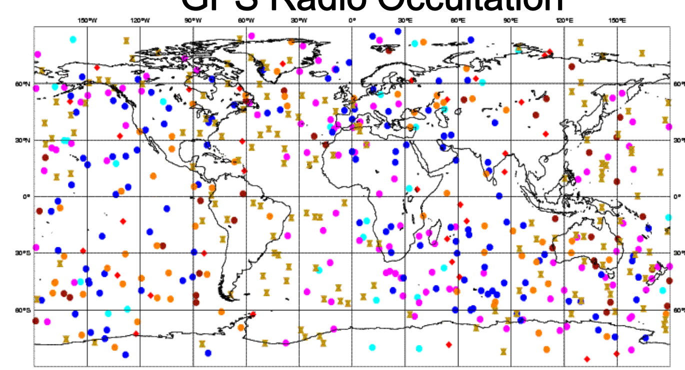
GEO imagers



Satellite Winds (AMVs)



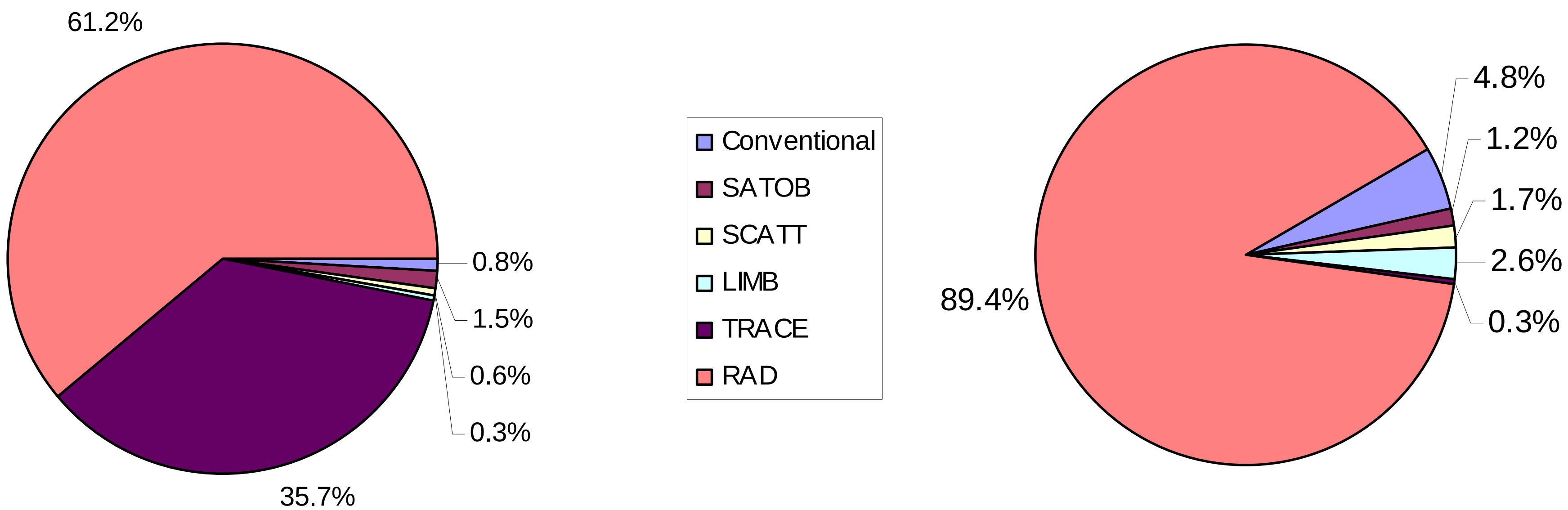
GPS Radio Occultation



Data types

Screening
24/04/2008 00UTC

Assimilation
24/04/2008 00UTC



- 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:

$$\mathbf{x}_o = \mathbf{x}_{o,b} + \delta\mathbf{x}_o$$

Observation operator at time t_i:

$$H_i(\mathbf{x}_i) = H_i(\mathbf{x}_{i,b}) + \mathbf{H}_i\delta\mathbf{x}_i, \qquad \delta\mathbf{x}_i = \mathbf{M}(\mathbf{x}_o, \mathbf{x}_i)\delta\mathbf{x}_o$$

Cost-function gradient:

$$\nabla_{\delta x_o} J = \mathbf{B}^{-1}\delta\mathbf{x}_o + \sum_{i=0}^{n} \mathbf{M}^T(t_i, t_o)\mathbf{H}_i^T\mathbf{R}_i^{-1}\left(\mathbf{d}_i - \mathbf{H}_i\delta\mathbf{x}_i\right)$$

$$\mathbf{d}_i = \mathbf{y}_{o,i} - H(\mathbf{x}_{i,b})$$

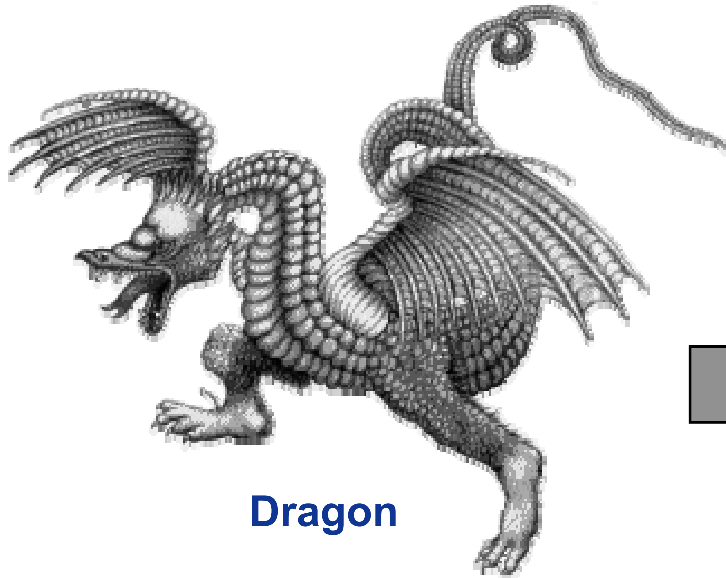
All **terms determine analysis impact of observations**
$\Rightarrow$ Ideally, impact diagnostics perform evaluation for *all* terms

(P. Lopez)

How is radiance information used?

Forward problem:

$$\mathbf{y} = H\,(\mathbf{x}_b)$$



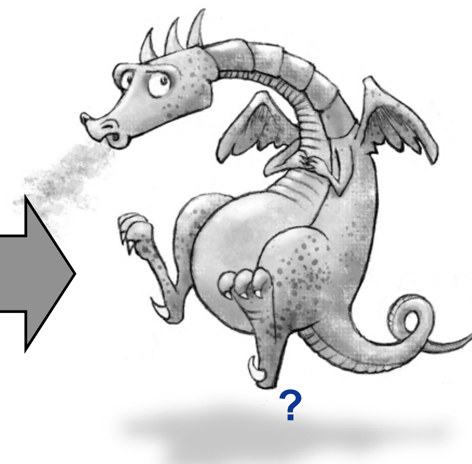
Dragon

Tracks

Inverse problem:

$$\mathbf{x}_a = H^{-1}\,(\mathbf{y}_o)$$

Tracks



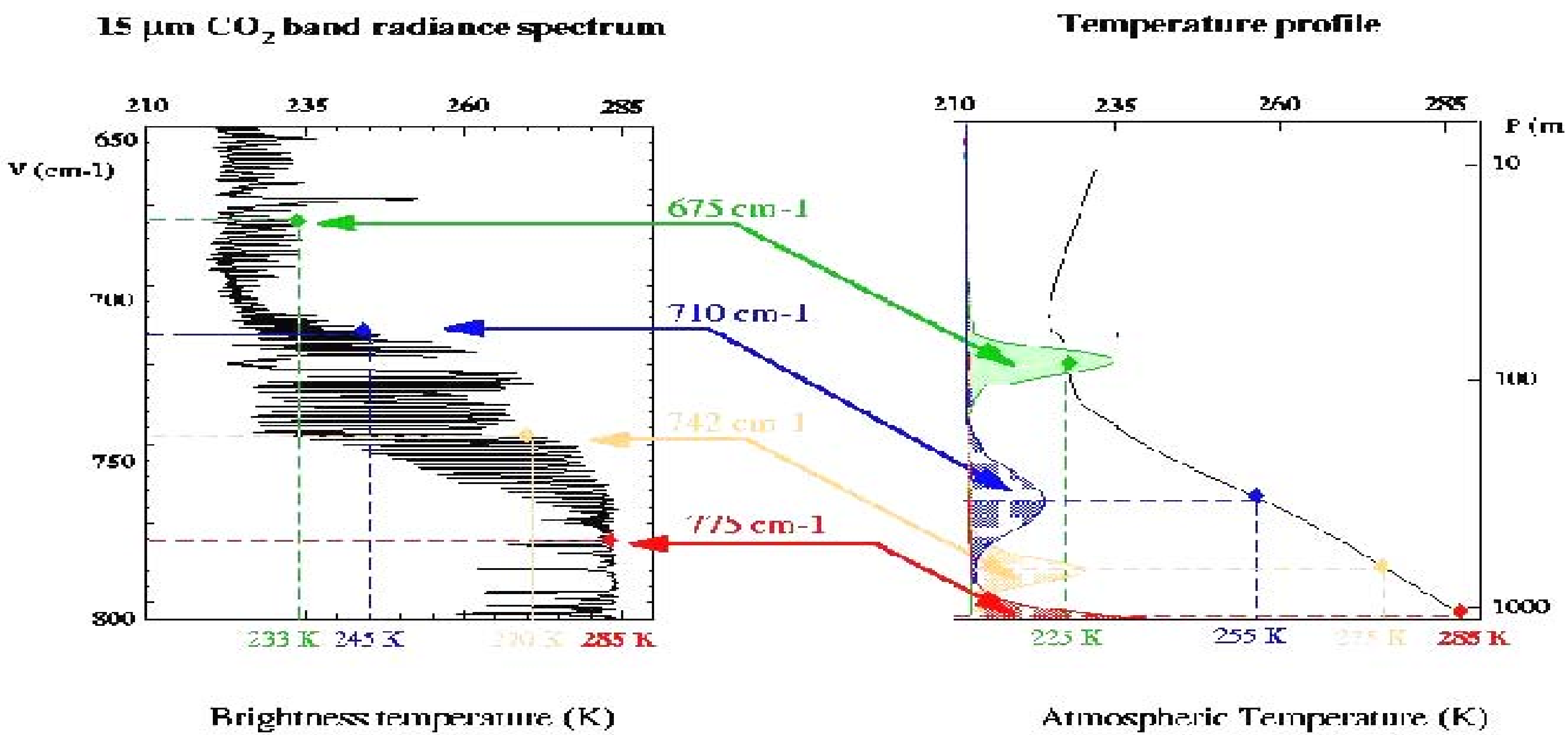
?

(G. Stephens)

Forward/inverse modeling

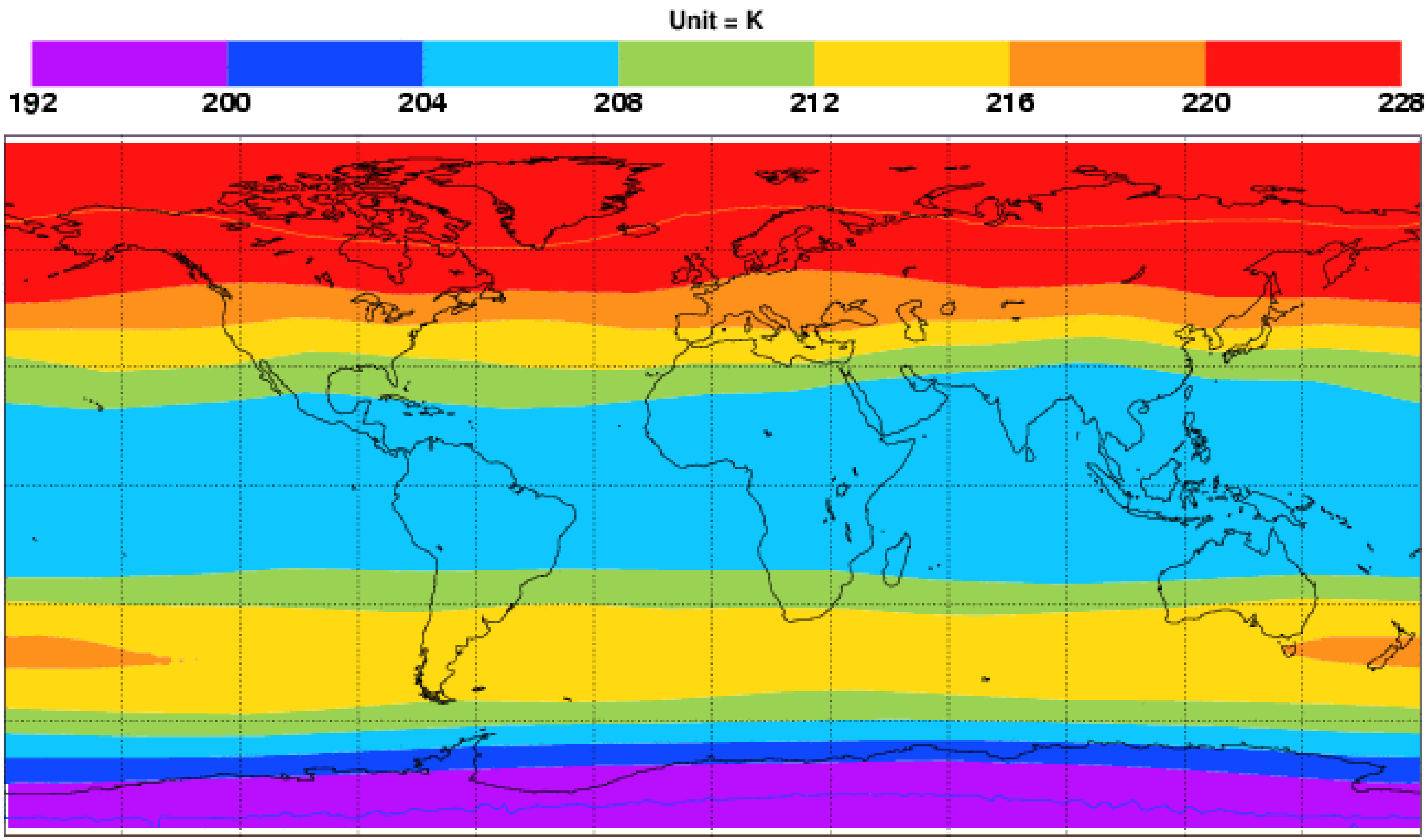
$\mathbf{y} = H(\mathbf{x}_b)$: Forward (interpolation + radiative transfer)

$\mathbf{x}_a = H^{-1}(\mathbf{y}_o)$: Inverse (interpolation + radiative transfer + a priori information)



AMSU-A observations

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



(M. Rodwell)

AMSU-A observation-model

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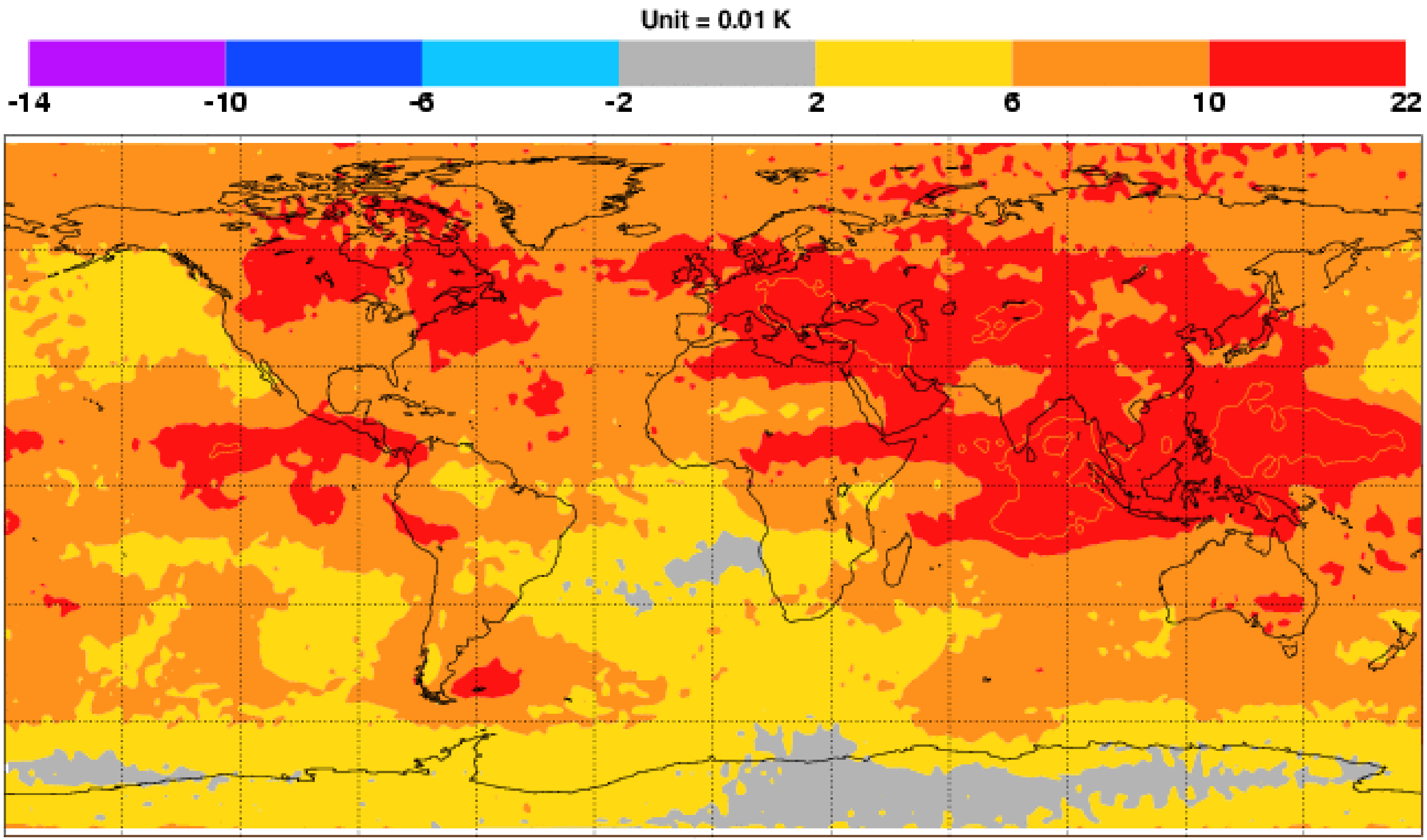
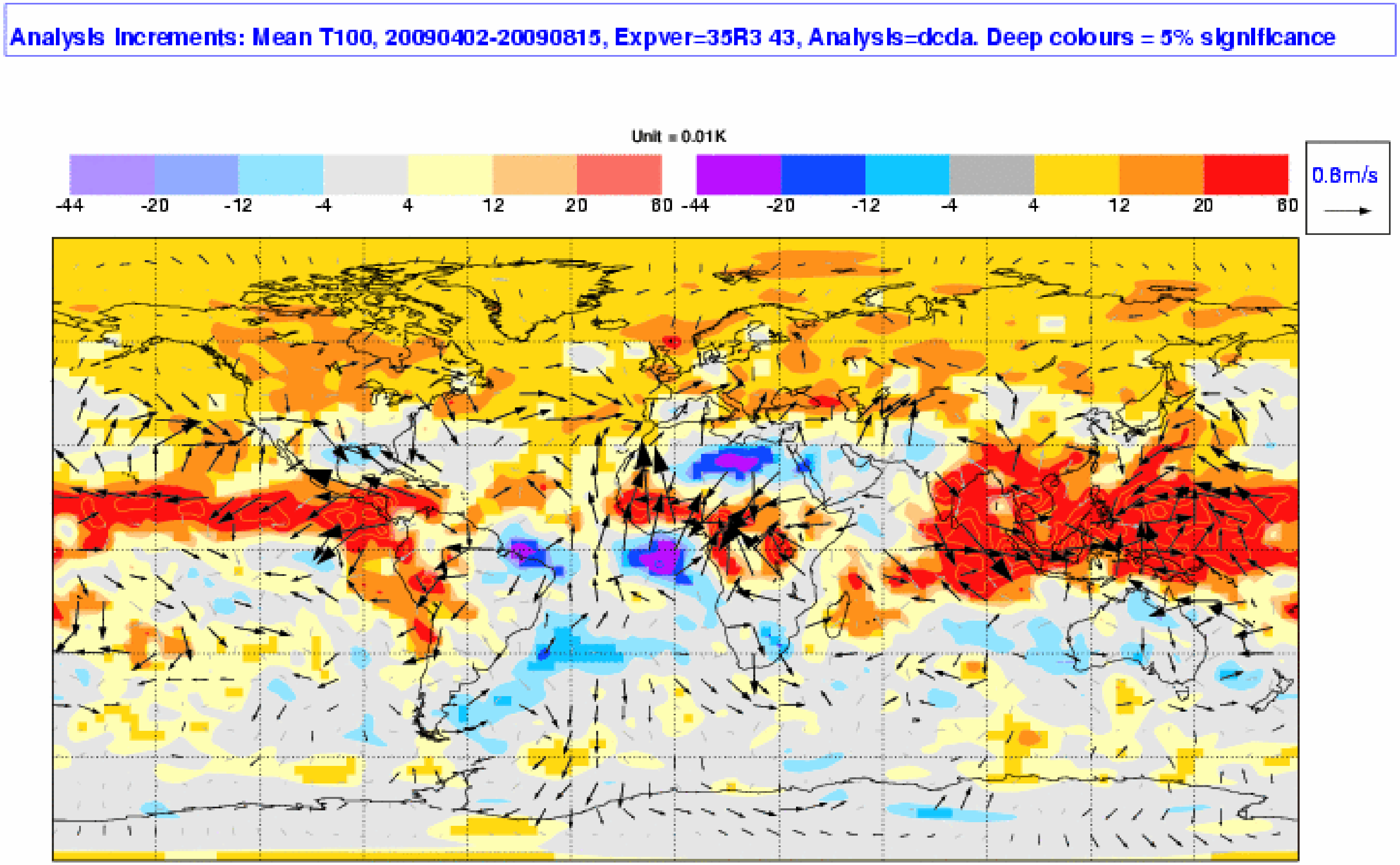
Microwave brightness temperature, weighting function: 150 to 30 hPa



