Observation Impact Studies with the HIRLAM 4DVar Algorithm

Presented by

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on behalf of the
HIRLAM DA group

What ? : **test the HIRLAM 4D-Var algorithm performance with an ample set of satellite and conventional (i.e. “in-situ”, not remote-sensed) observation types. Determine the impact over the current default obs usage configuration. Detect possible detrimental combinations of types and adjust the algorithm calibration if necessary.**

Why ? : **our goal is to improve on the current observation usage at the different HIRLAM centers. We are interested too in setting up a benchmark for validation of other DA algorithms (e.g. HARMONIE 3/4D-Var).**

Who ? : **these experiments have been possible because of a joint effort of several members of the HIRLAM DA group supervised by *Nils Gustafsson*, namely: *B.Amstrup, P.Dahlgren, J. De Vries, O. Vignes, E.Whelan, X.Yang* and myself, *C.Geijo*.**

In this bunch of experiments we have focused on the following satellite data:

- **Microwave T-sounder AMSU-A and q-sounders AMSU-B and MHS. These data were acquired by radiometers on board the satellites:**

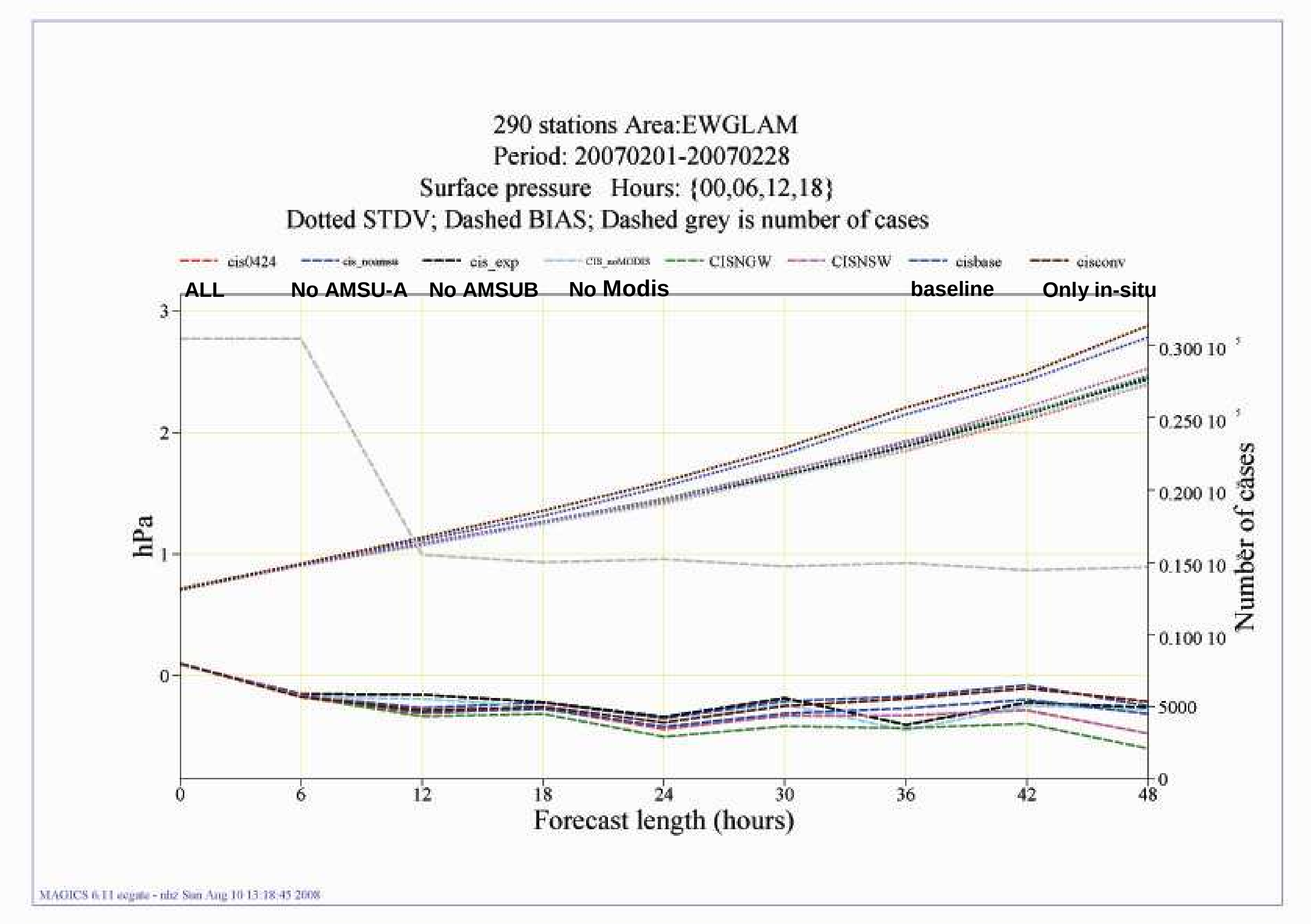
  NOAA15(1998) NOAA16(2000), NOAA17 (2002,no AMSU-A since October 2003) and NOAA18(2005, MHS).