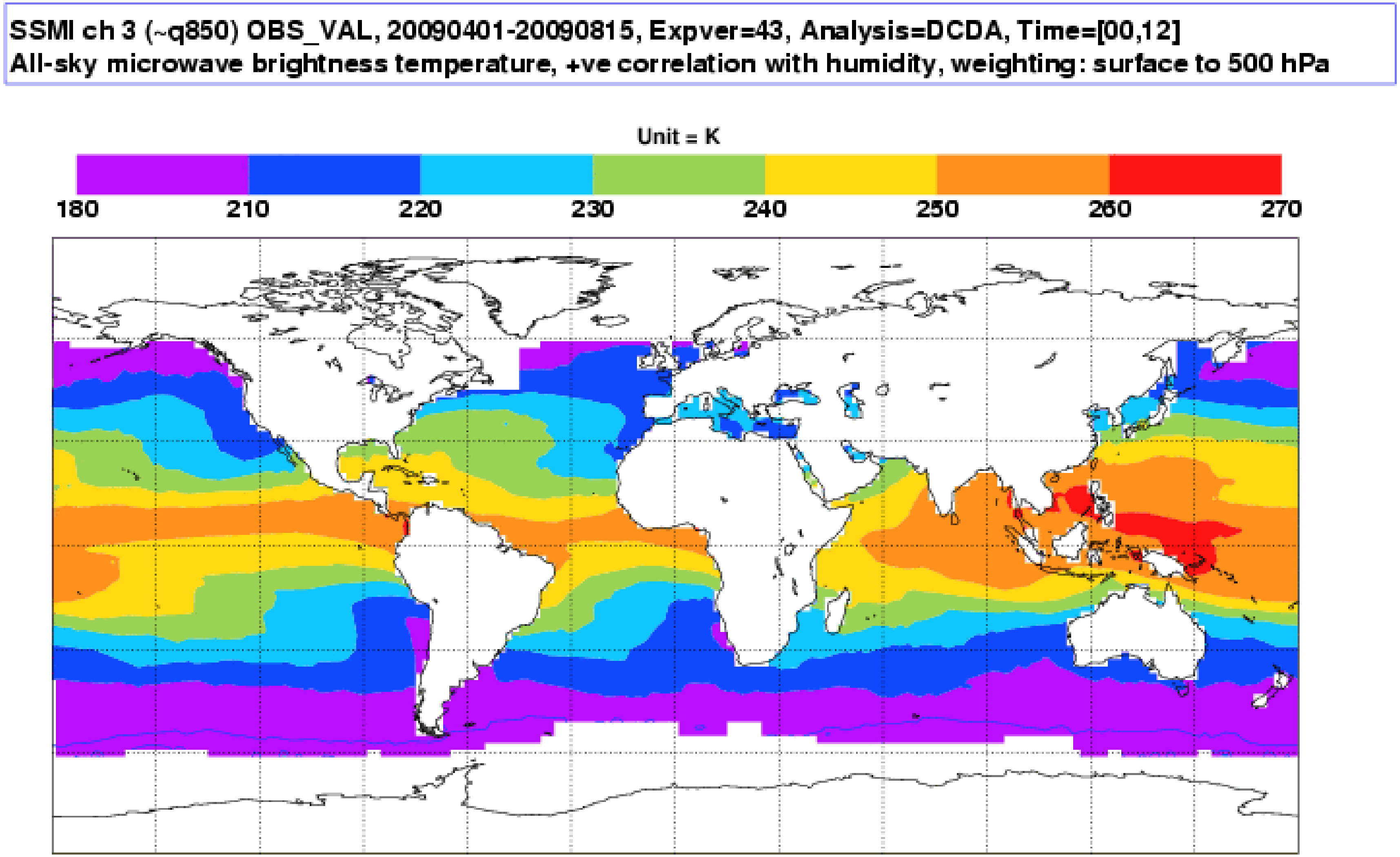
(M. Rodwell)

Mean T-increment



(M. Rodwell)

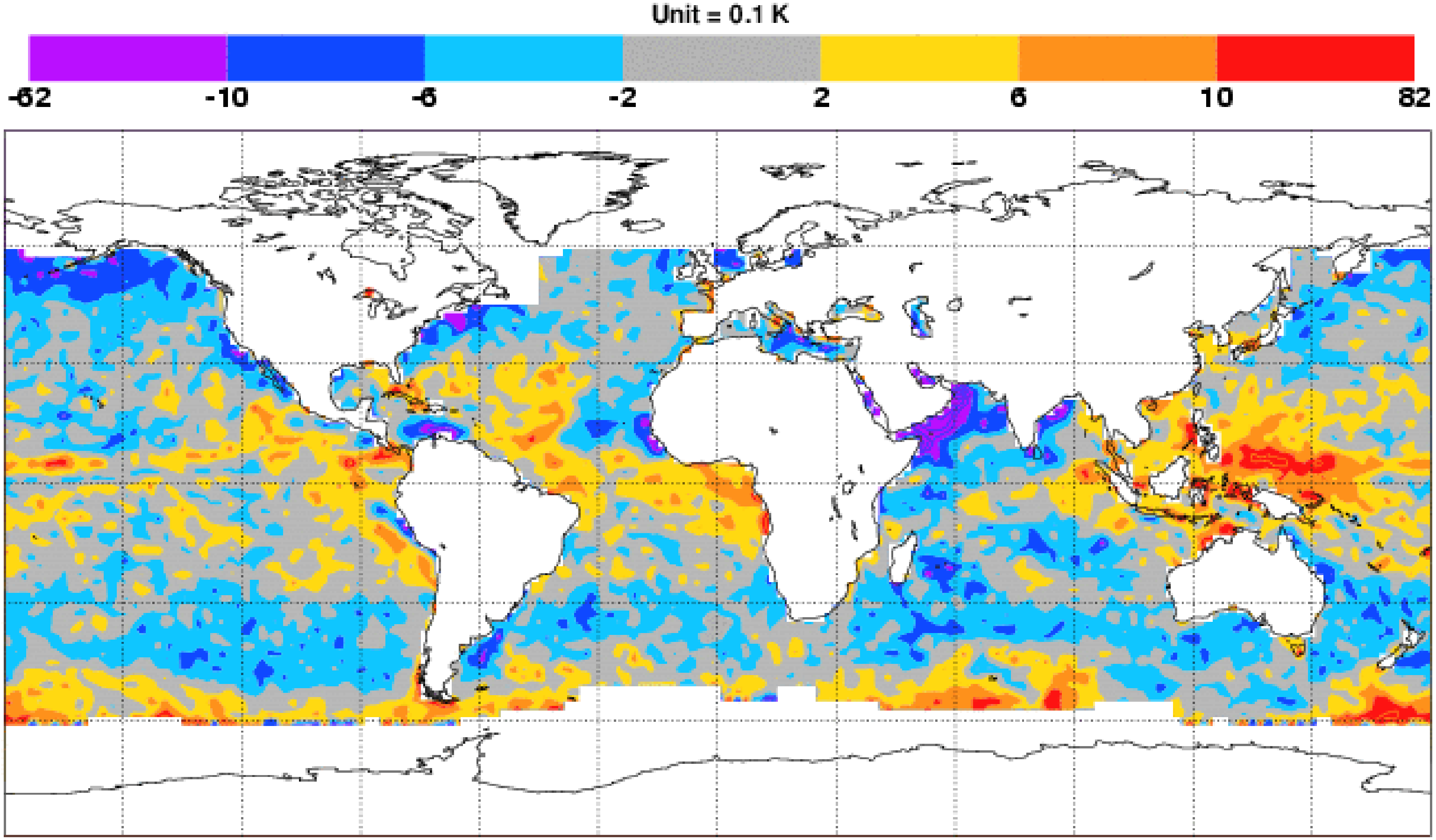
SSM/I observations



(M. Rodwell)

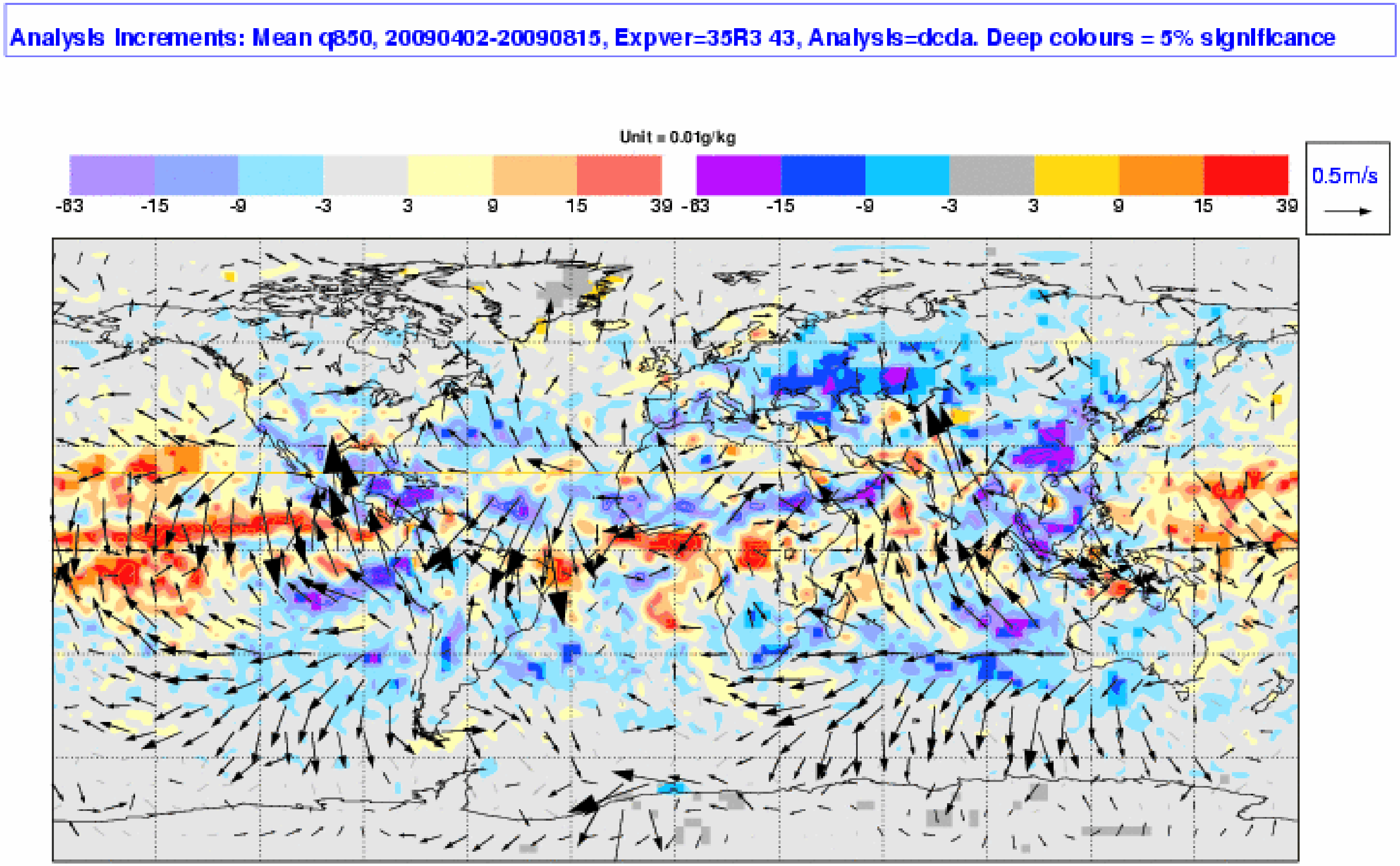
SSM/I observation-model

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



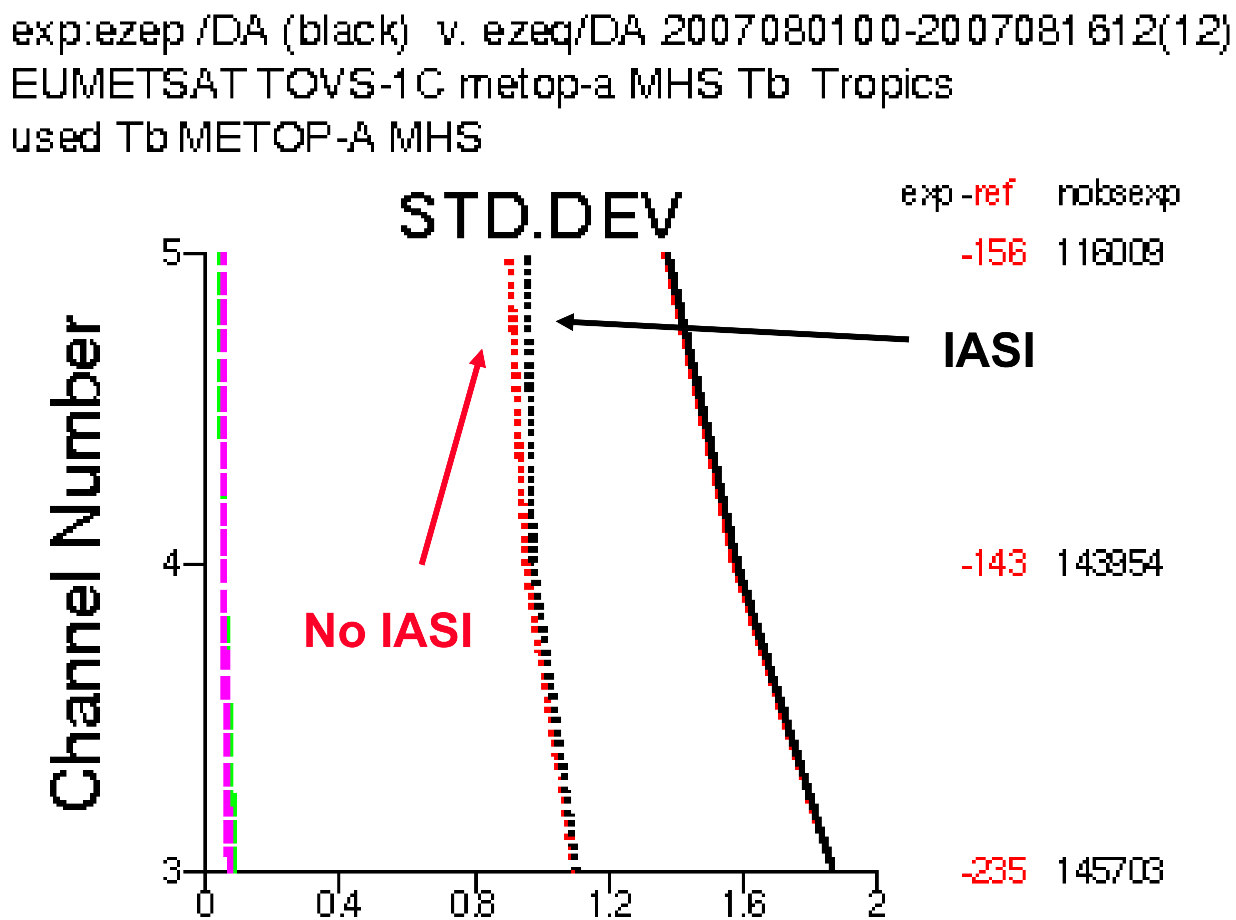
(M. Rodwell)

Mean q-increment



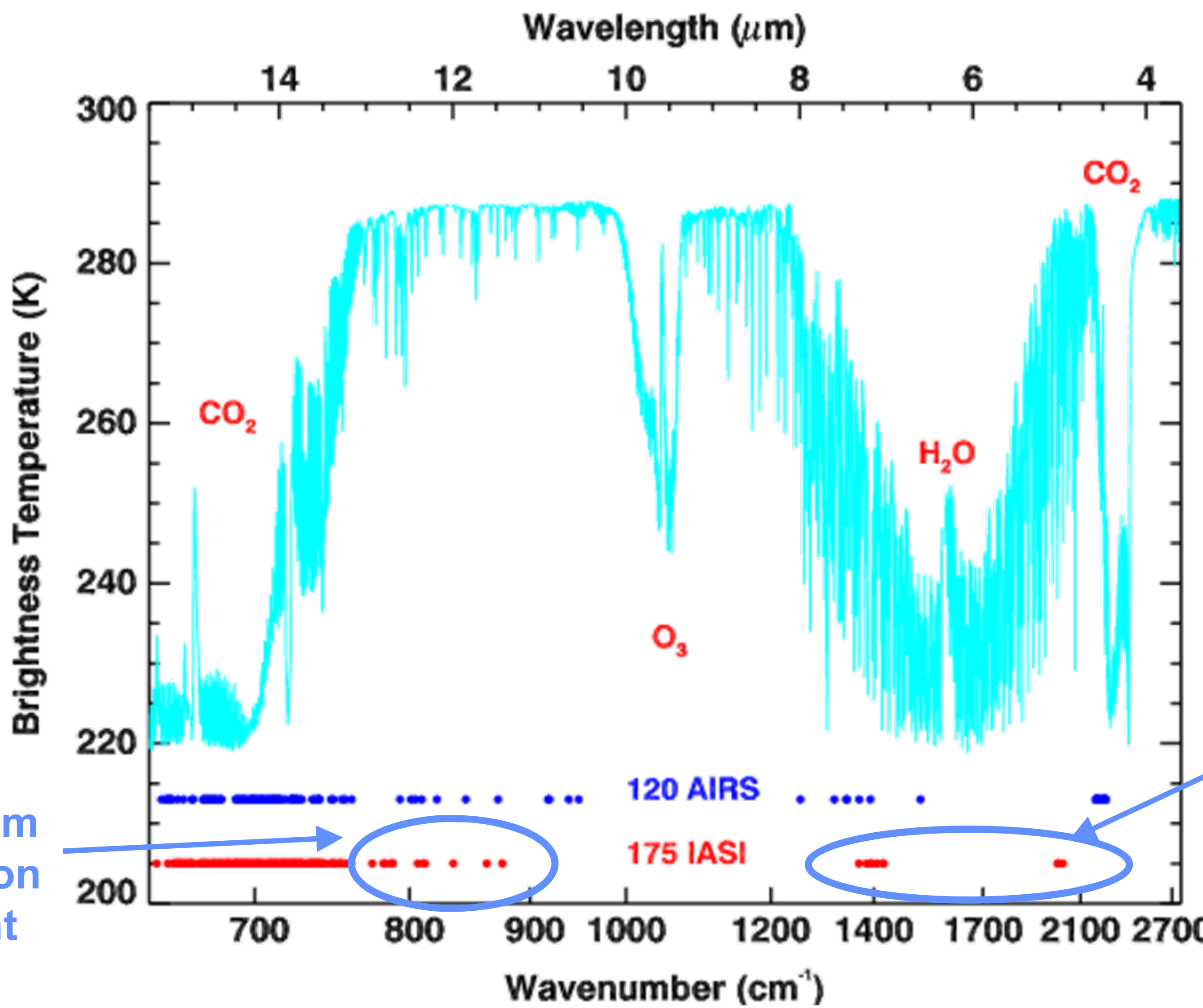
(M. Rodwell)

The curious case of degrading MHS channel 5 by adding IASI



(A. Collard)

… without assimilating IASI water vapour channels



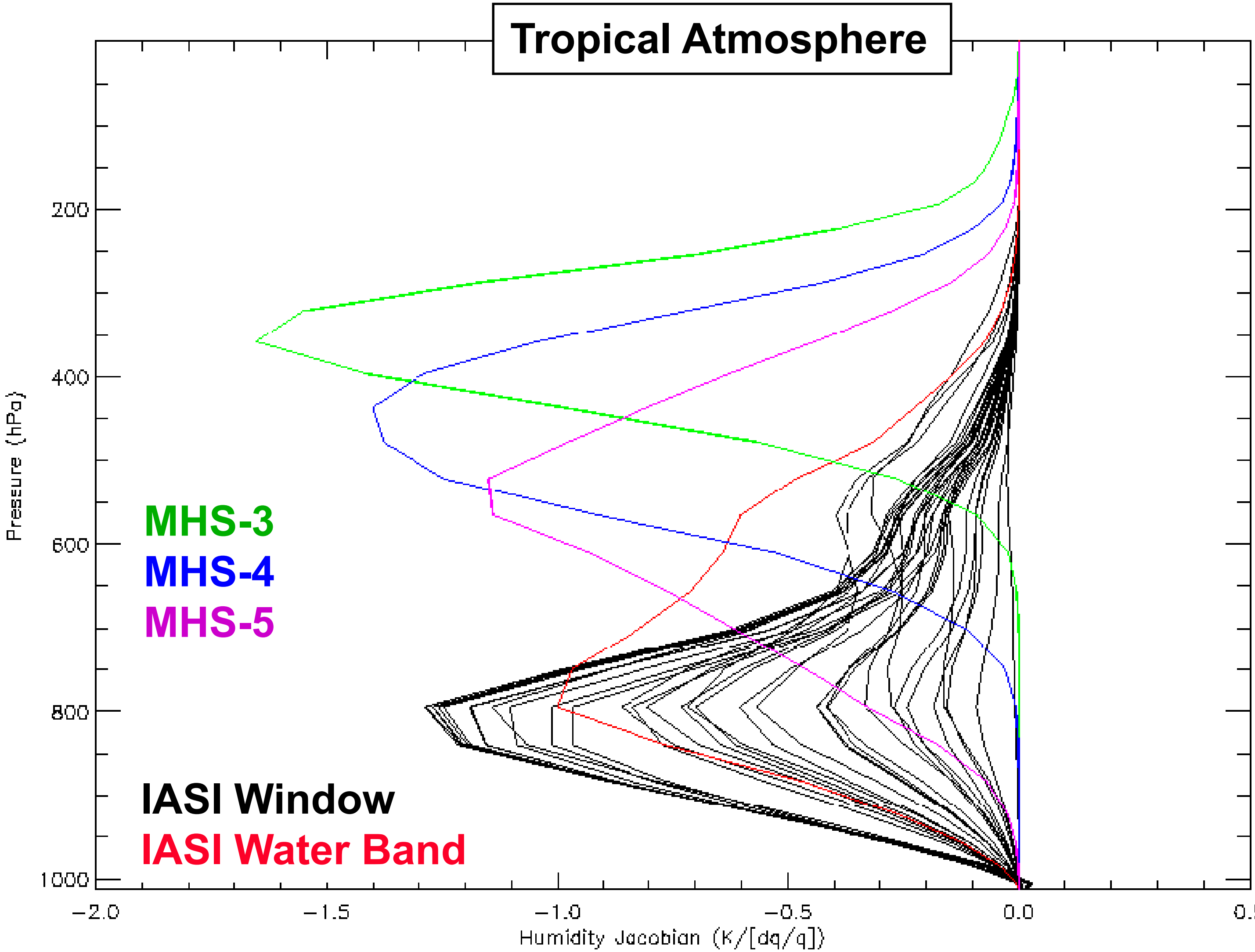
Water continuum absorption important here

Water channels added in CY35R2

(A. Collard)

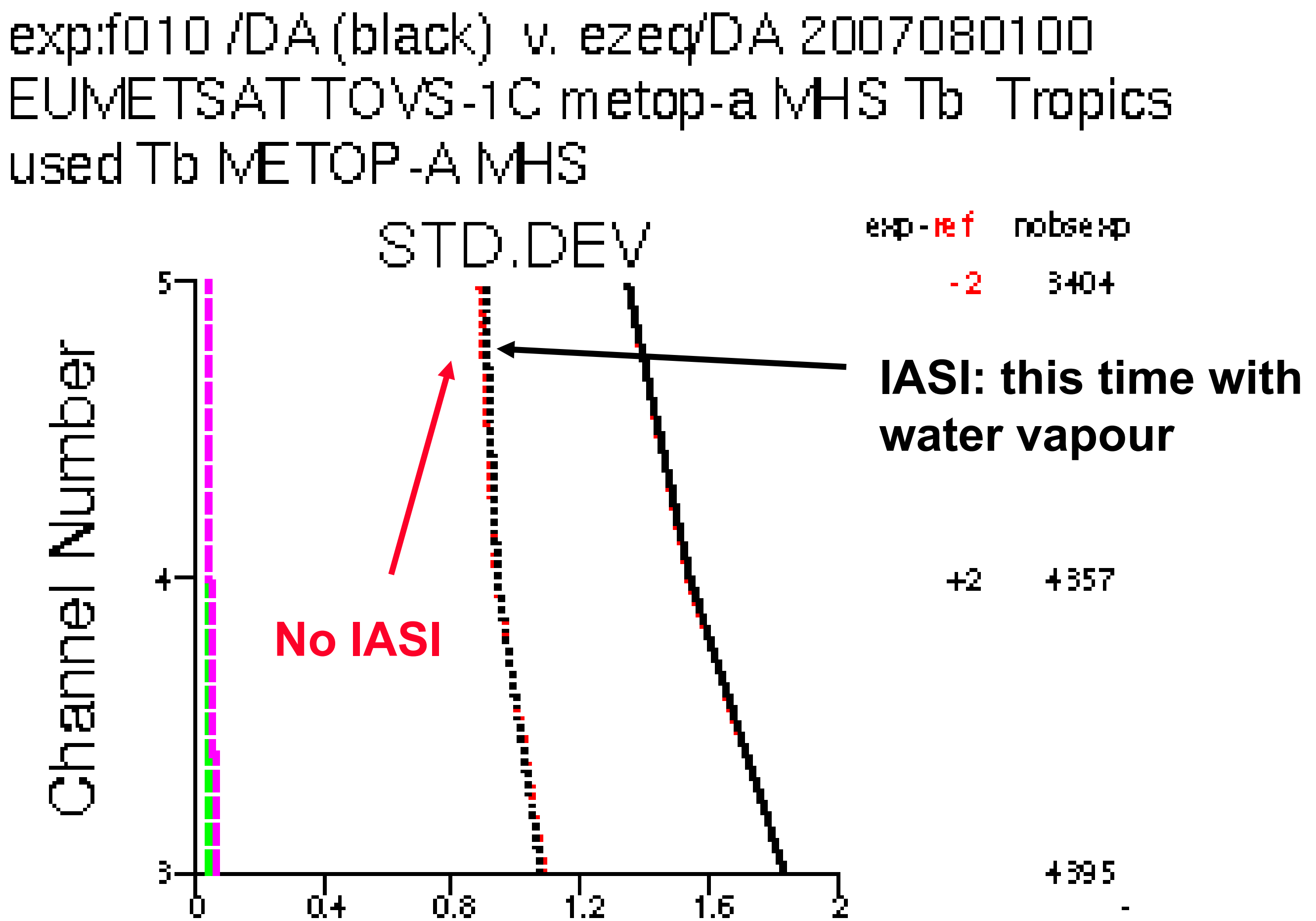
ECMWF

IASI window (water vapour) Jacobians



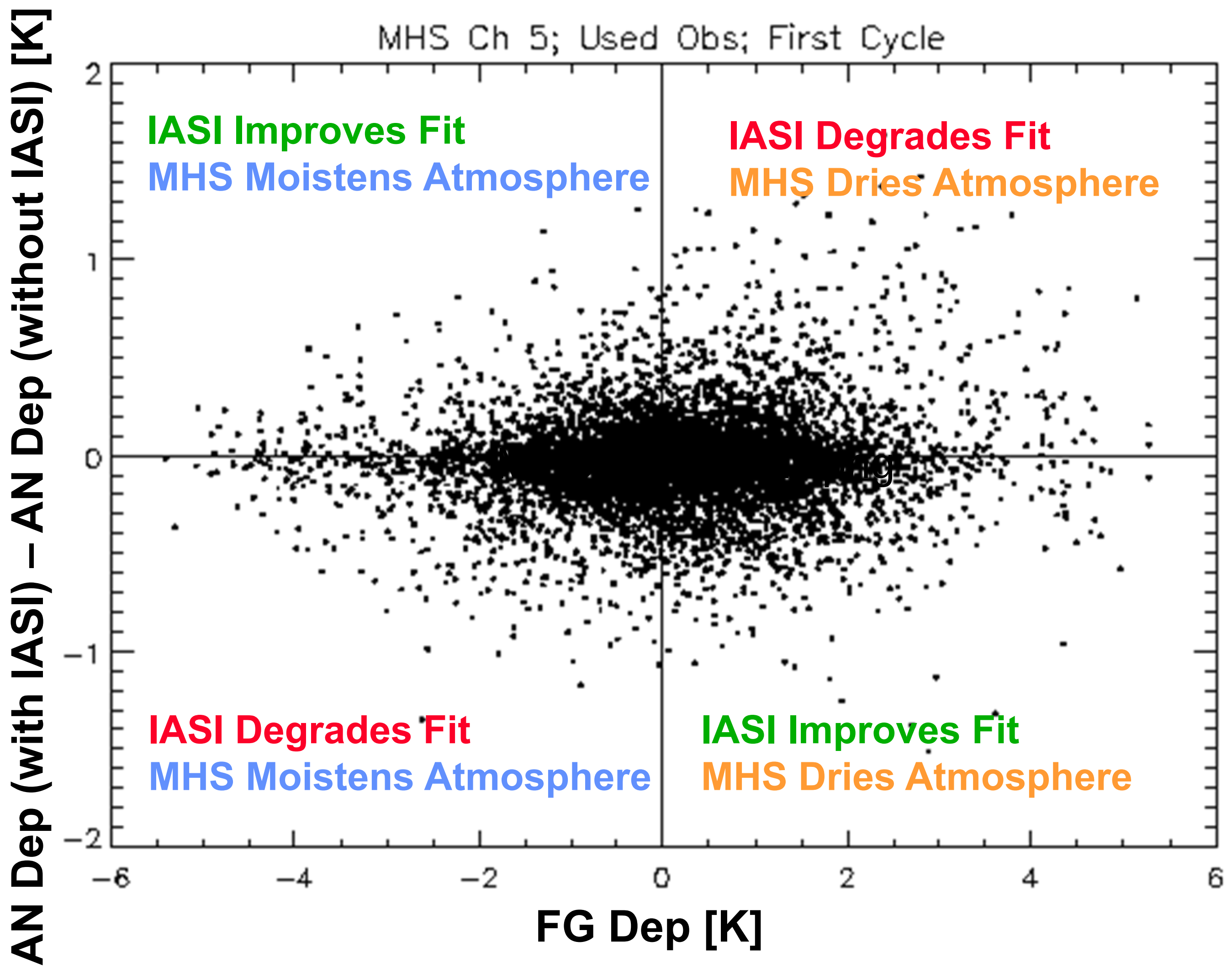
(A. Collard)

… and with assimilating IASI water vapour channels



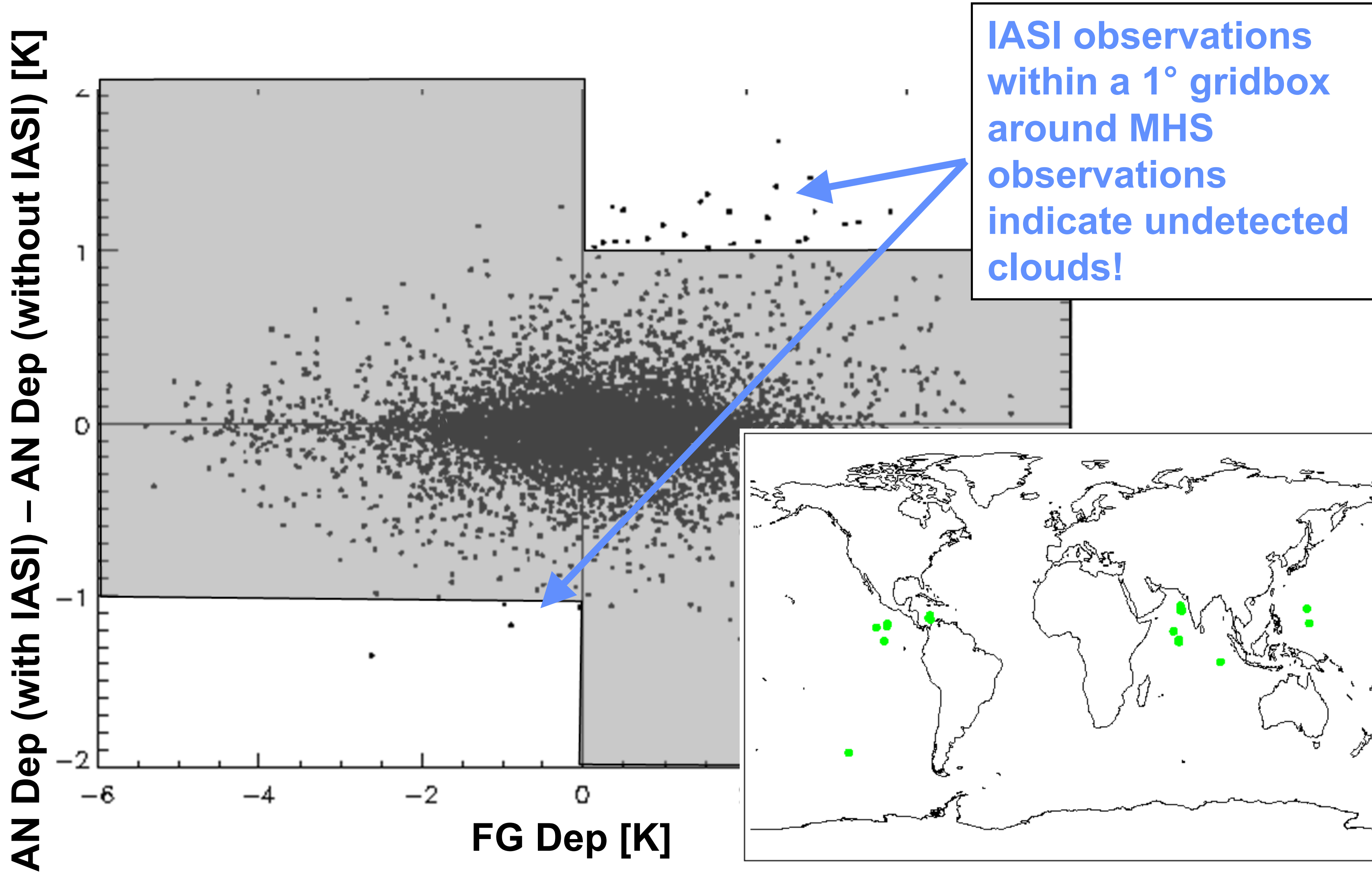
(A. Collard)

Why is MHS-5 Analysis Degraded?



(A. Collard)

Why is MHS-5 Analysis Degraded?

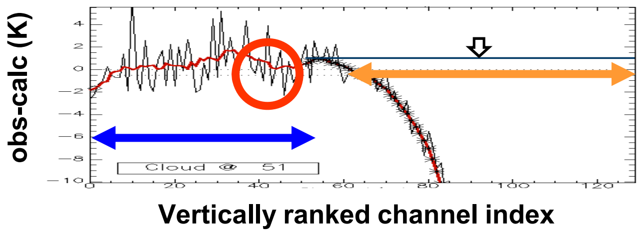


(A. Collard)

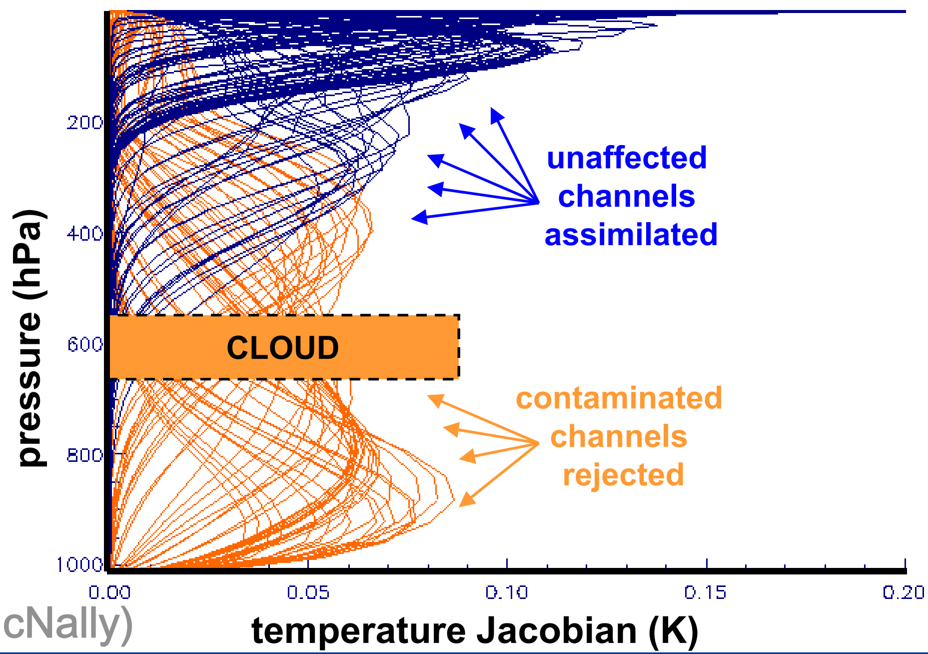
ECMWF

AIRS/IASI cloud detection

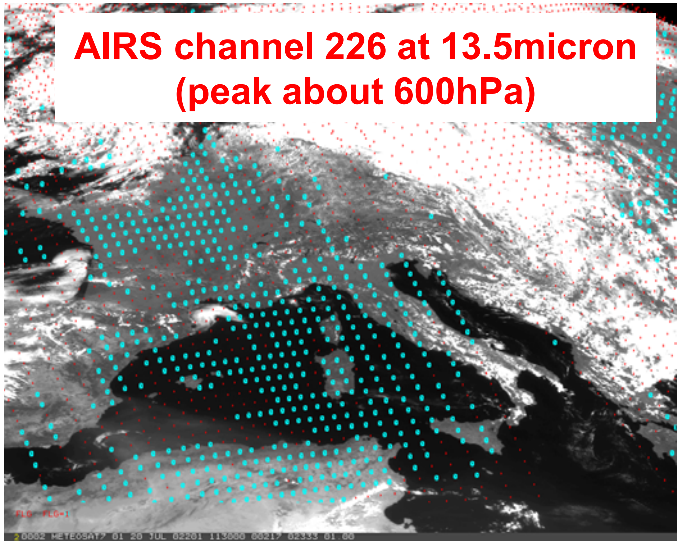
A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.

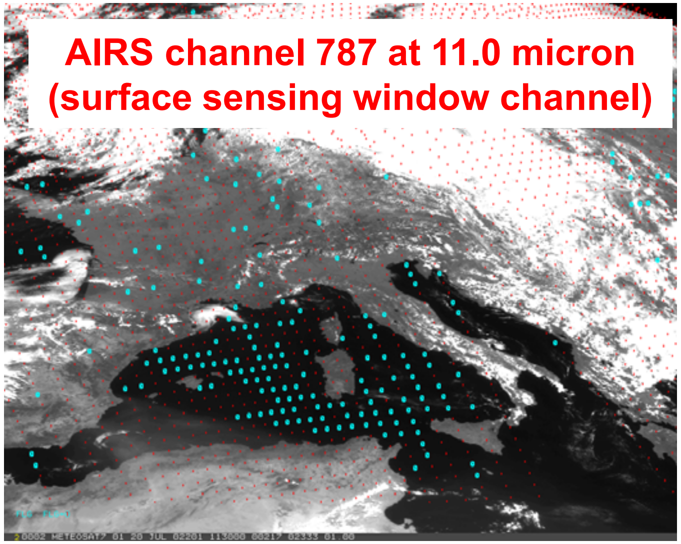


This identifies the characteristic signal of cloud in the data and allows contaminated channels to be rejected

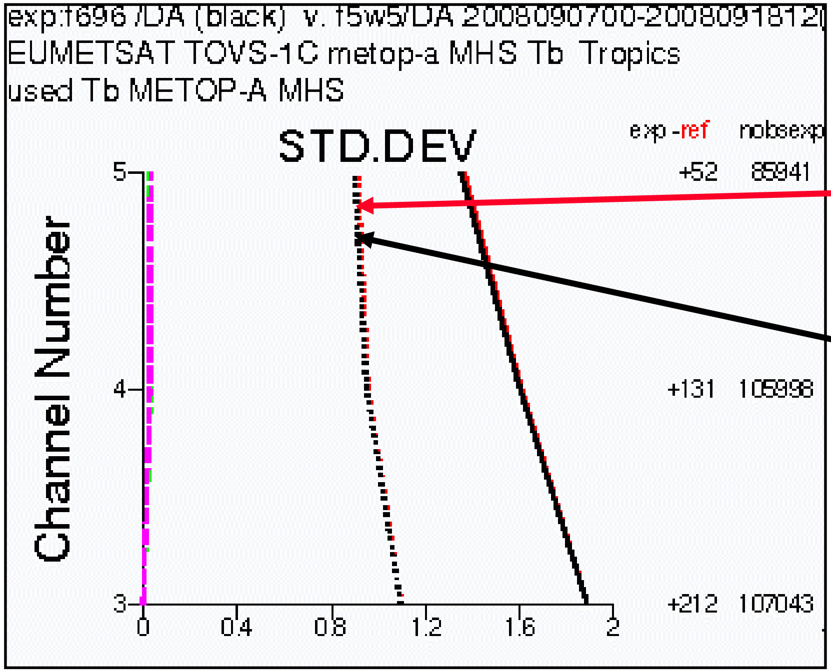


(T. McNally)





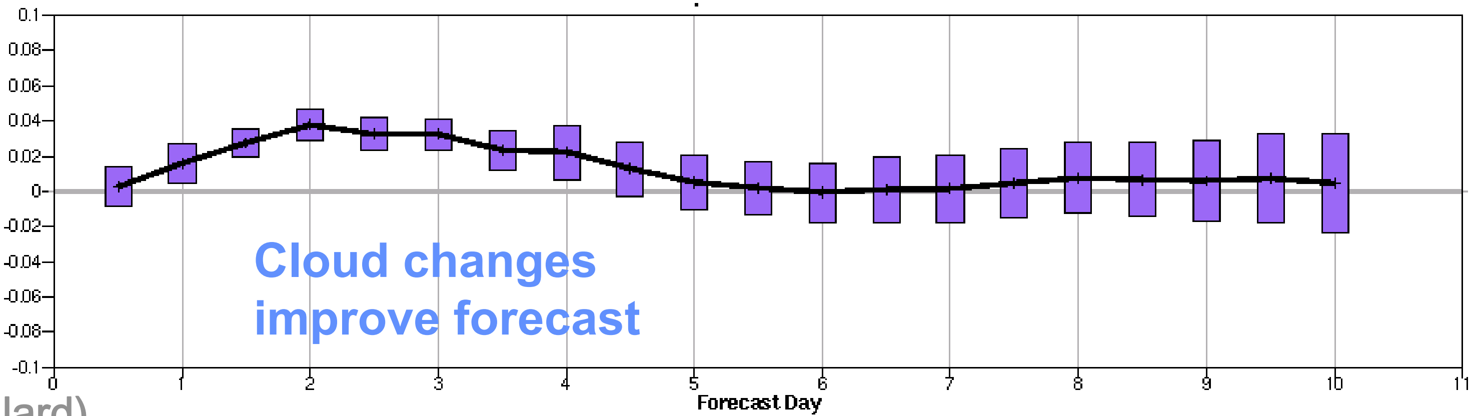
MHS observation statistics/scores



IASI without water vapour and unsafe cloud detection

IASI: this time with water vapour & cloud fix

NH RMS 100 hPa z



Cloud changes improve forecast

(A. Collard)

Satellite data usage at ECMWF

Impact of existing satellite data

- Data monitoring
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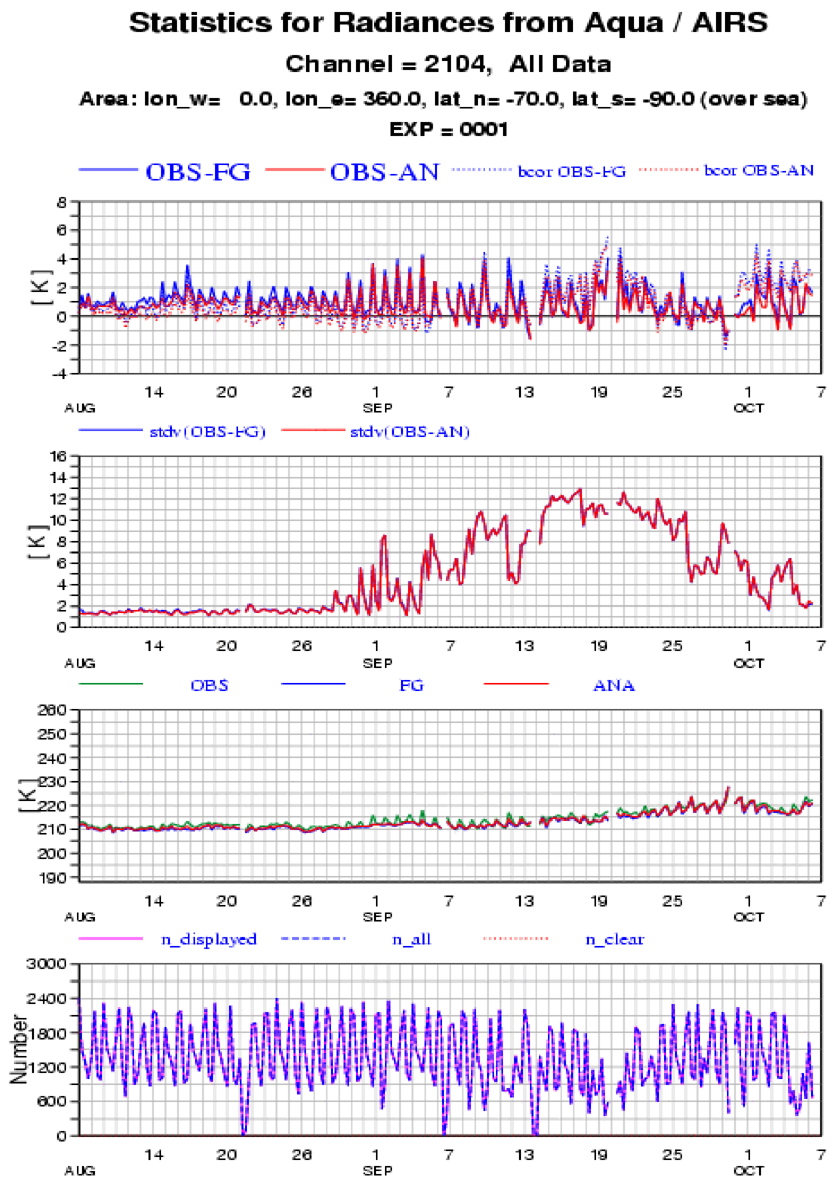
- Advanced diagnostic tools

Impact of future satellite data

Summary

Data monitoring – time series



Time evolution of statistics over predefined areas/surfaces/flags

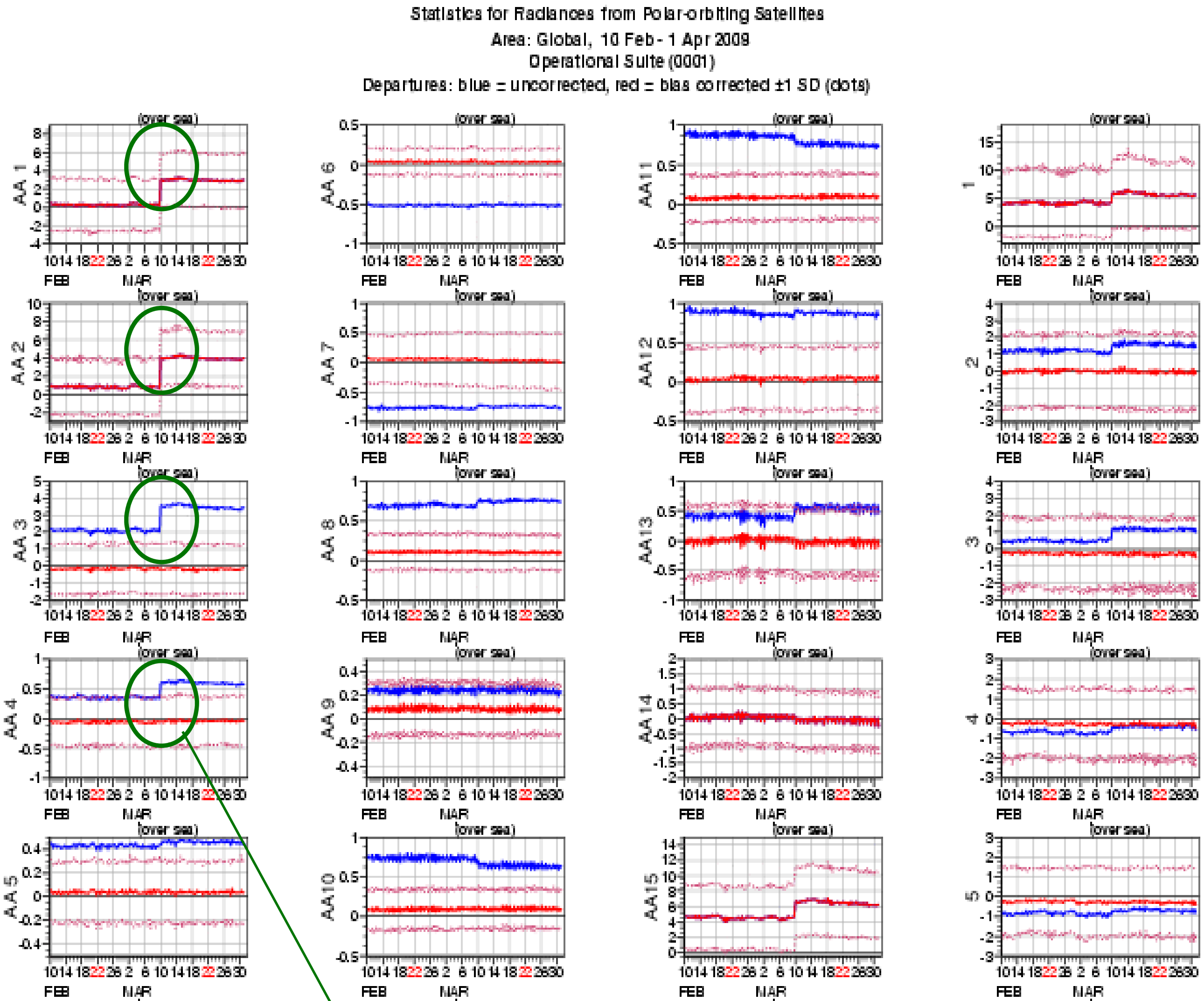
(M. Dahoui)

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

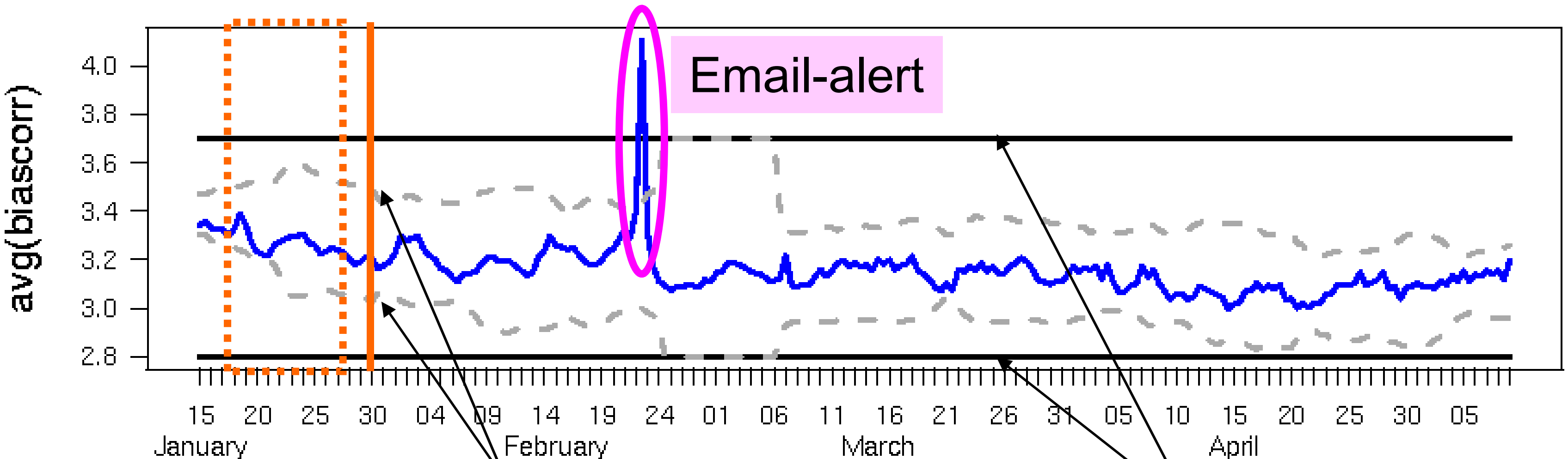
(M. Dahoui)

Data monitoring – automated warnings

http://www.ecmwf.int/products/forecasts/satellite_check/

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 2
ending 2 days earlier)

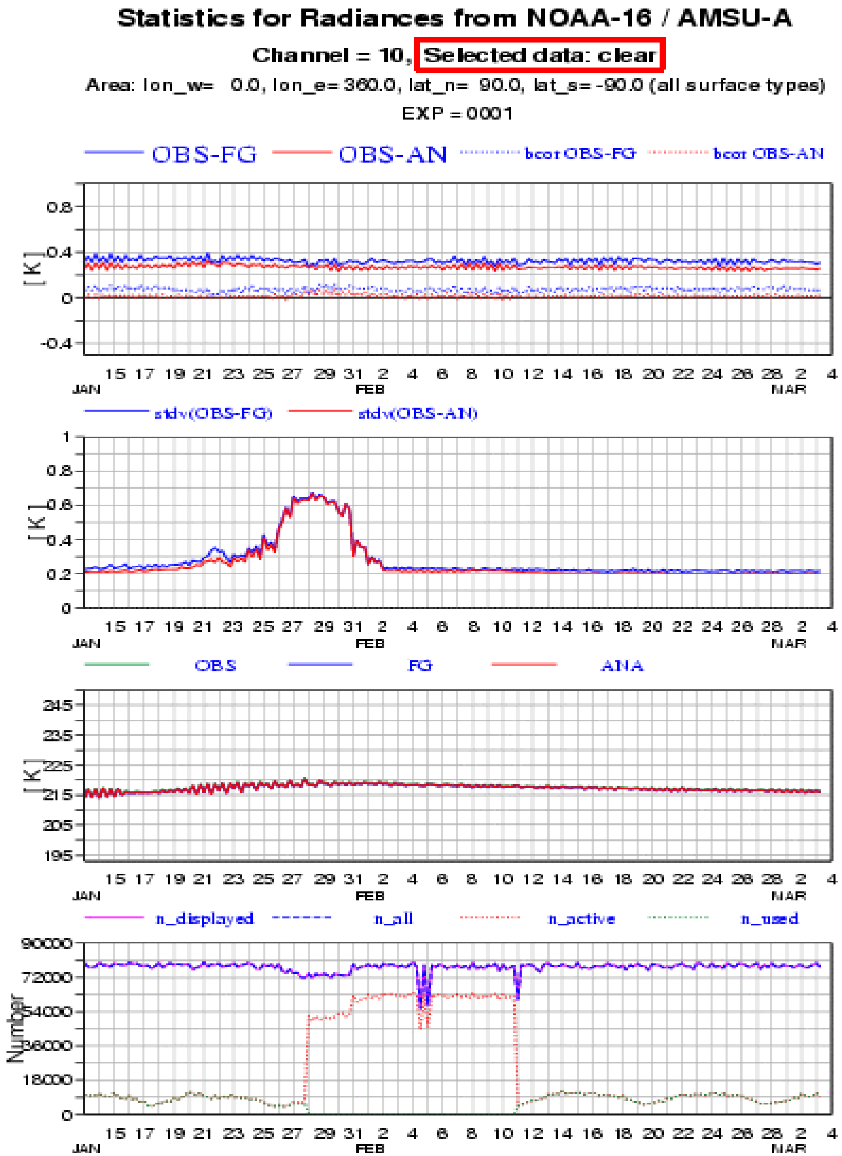
Hard limits (fixed)

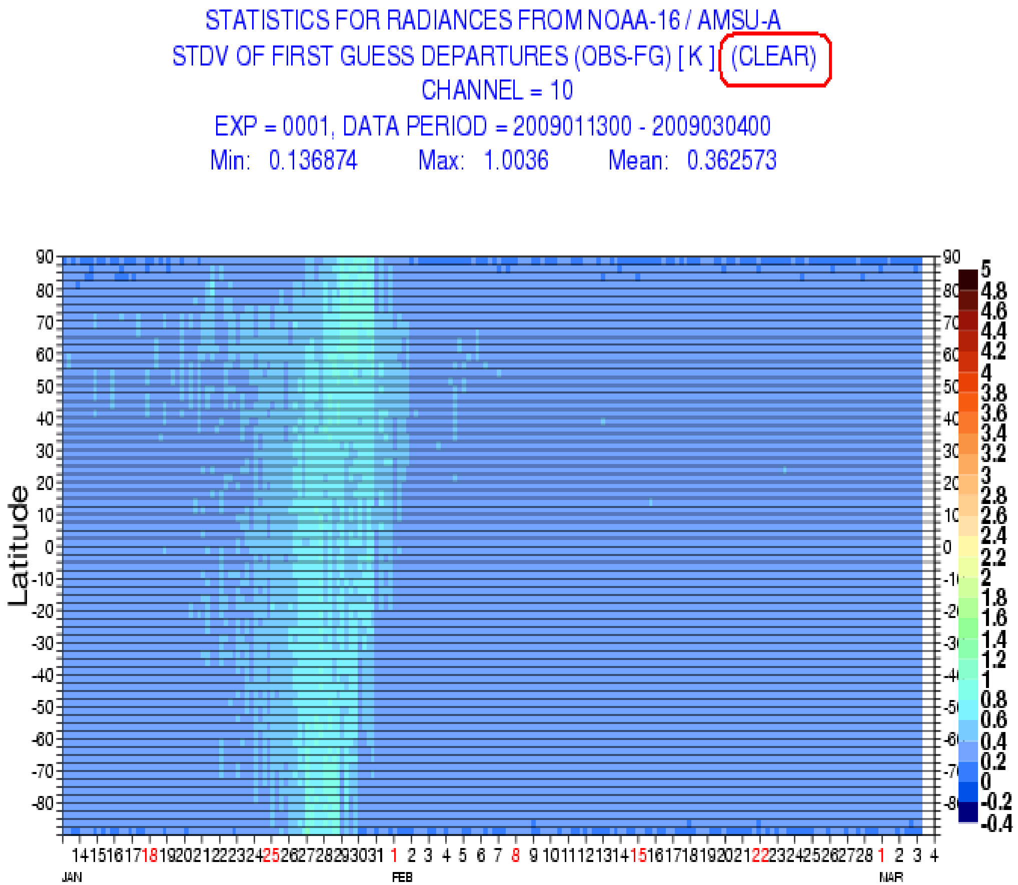
Email alert:

```
GOES-12 GOESIMG 2 clear radiances : out of range:
   avg(fg_depar)=1.34775547847879,  expected range: -0.38 0.47
   avg(biascorr)=4.10498646958382,  expected range: 3.0 3.4
```

(M. Dahoui & N. Bormann)

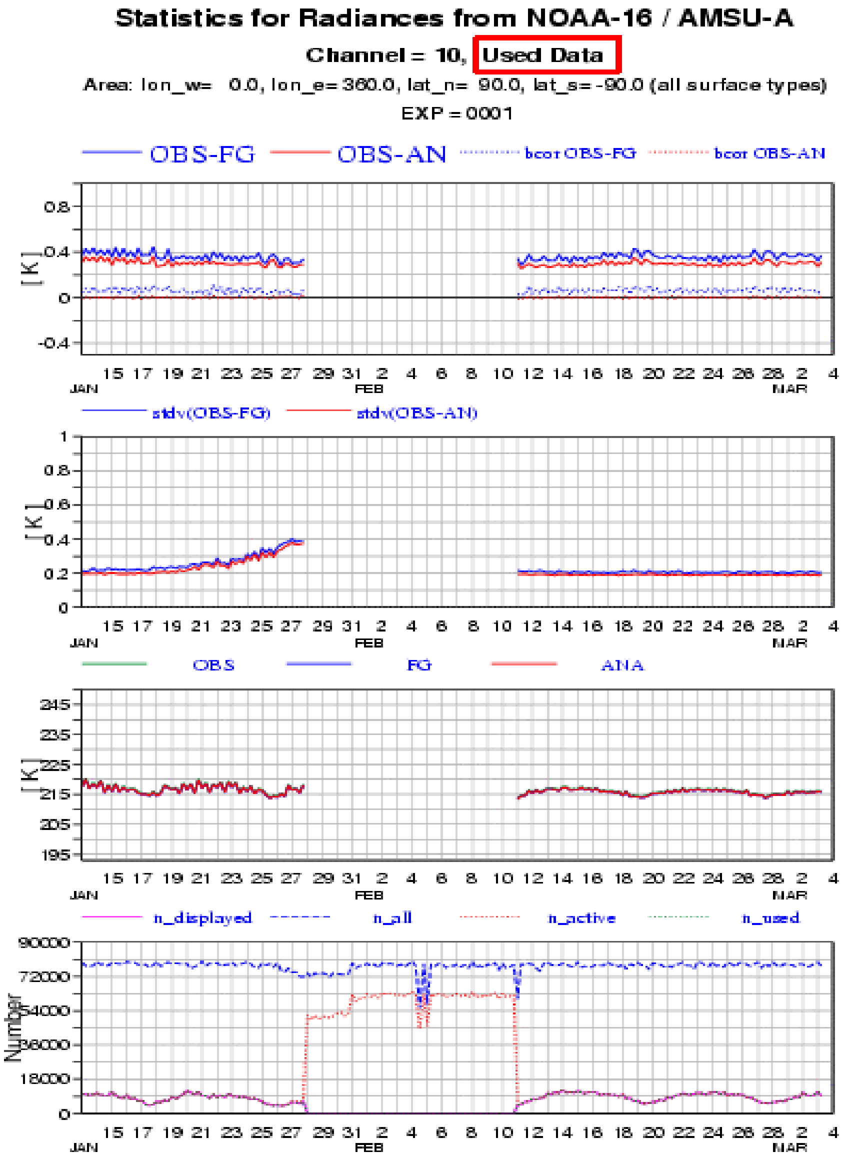
Data monitoring – automated warnings

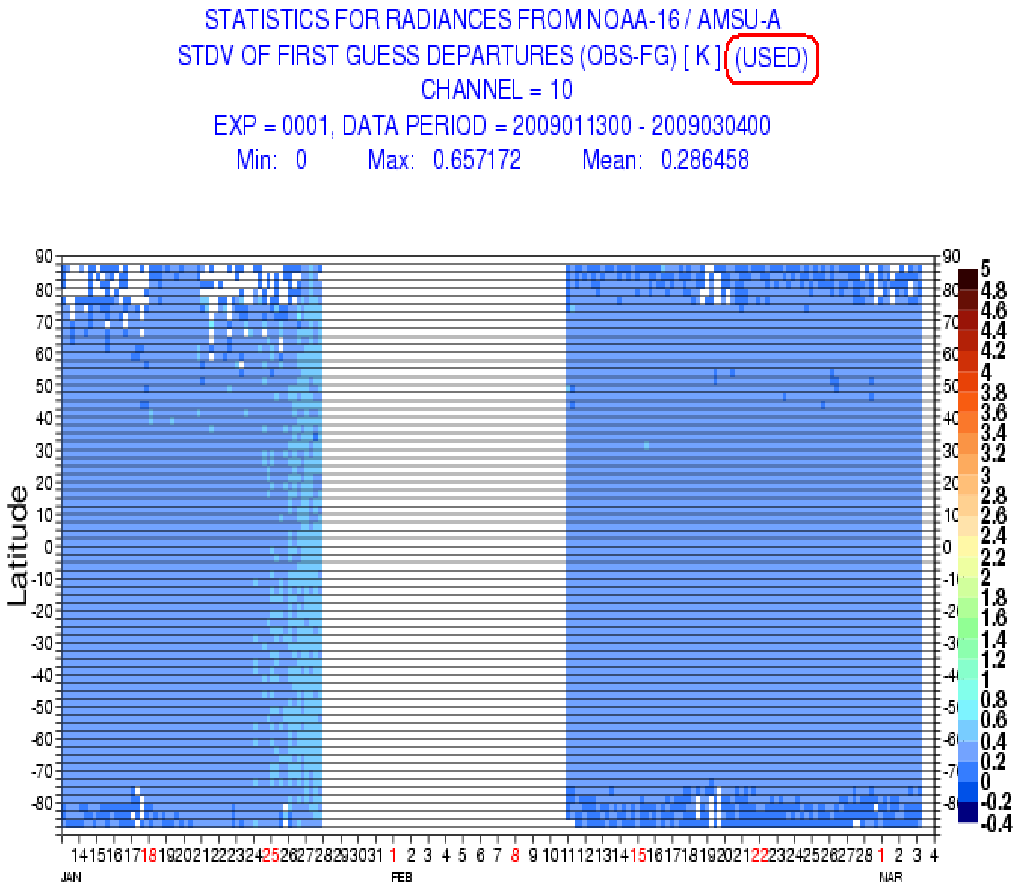




(M. Dahoui & N. Bormann)

Data monitoring – automated warnings





(M. Dahoui & N. Bormann)

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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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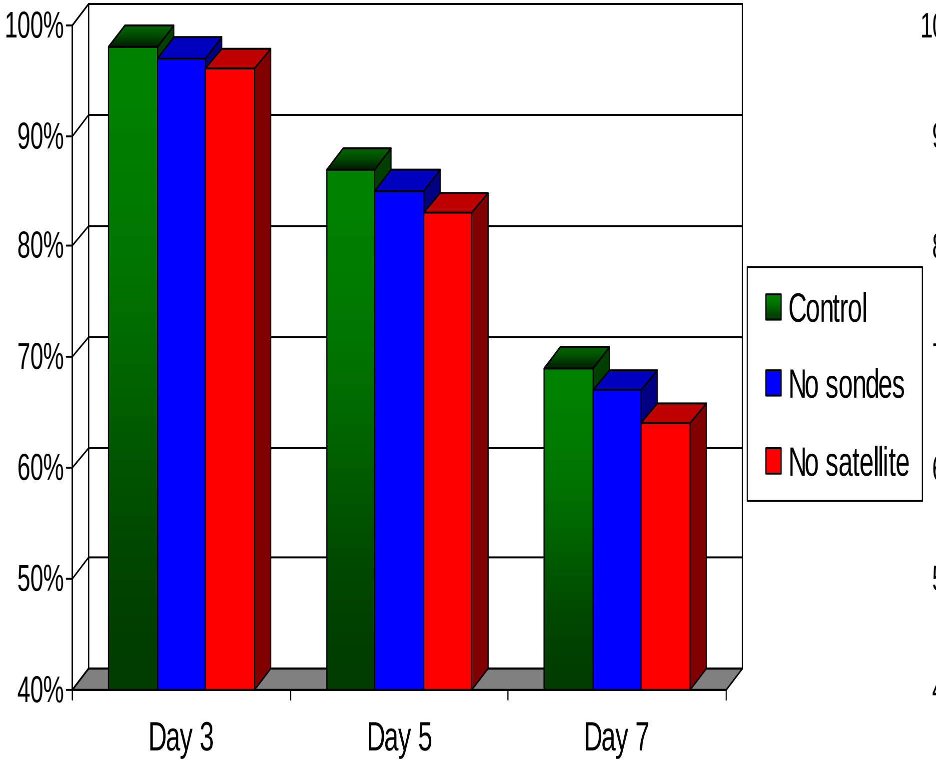
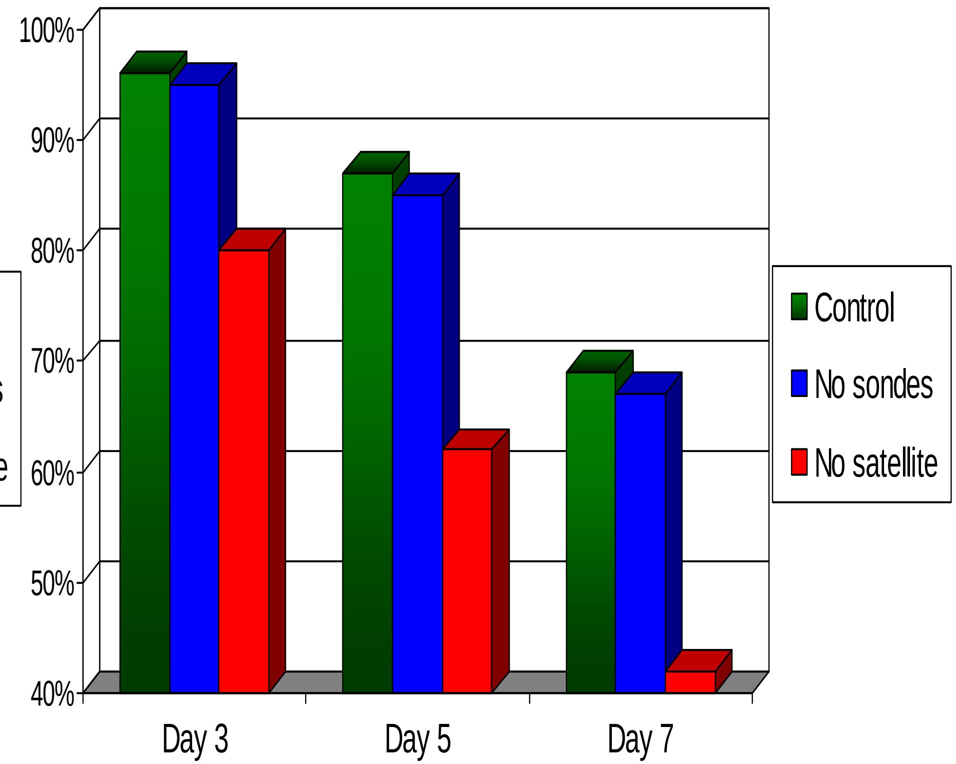
Impact of conventional *vs* satellite data

Observing System Experiments

Anomaly correlation of 500hPa height for Northern hemisphere

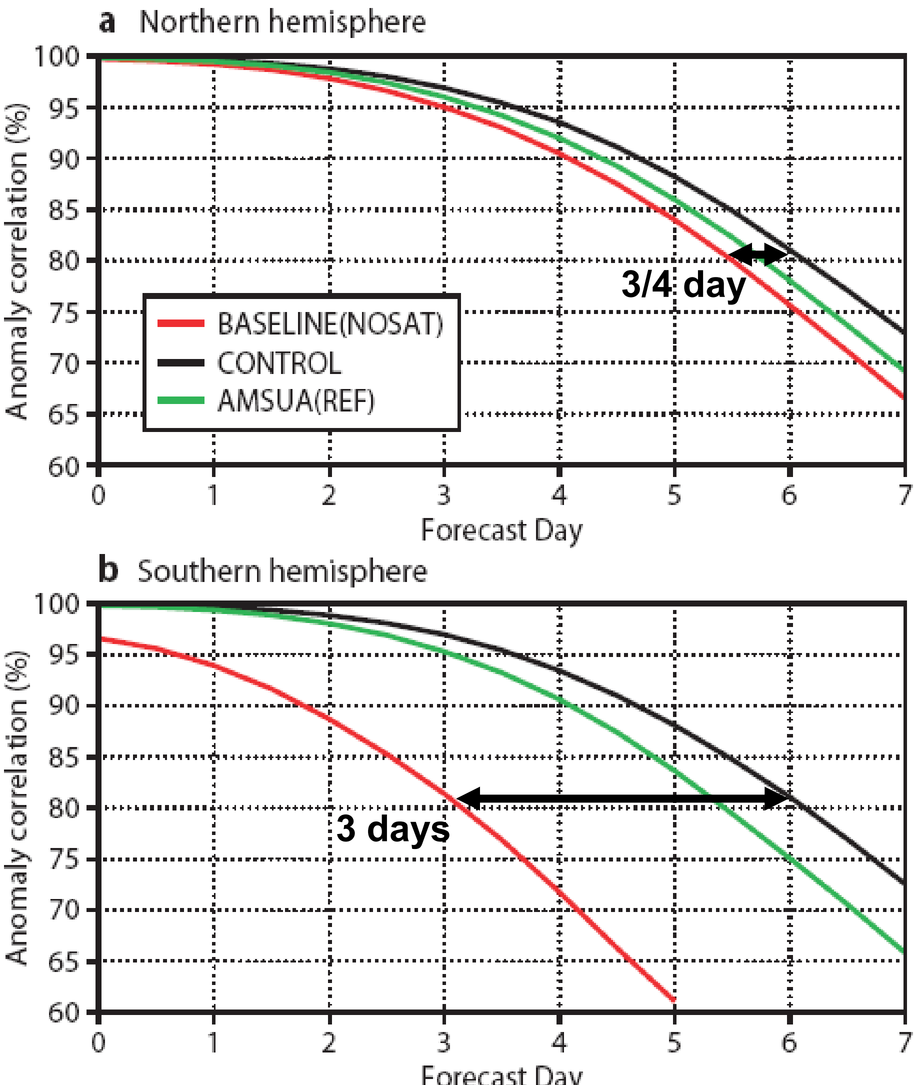


Anomaly correlation of 500hPa height for Southern hemisphere



(J.-N. Thépaut & G. Kelly)

Combined impact of all satellite data



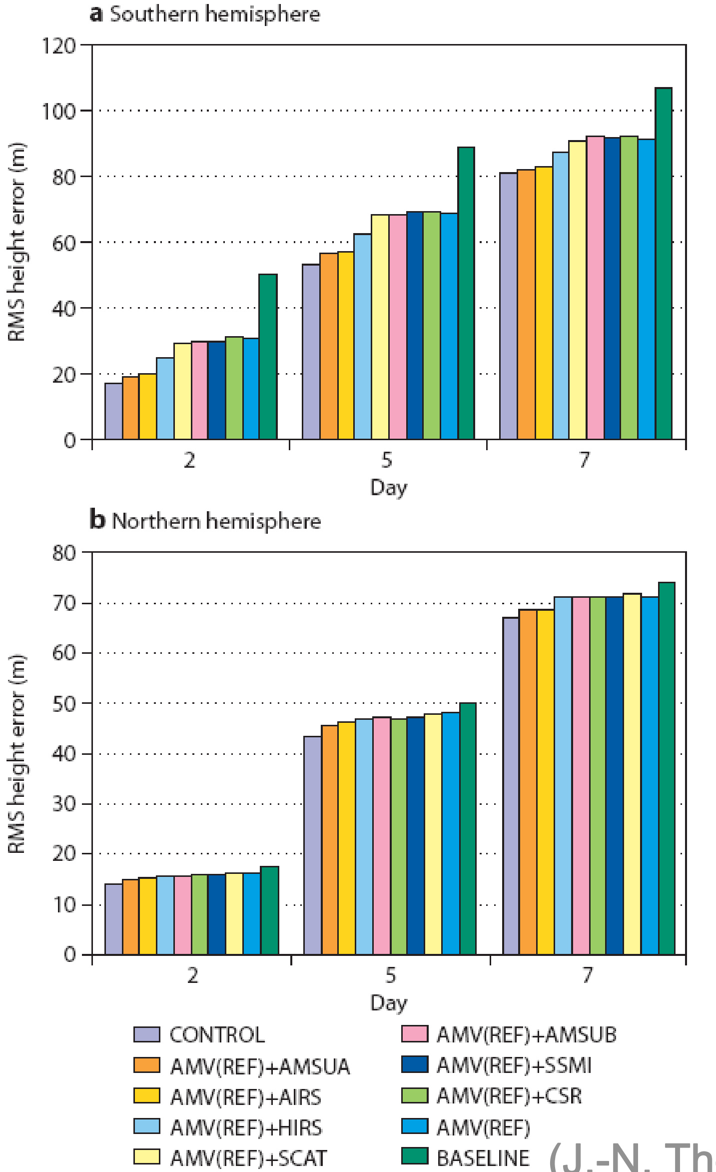
(J.-N. Thépaut & G. Kelly)

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

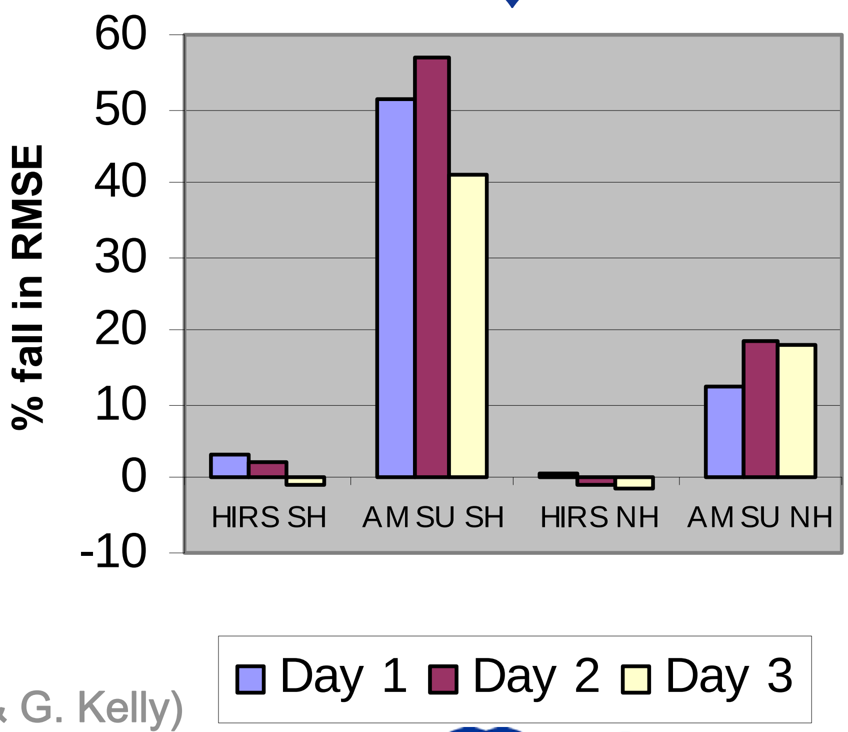


500 hPa *geopotential height* RMS error:

← 2007 ECMWF

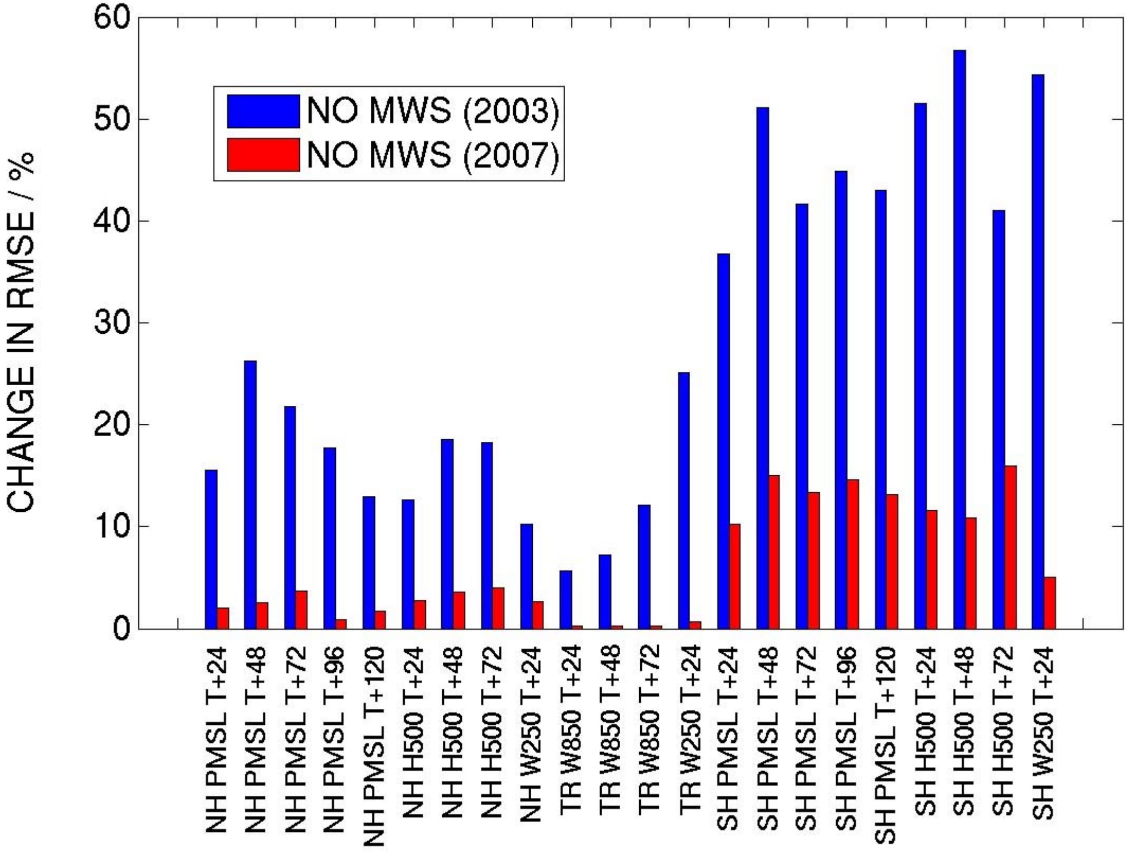
2003 Met Office

↓



(J.-N. Thépaut & G. Kelly)

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

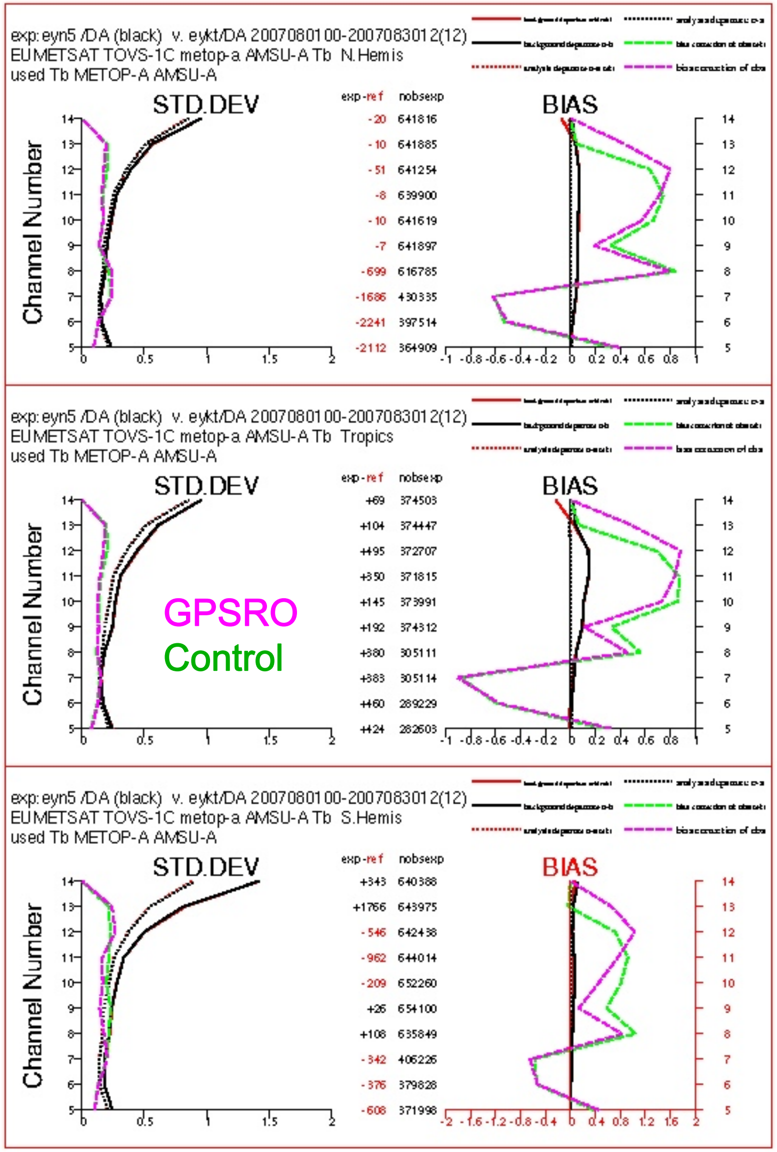
Example: How do GPSRO data (unbiased – not bias corrected) affect variational bias correction of AMSU-A radiance data (at levels where model temperature biases are significant)?

- 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?)

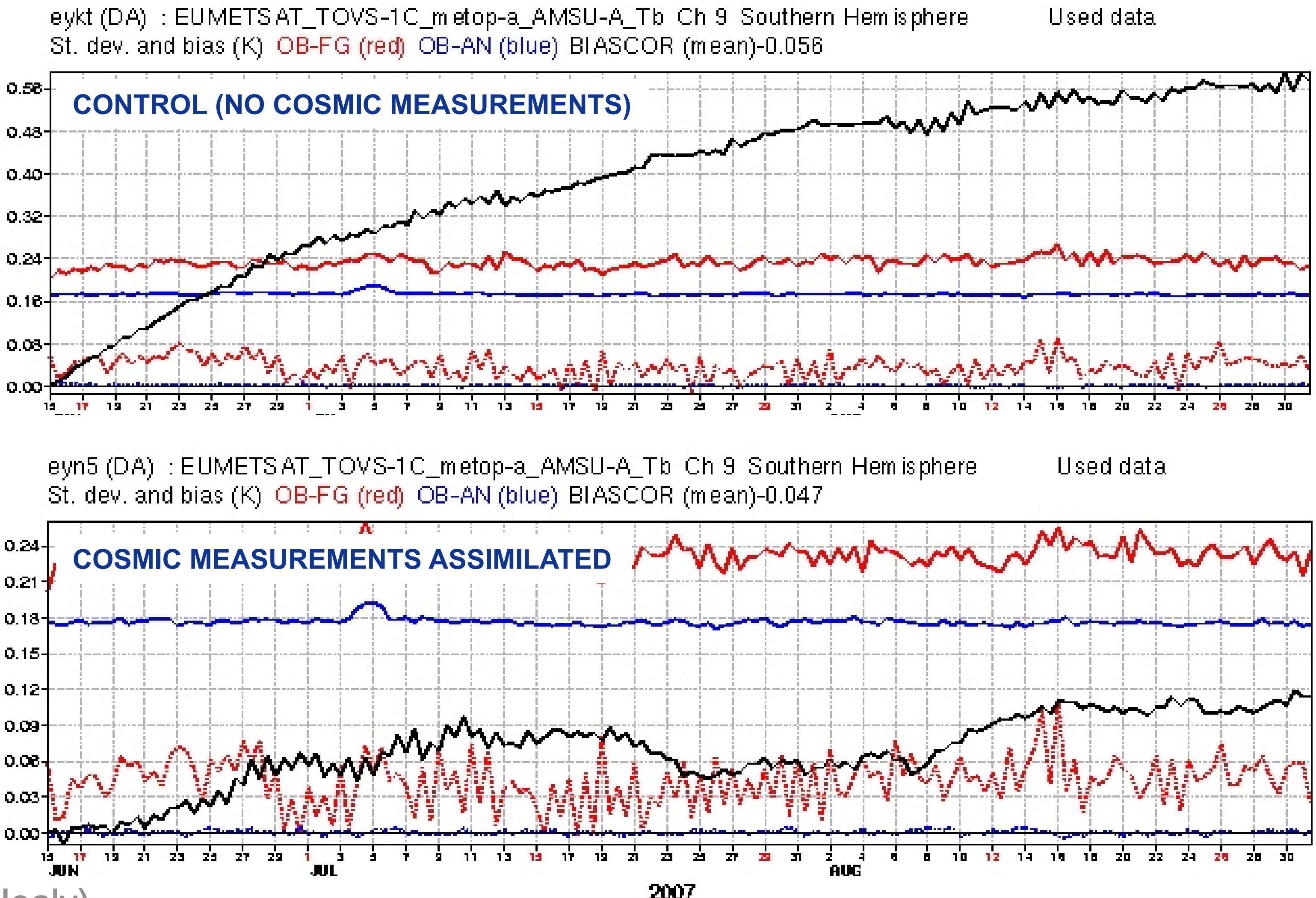
(AMSU-A channel 14 bias frozen)



(S. Healy)

Investigating fundamental observation impact: GPSRO

Metop AMSU-A channel 9 departure & bias correction evolution



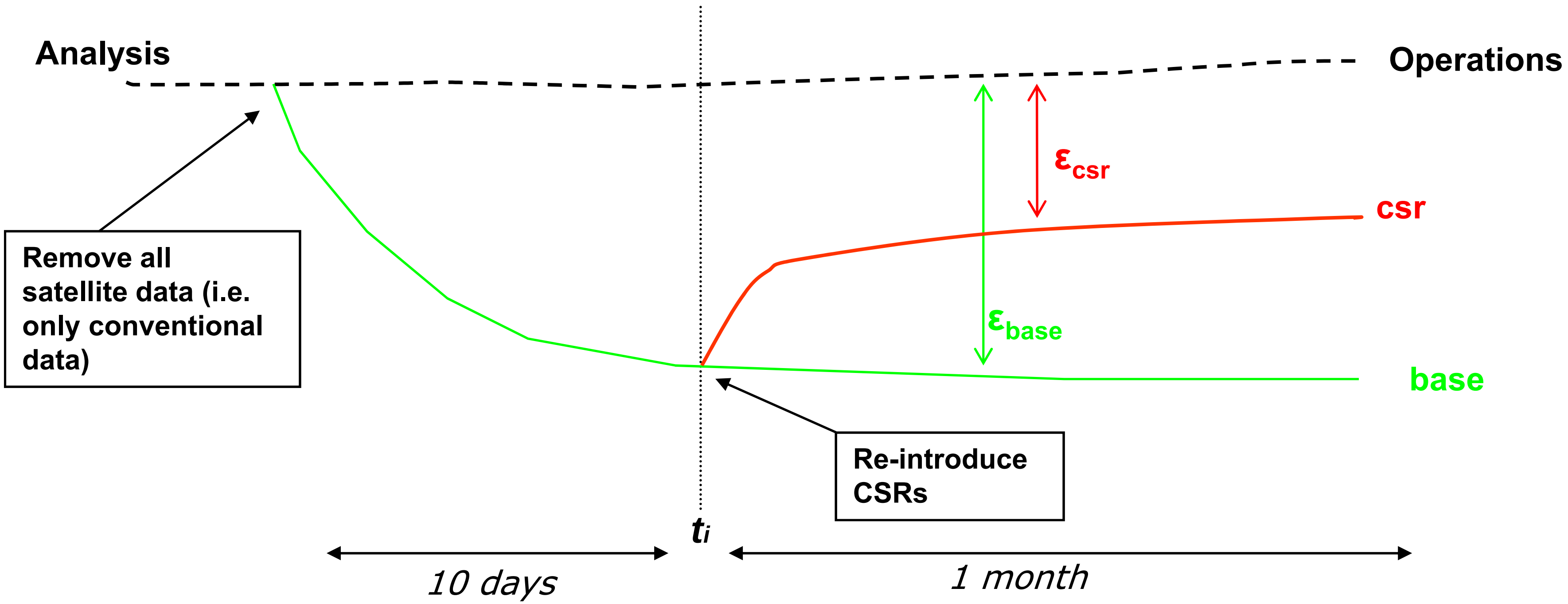
(S. Healy)

ECMWF

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)**



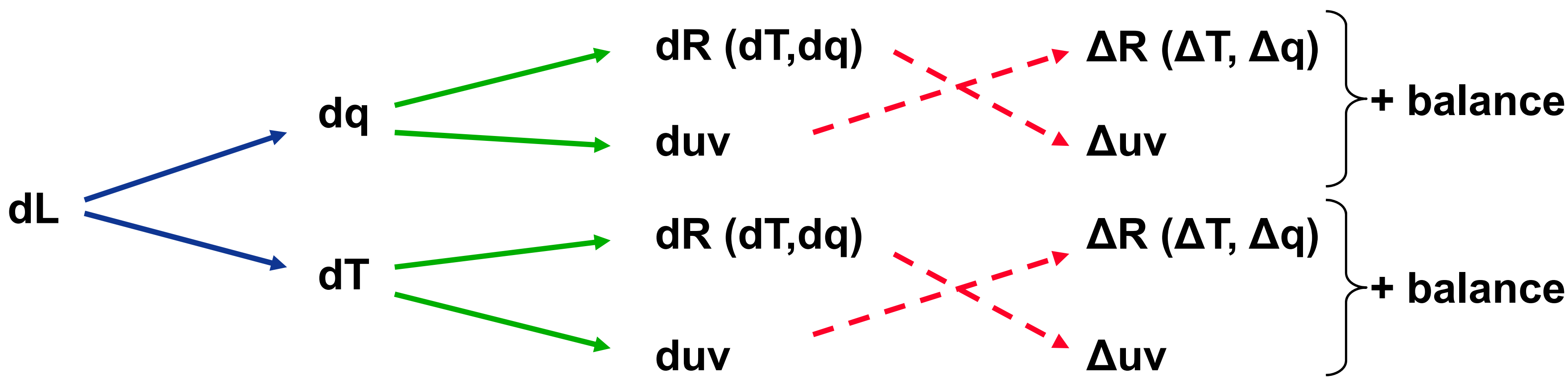
$(\varepsilon_{base}-\varepsilon_{csr}) > 0$ ➔ positive impact

(C. Peubey & T. McNally)

ECMWF

Investigating fundamental observation impact: CSRs from geostationary satellite radiometers

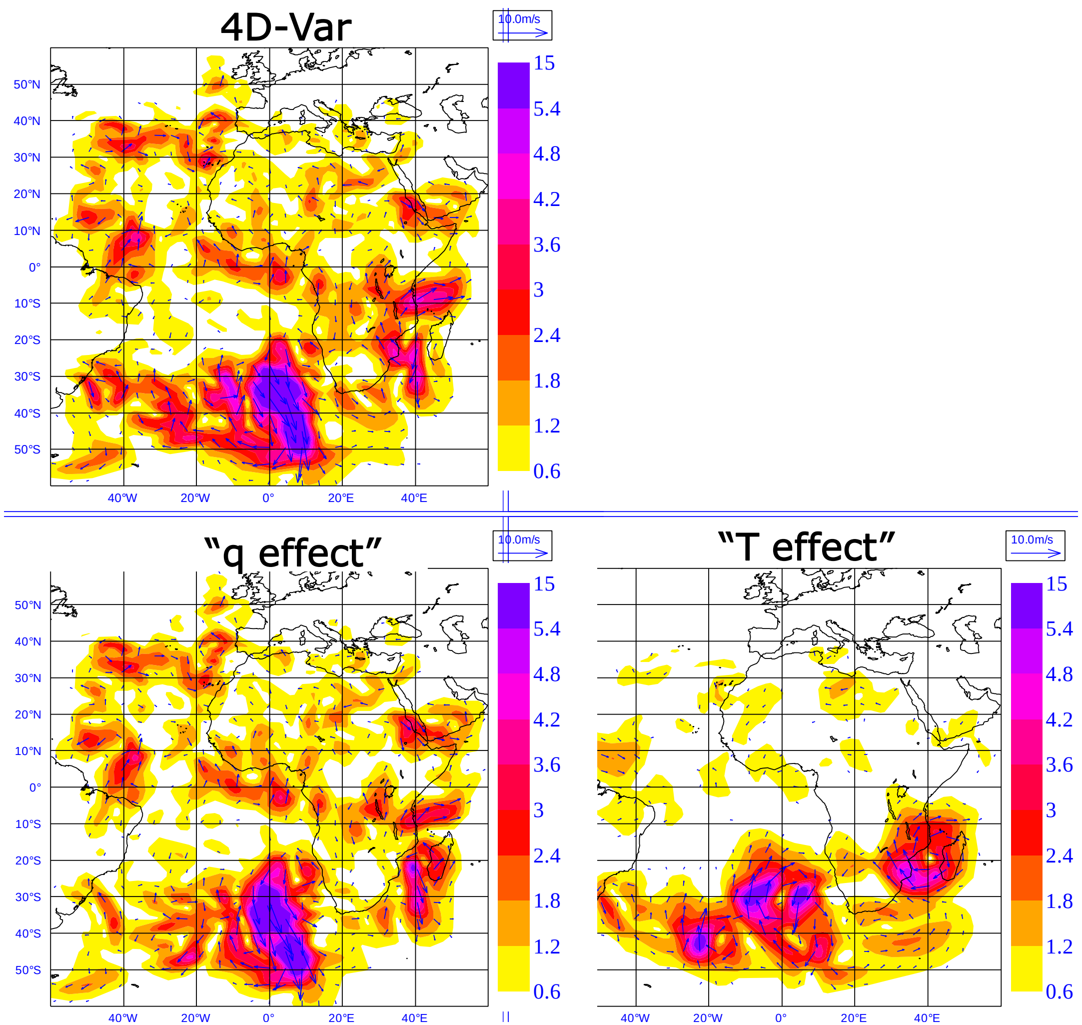
$$\nabla_{\delta x_o} J = \mathbf{B}^{-1}\delta\mathbf{x}_o + \sum_{i=0}^{n} \mathbf{M}^T(t_i, t_o)\mathbf{H}_i^T\mathbf{R}_i^{-1}\left(\mathbf{d}_i - \mathbf{H}_i\delta\mathbf{x}_i\right)$$



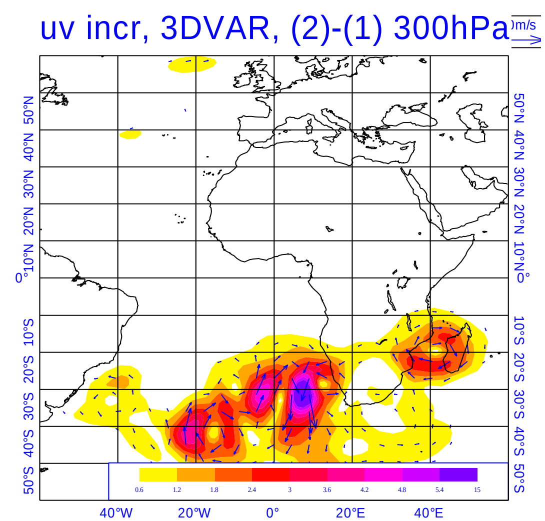
Experiments:
- Baseline + "4D-Var" CSRs
- Baseline + "T tracer effect" CSRs (i.e. no q sensitivity)
- Baseline + "q tracer effect" CSRs (i.e. no T sensitivity)

(C. Peubey & T. McNally)

300 hPa wind increments 1st analysis cycle



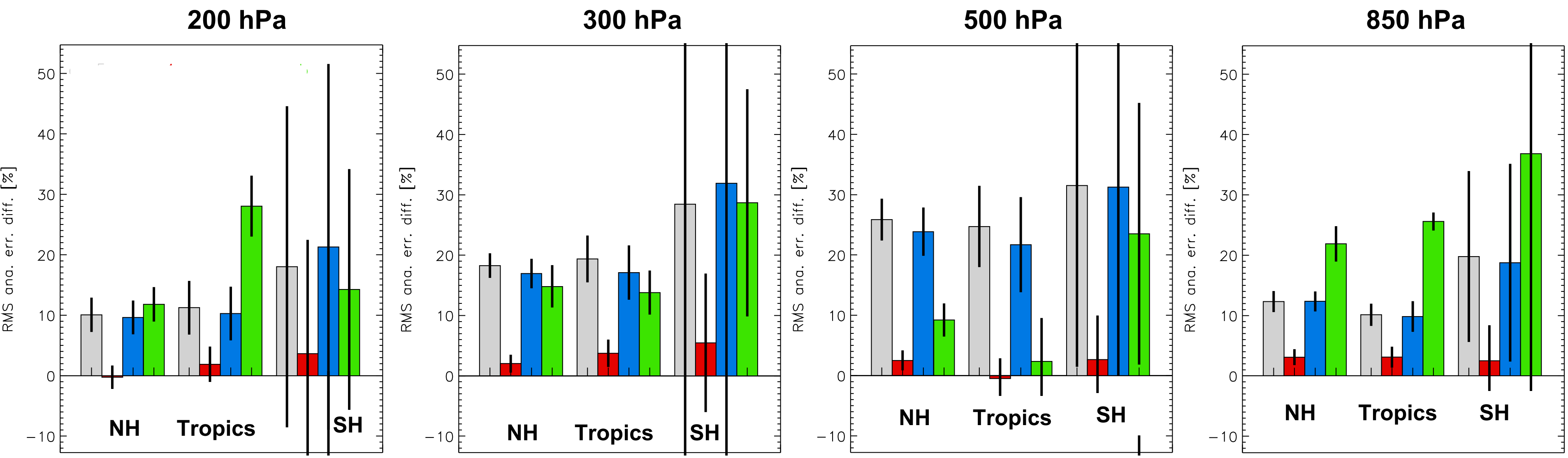
No q-tracing due to missing model integration



(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



→ **With cycling alone (no 4D-Var), CSRs do not have a significant impact on winds.**

→ **Most of the CSR impact on wind seem to come from the 4D-Var tracer effect of humidity.**

→ **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)

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.

⇒ The continued assessment is currently only performed through operational radiance monitoring (departures, biases) and irregular (costly) OS experimentation!

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

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

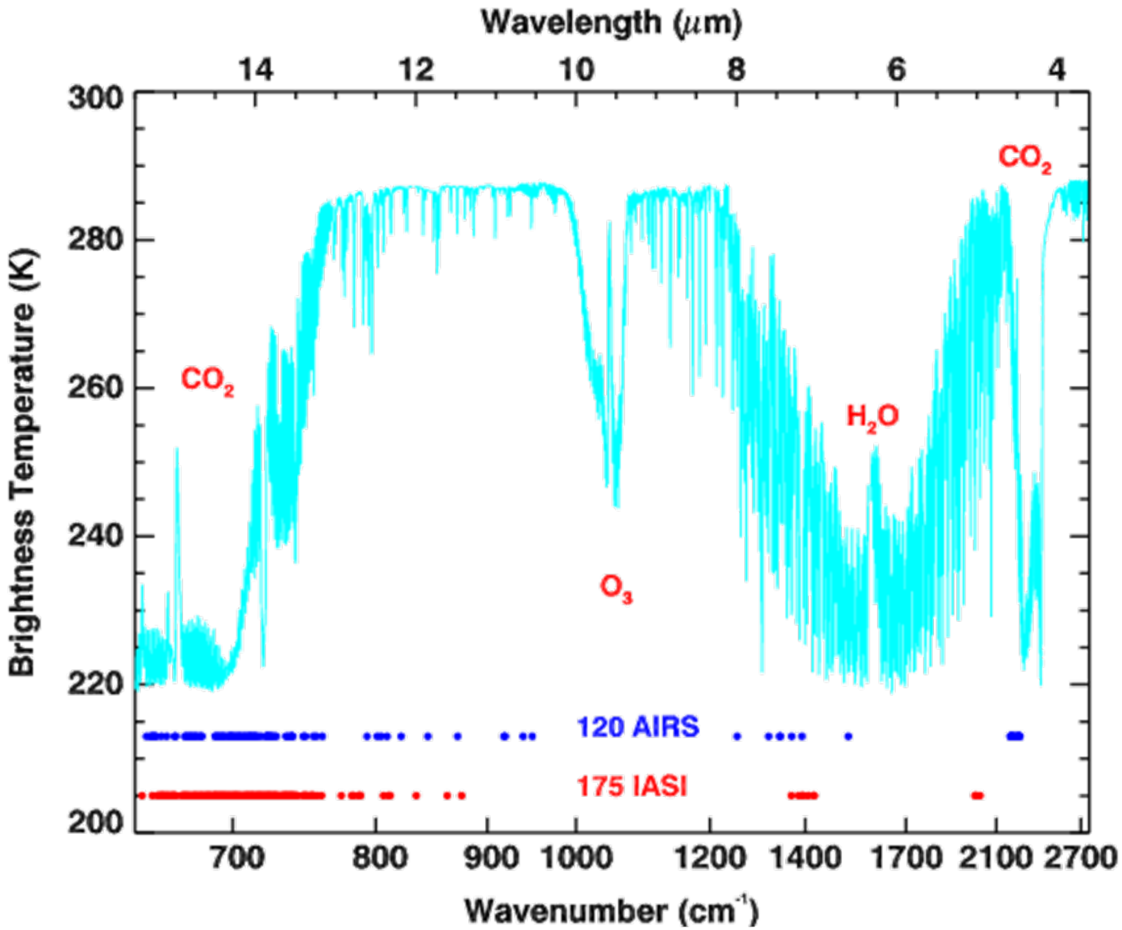
Diagnostics

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

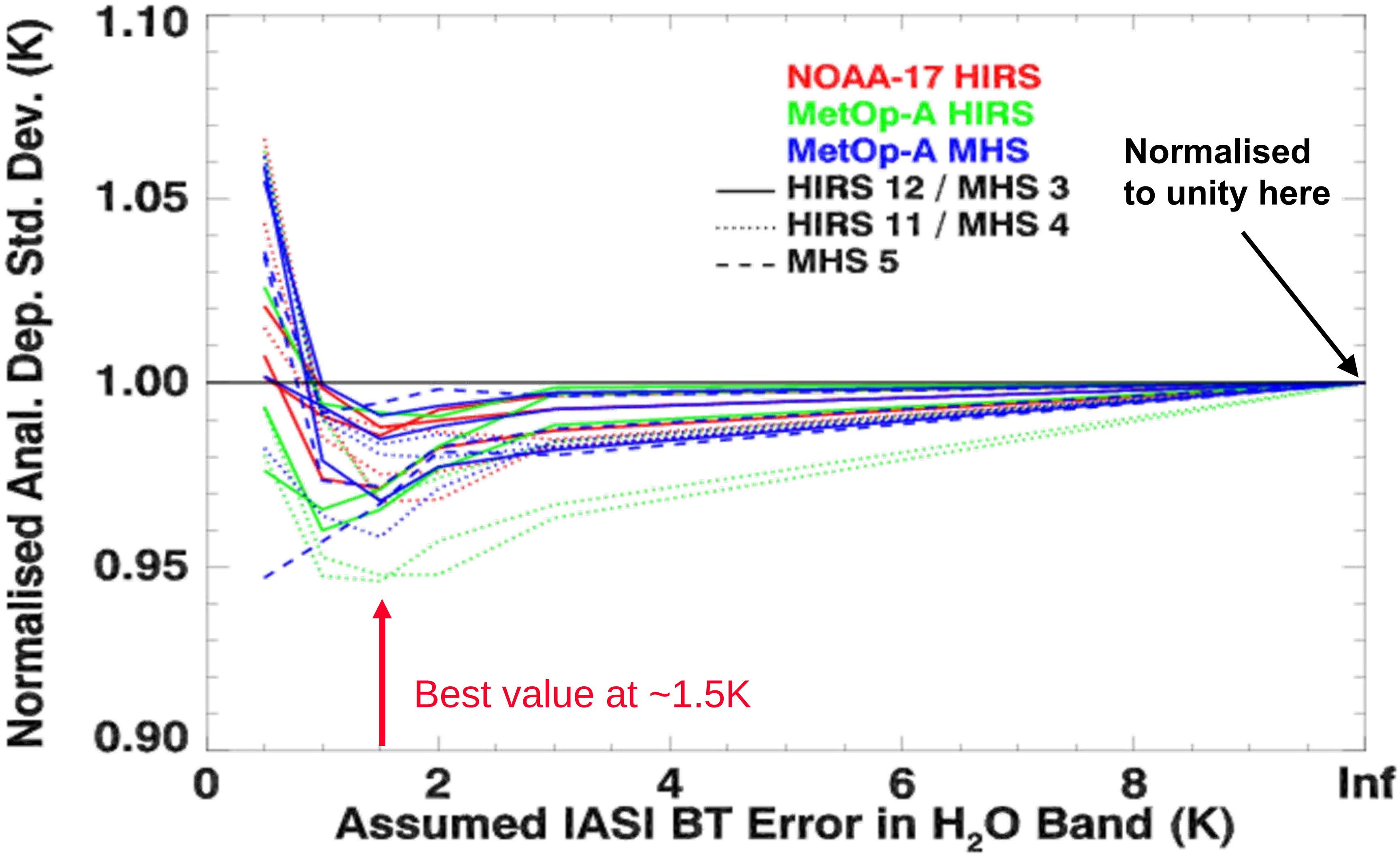
Example – Advanced IR sounders



- AIRS CO_2 and H_2O channels assimilated since October 2003.
- IASI CO_2/H_2O 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.

(A. Collard)

Adding 10 IASI water vapour channels

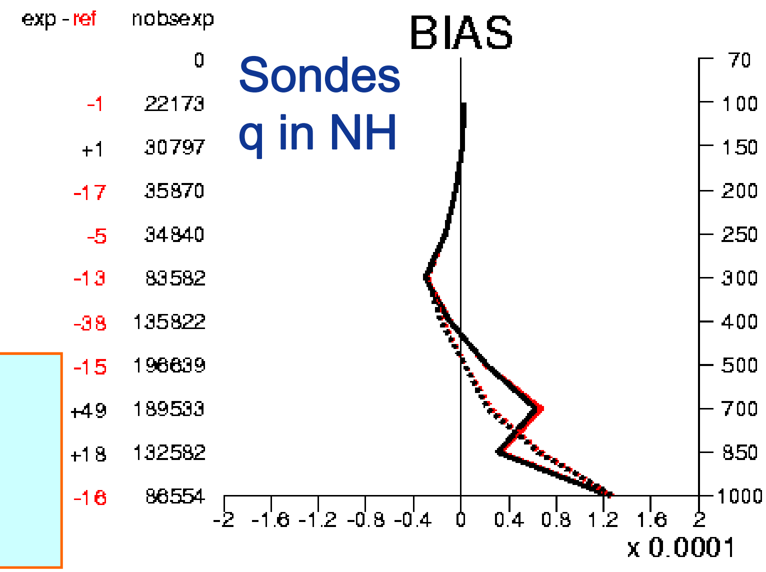


(A. Collard)

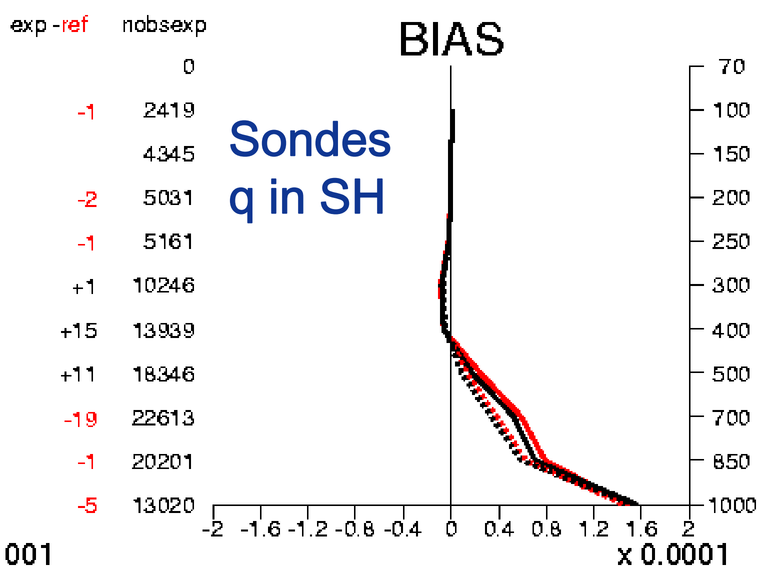
ECMWF

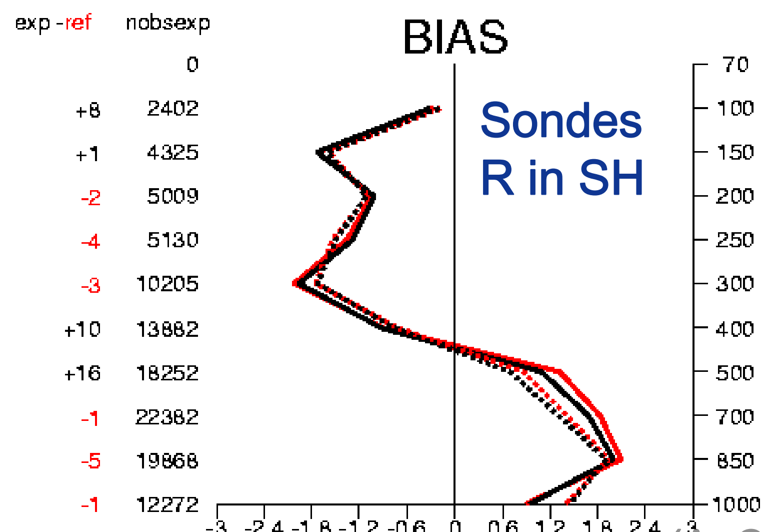
Fit to other observations: Radiosondes

Black: IASI w/ humidity channels
Red: Control



The addition of the IASI water band improves the analysis fit to radiosondes



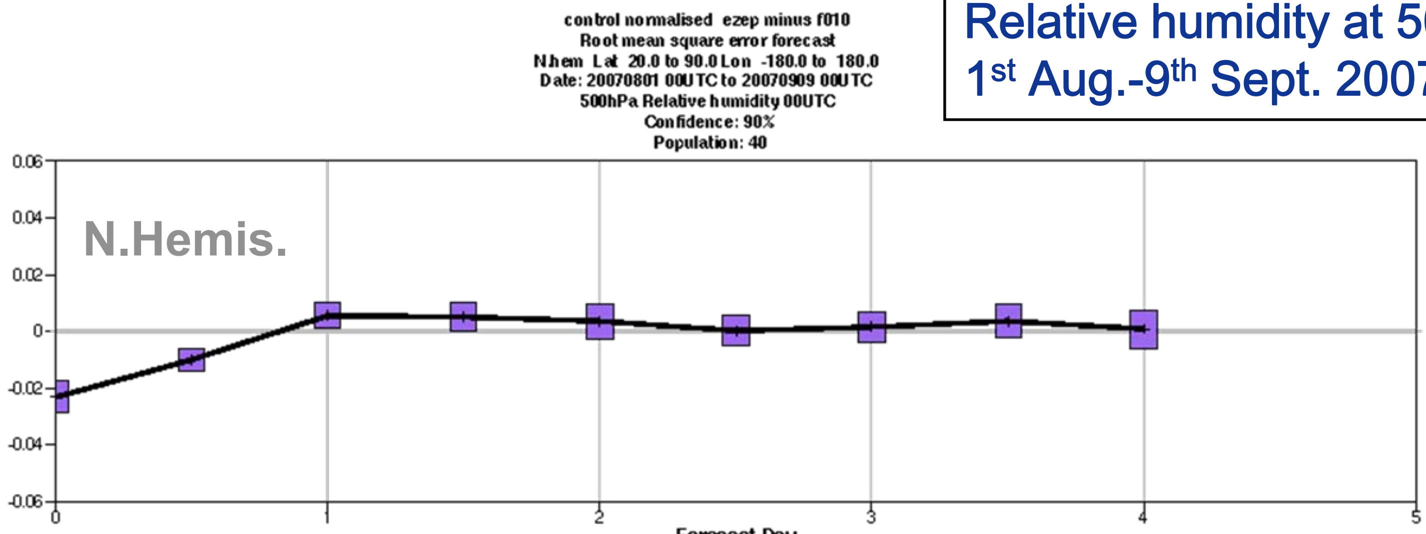


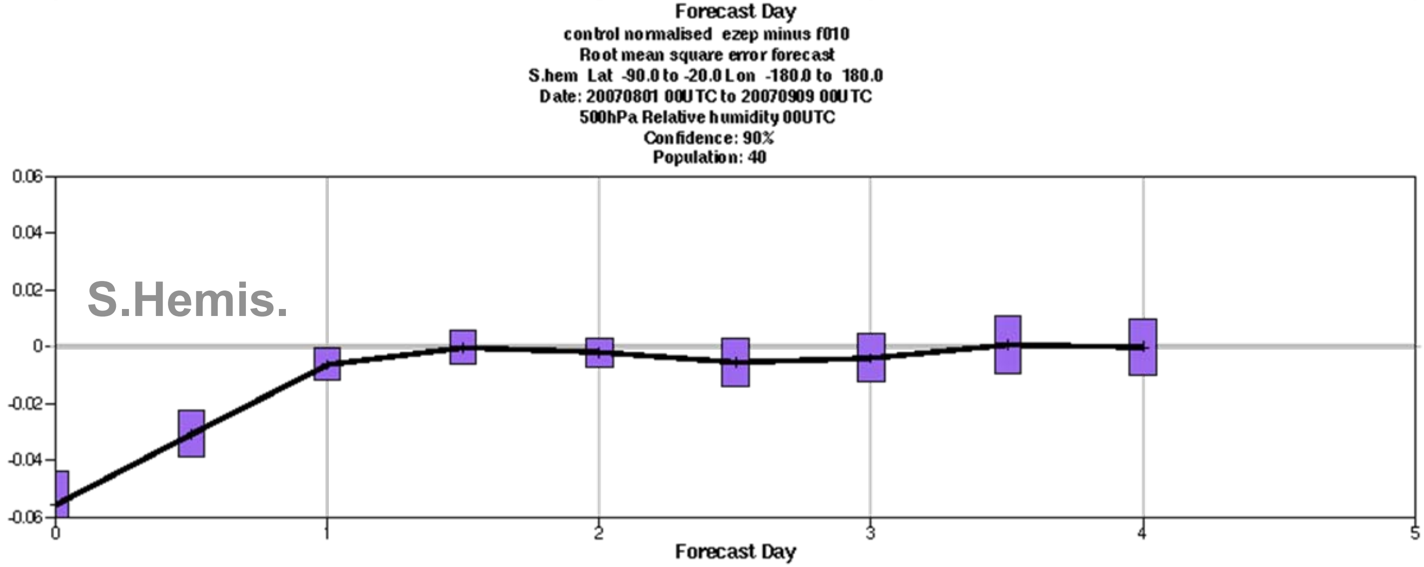
(A. Collard)

ECMWF

Forecast skill: Verified with operational analysis

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





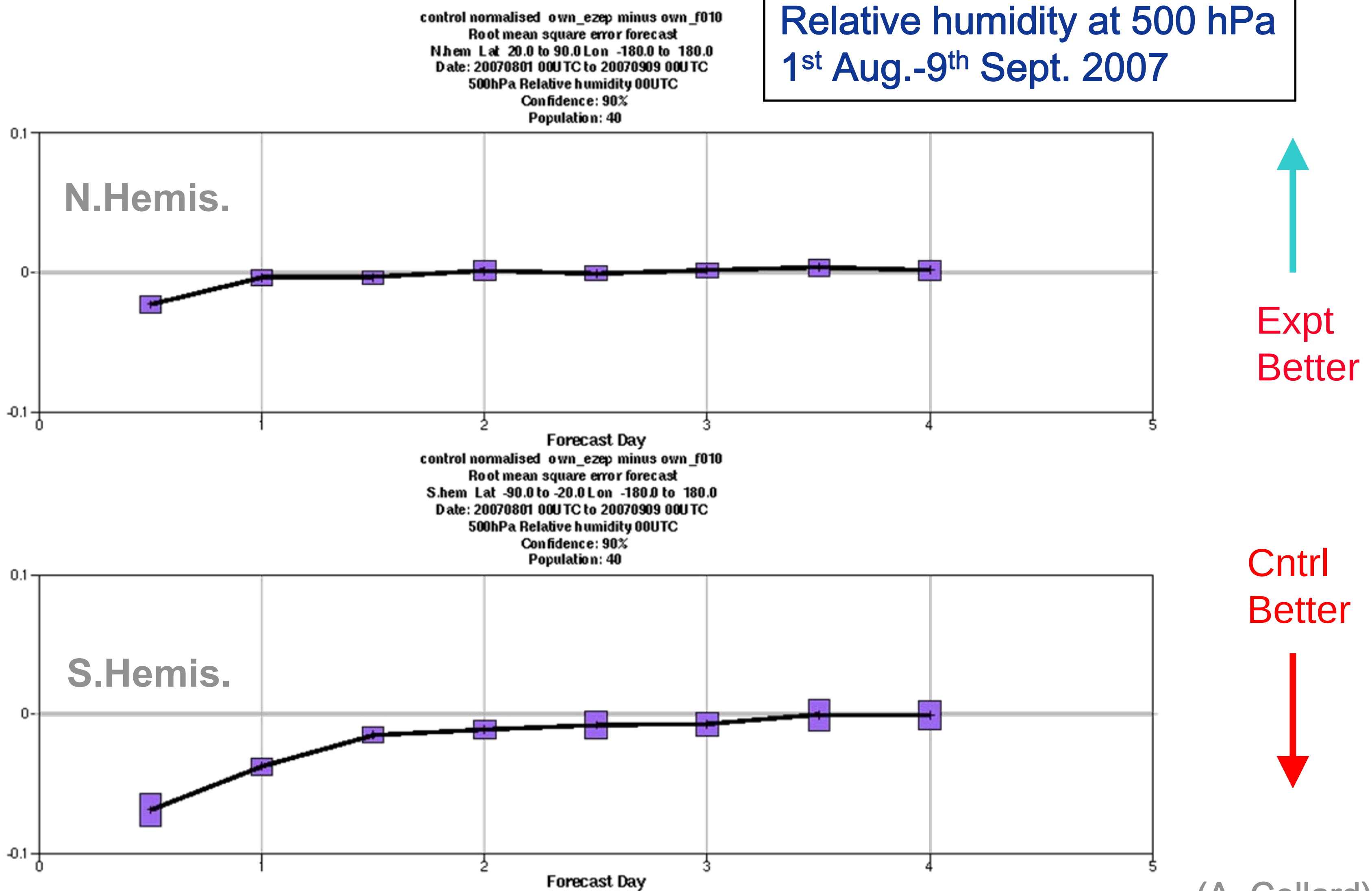
Expt Better

Cntrl Better

(A. Collard)

Forecast skill: Verified with own analysis

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

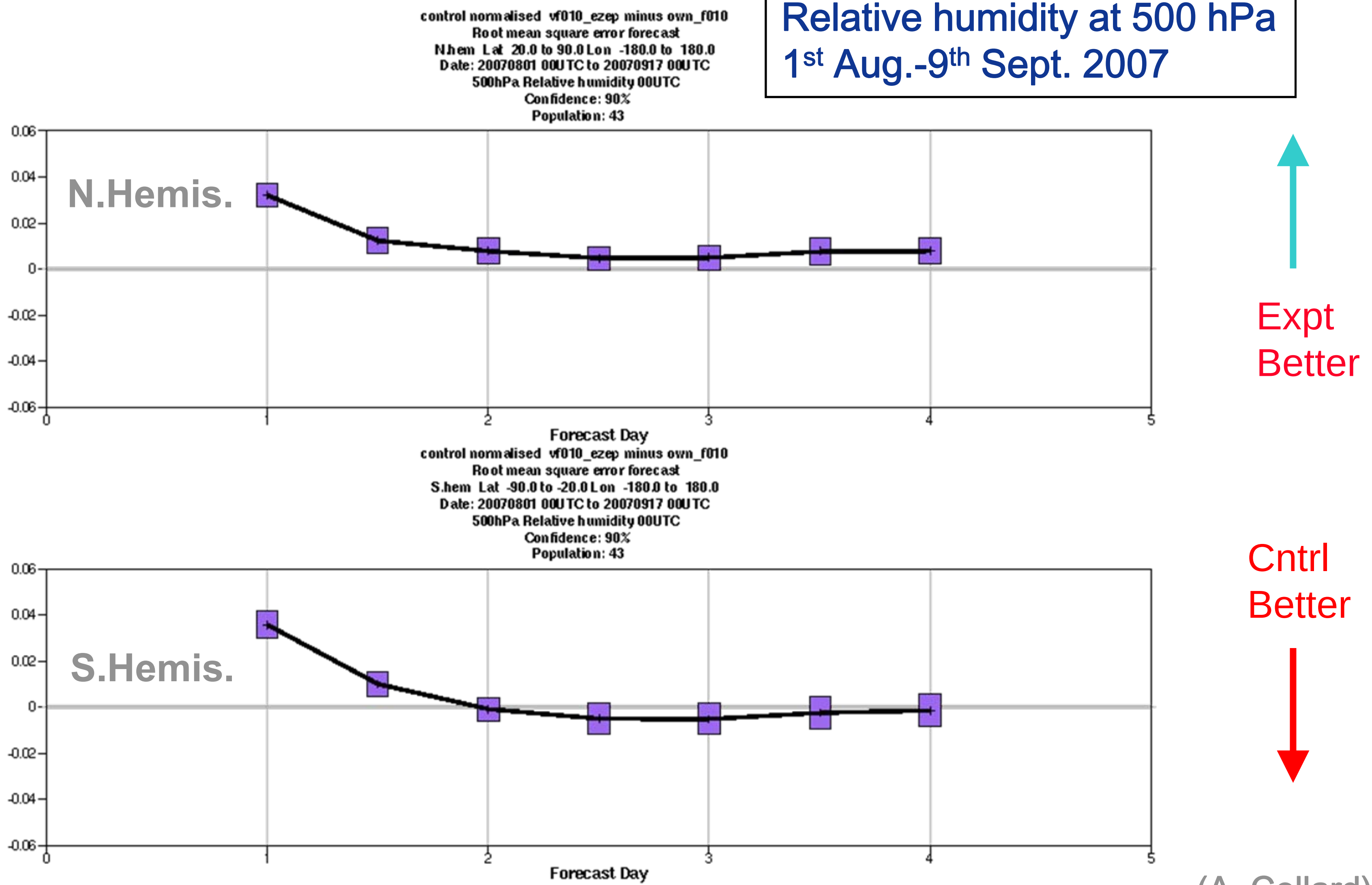


(A. Collard)

ECMWF

Forecast skill: Verified with experiment's analysis

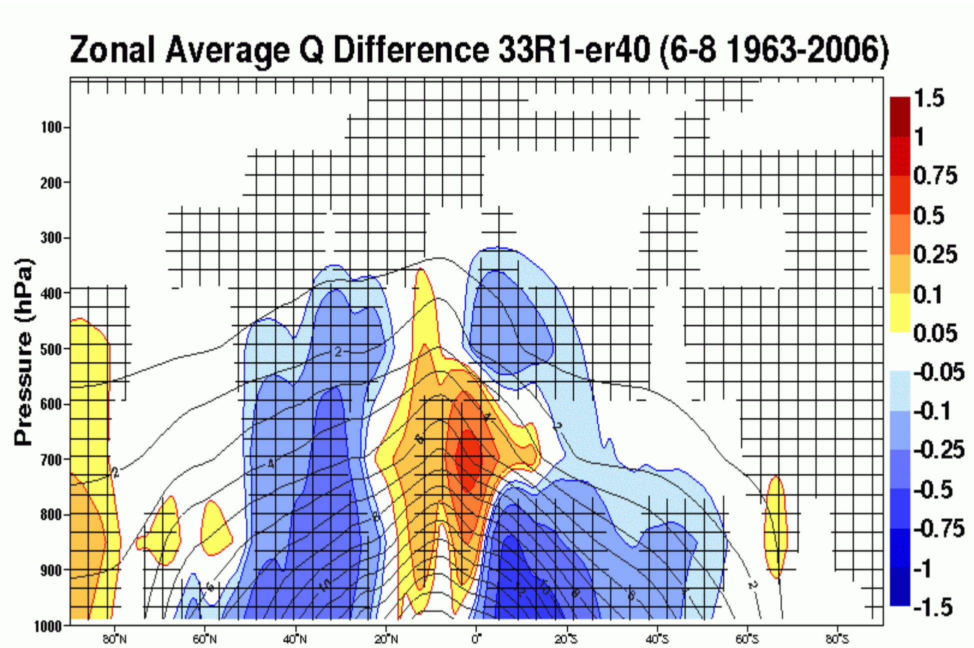
Relative humidity at 500 hPa
1st Aug.-9th Sept. 2007



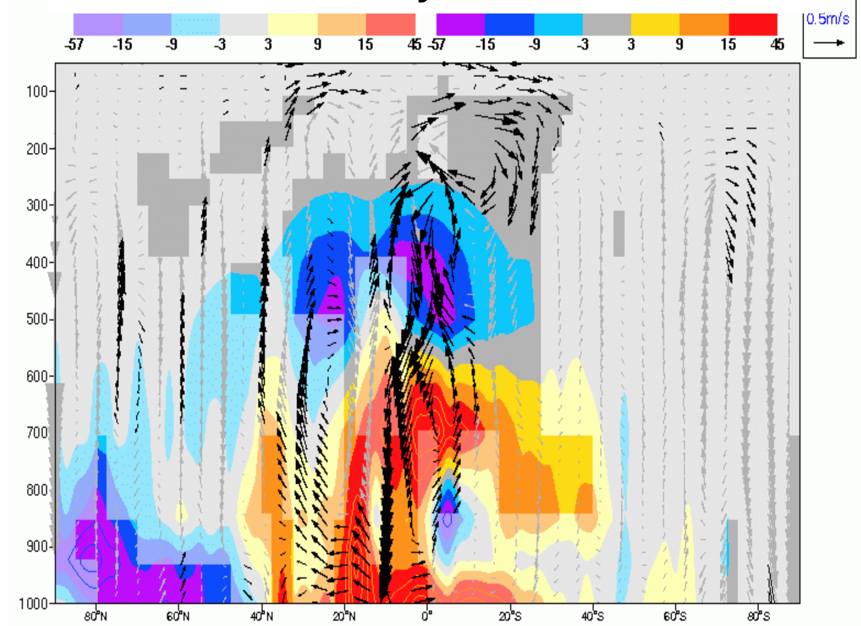
(A. Collard)

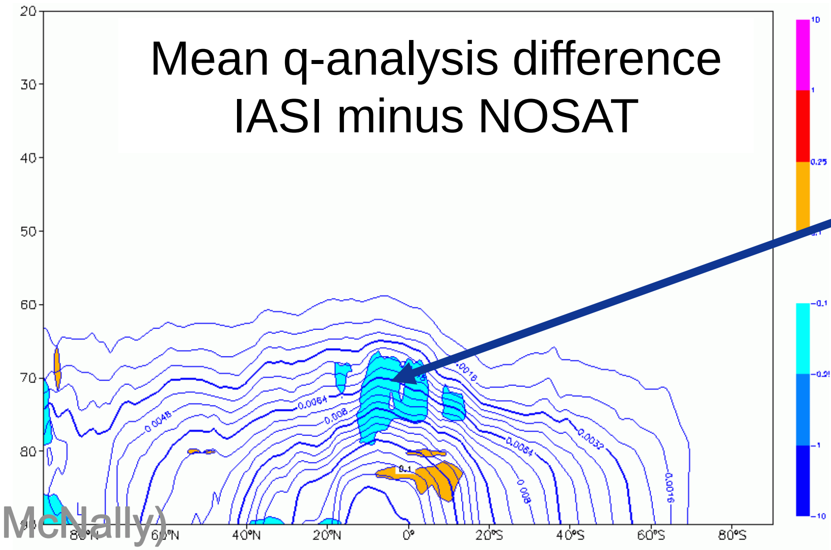
ECMWF

Forecast skill and model bias



Annual mean day-5 forecast error





(T.McNally)

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

- Data monitoring
- Observing system experiments
- Advanced diagnostic tools

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

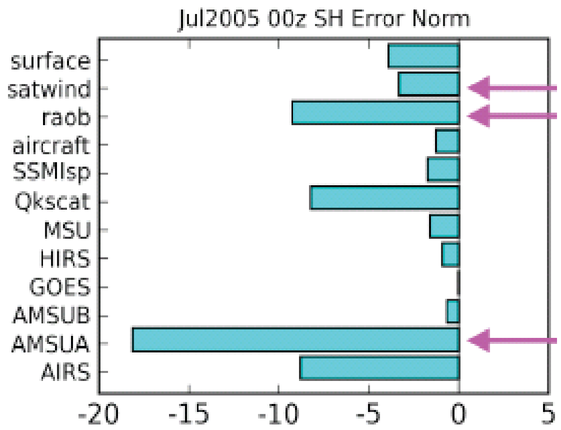
ADJ: measures the impact of observations in each analysis cycle separately and against the control background

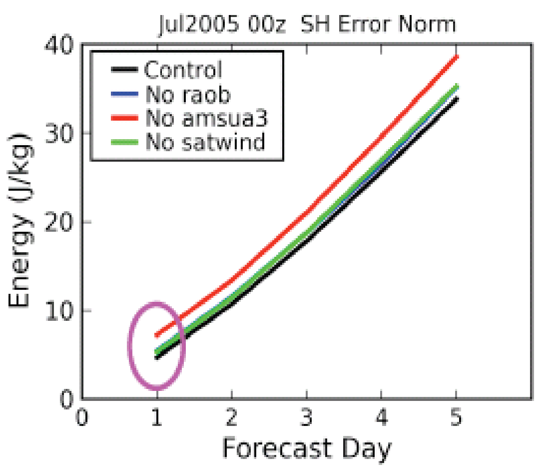
OSE: measures the impact of removing information from both the background and analysis in a cumulative manner

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

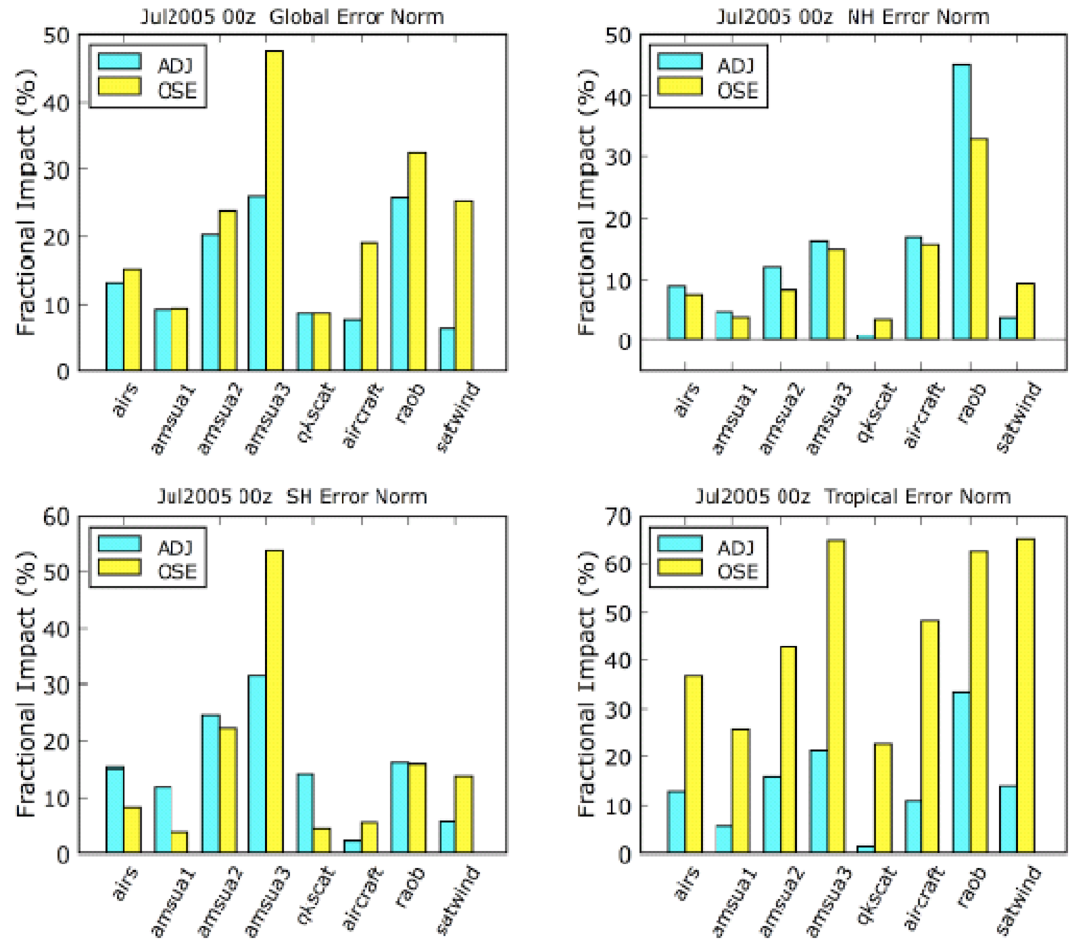
Adjoint diagnostics - OSEs





% Contributions to 24hr Forecast Error Reduction

July 2005



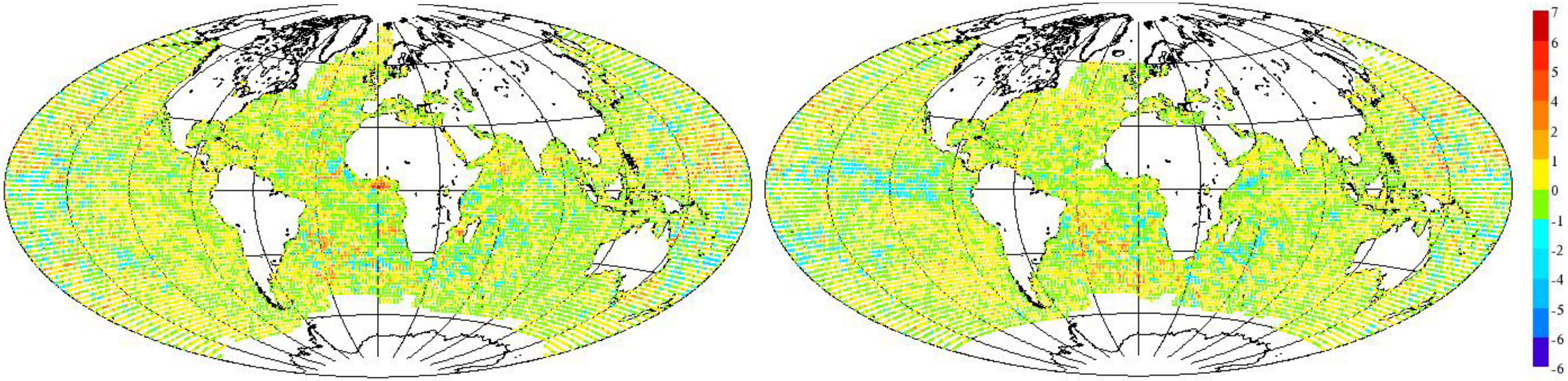
(R. Gelaro)

(Y. Zhu & R. Gelaro 2009)

Investigating fundamental observation impact: TCWV

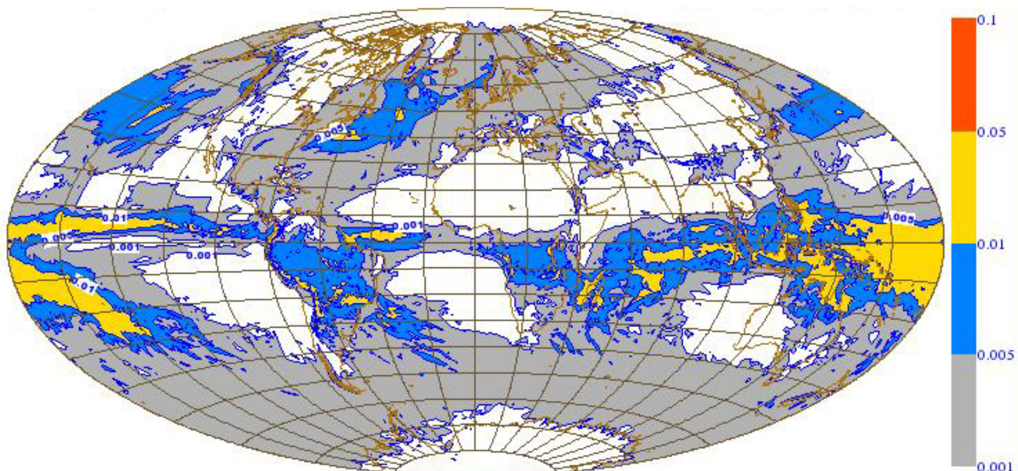
Forecast sensitivity to observations in analysis

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



[J/kg]

Mean 36-12h precipitation forecast initialized at 12 UTC

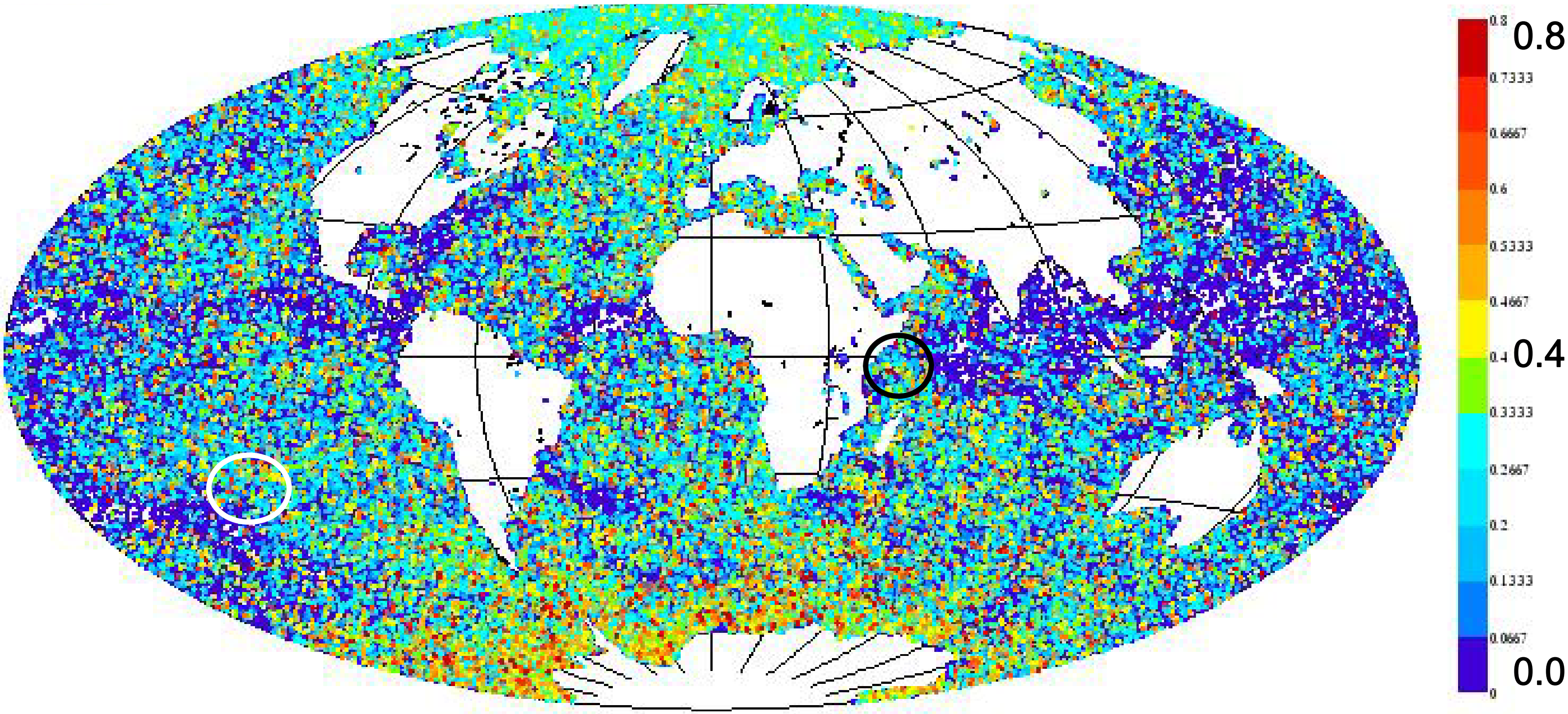


[10^{-3} mm]

(C. Cardinali)

IASI – channel 212 (250 hPa)

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



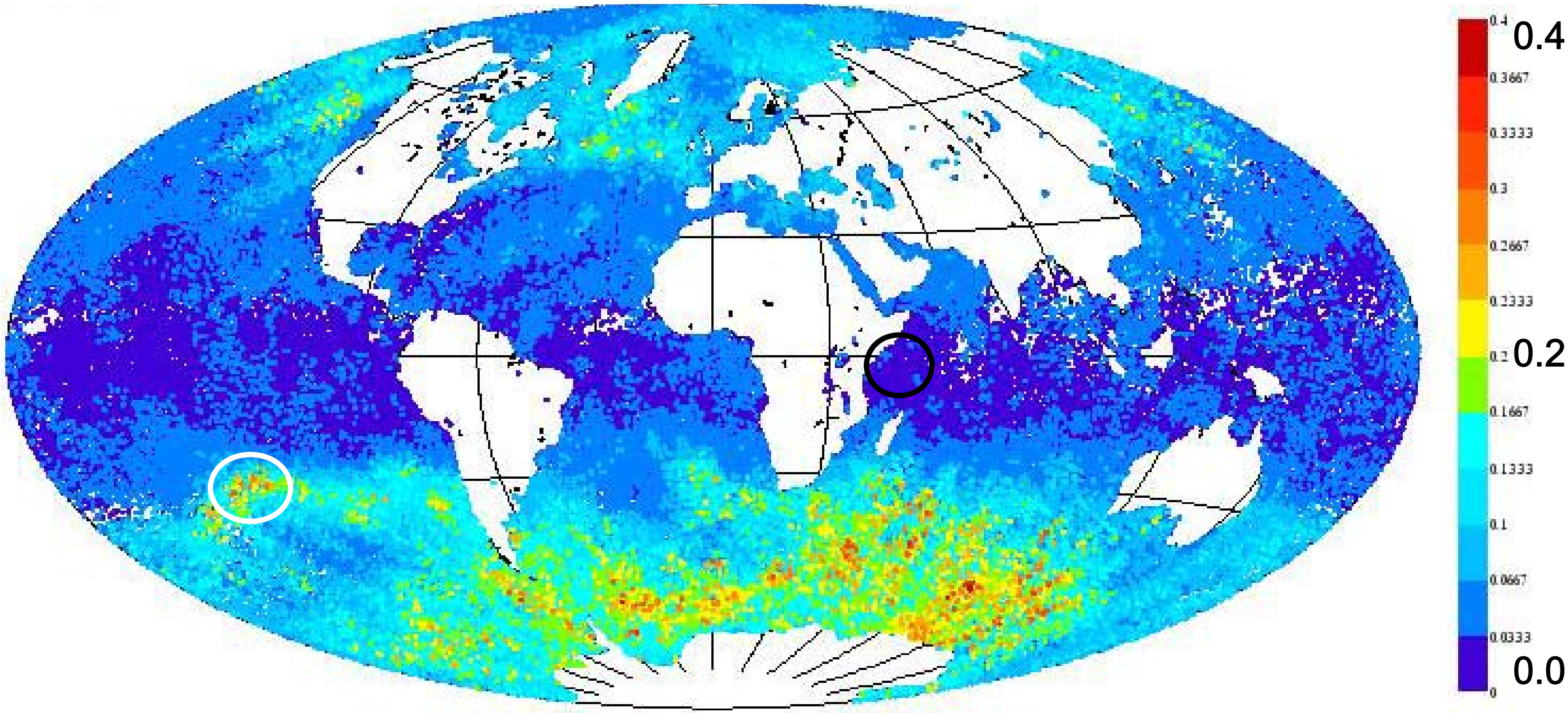
⇒ Information available for analysis from observations (= innovation)

(G. Radnoti)

ECMWF

IASI – channel 212 (250 hPa)

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

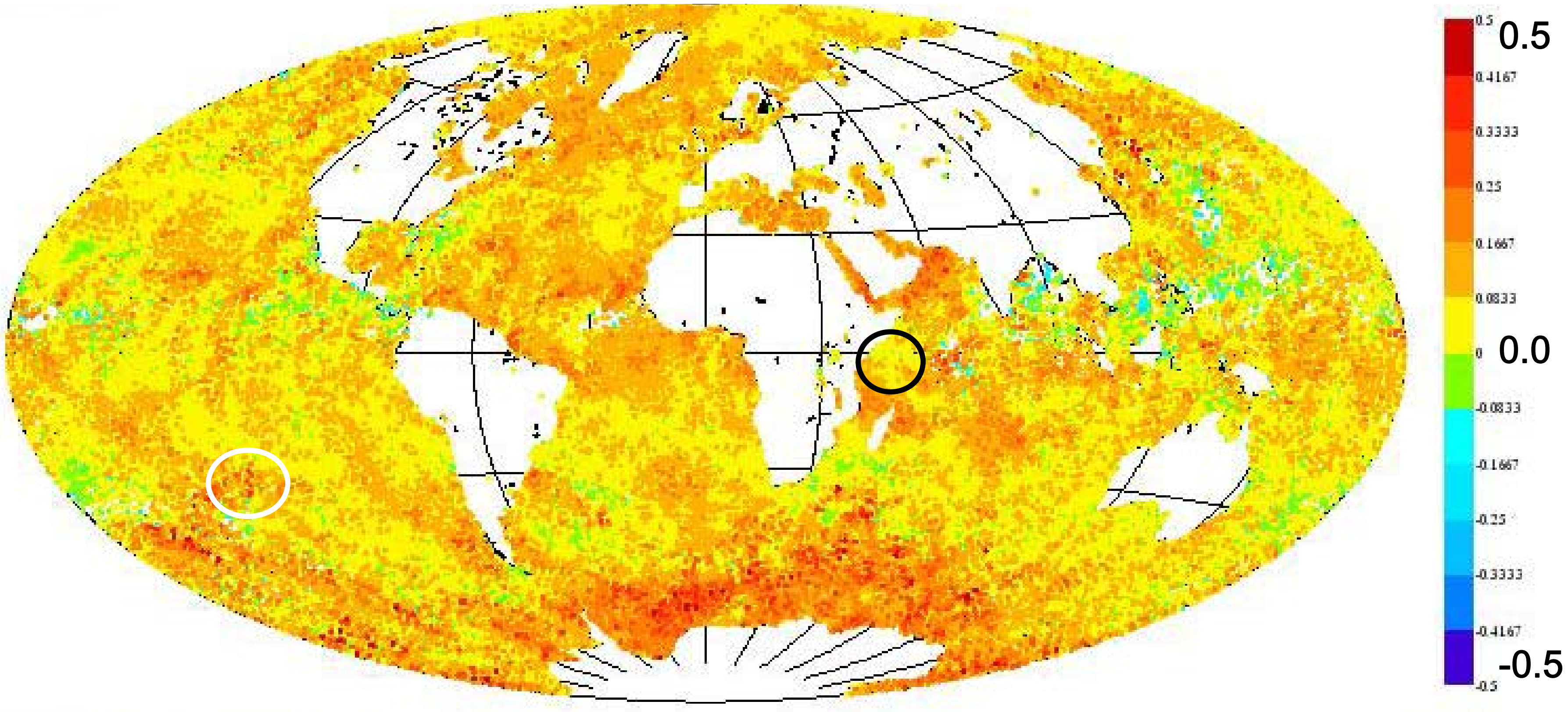


⇒ Sensitivity of the analysis to those observations
(* or self-sensitivity, see Cardinali et al. (2004))

(G. Radnoti)

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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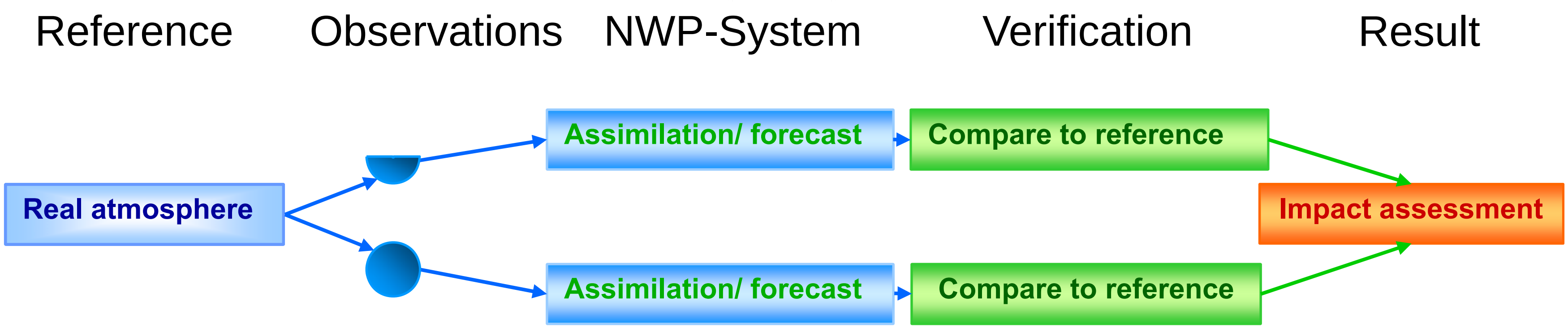
Impact of future satellite data

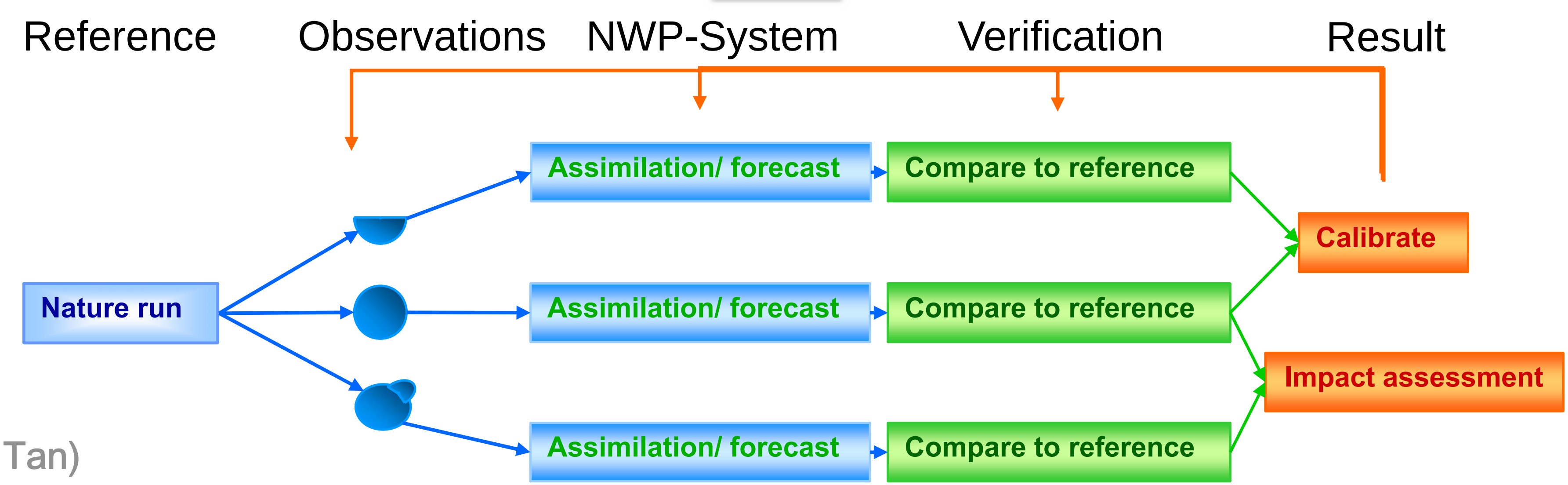
Summary

OSEs and OSSEs

OSE

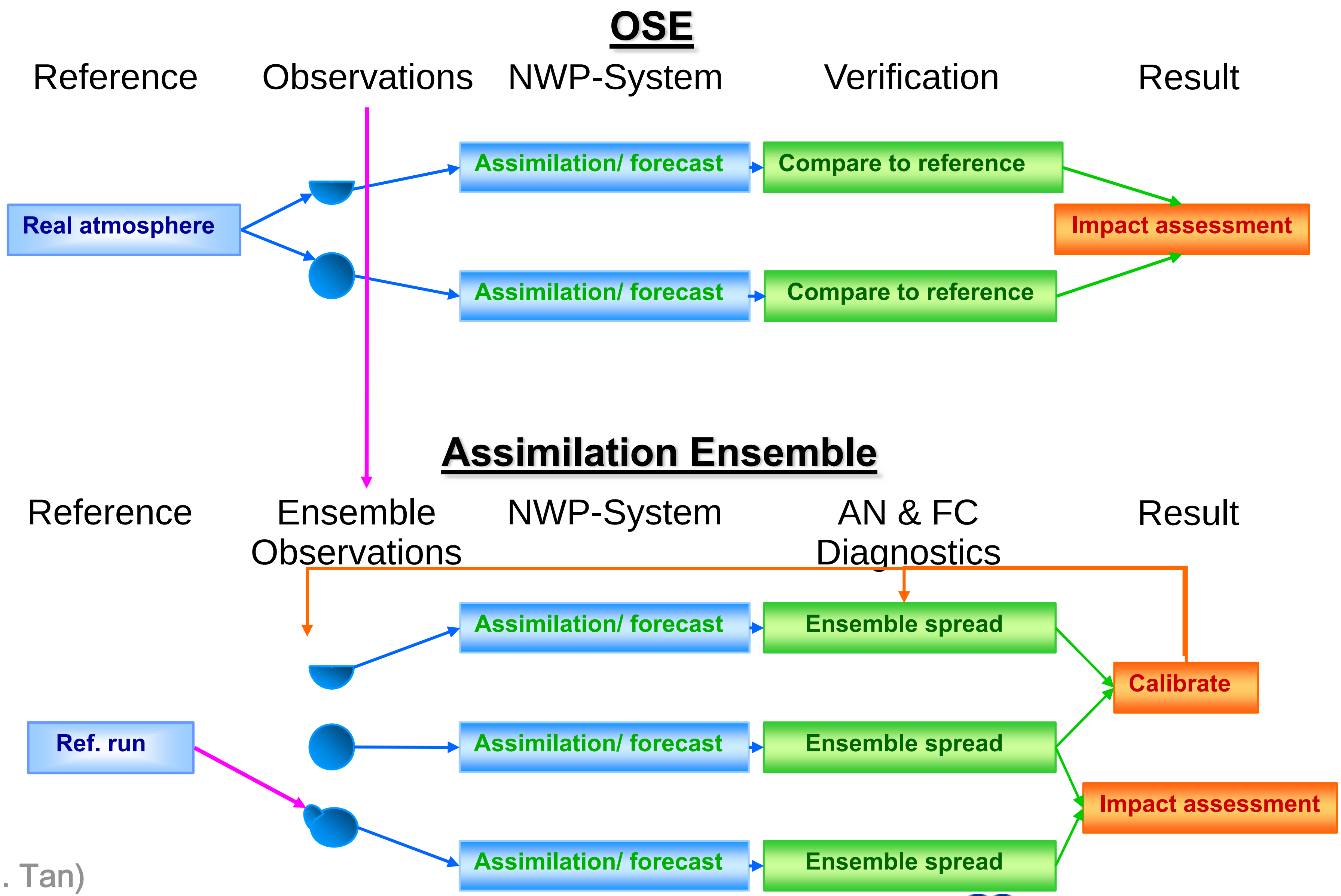


OSSE



(D.Tan)

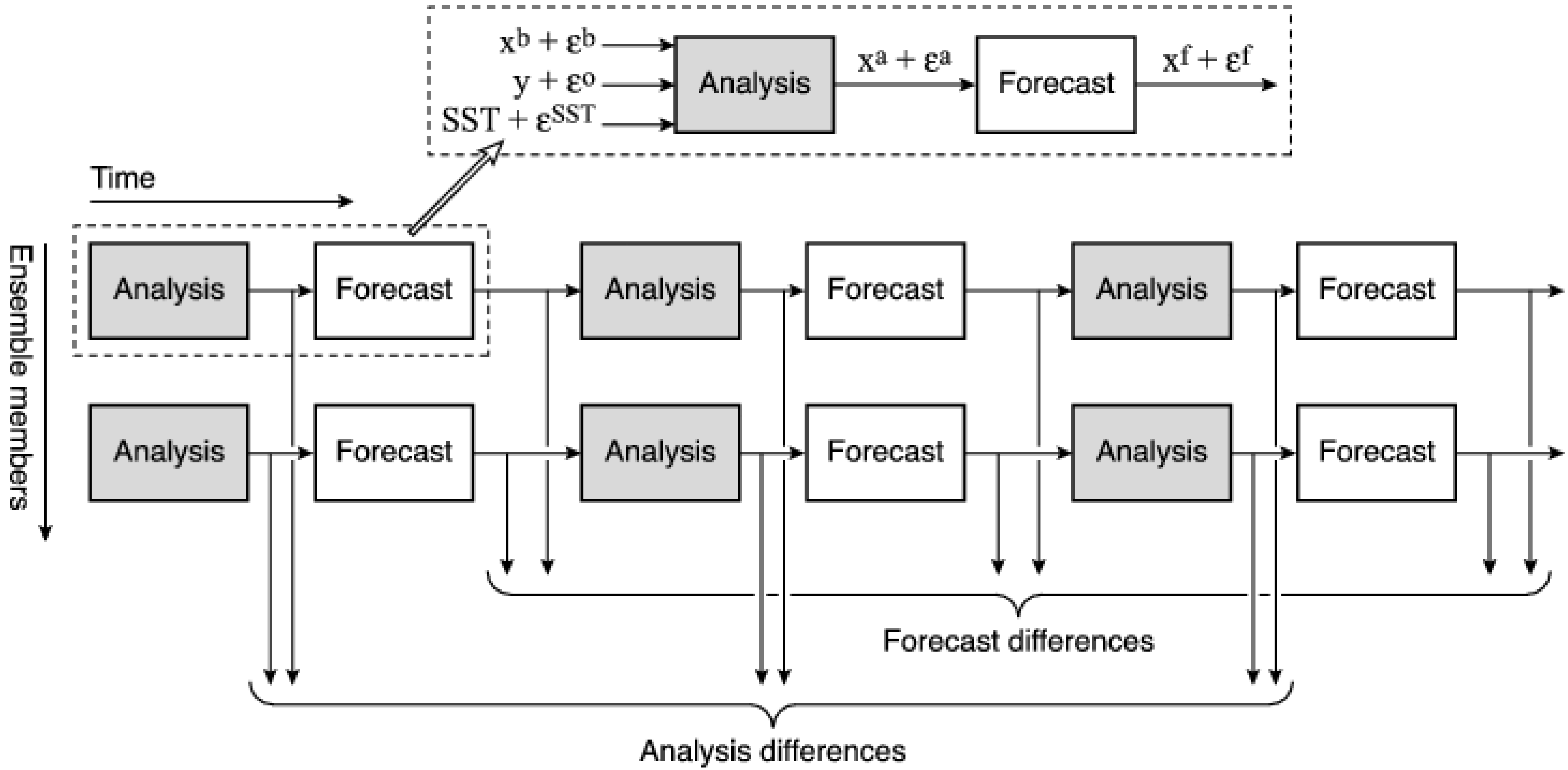
OSEs and Ensembles



(D. Tan)

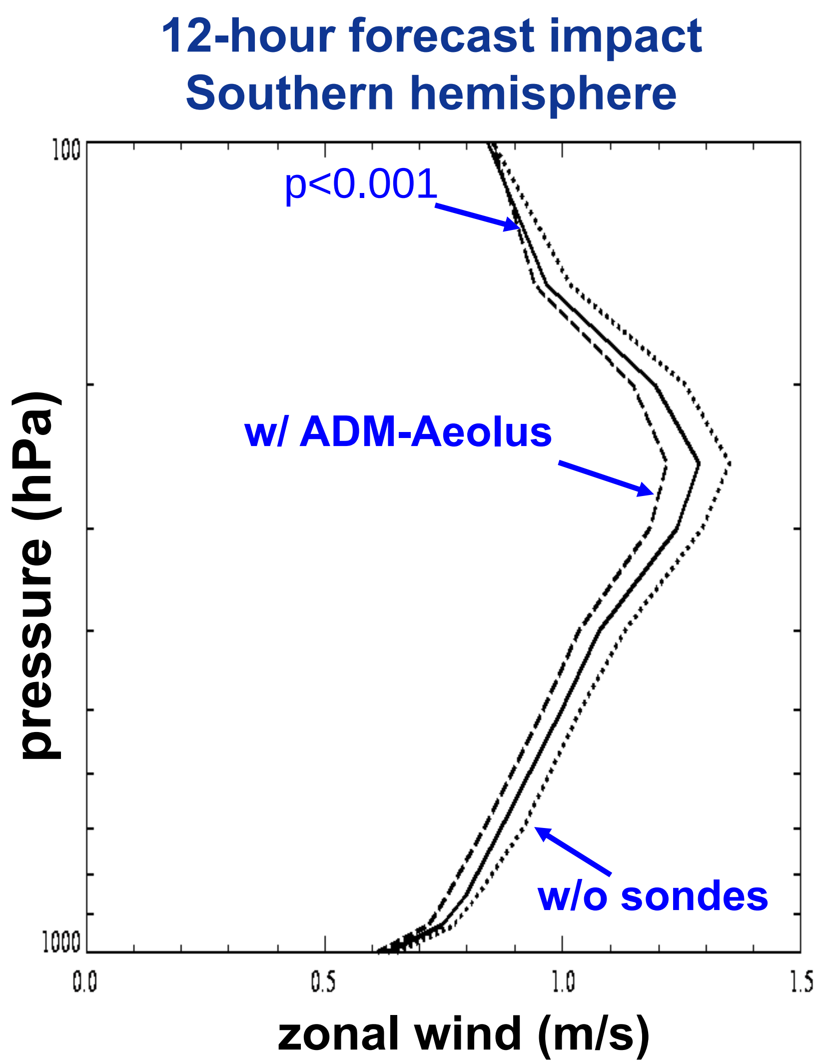
ECMWF

Data assimilation ensembles



(D. Tan)

Data assimilation ensembles



Ensemble spread in zonal wind (u, m/s) ≈ forecast error

Scaling factor ~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)

ECMWF

Satellite data usage at ECMWF

Impact of existing satellite data

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- Observing system experiments
- Advanced diagnostic tools

Impact of future satellite data

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').