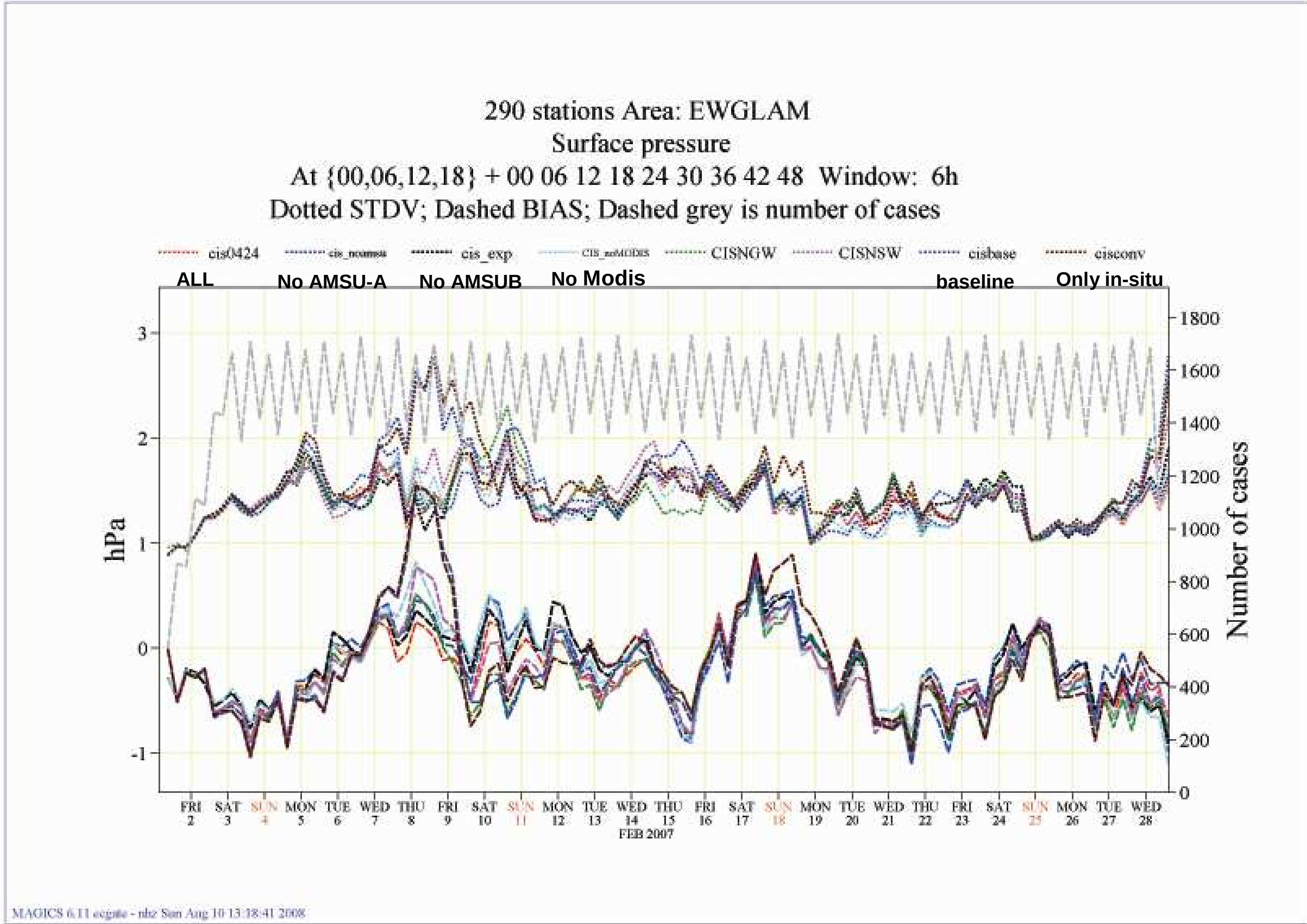
- **SeaWinds scatterometer data from QuikScat satellite (launched in 1999).**

- **AMV data from MSG-9 (2005, SEVIRI winds) and polar satellites "Aqua" (2002) and "Terra" (2000) (MODIS winds).**

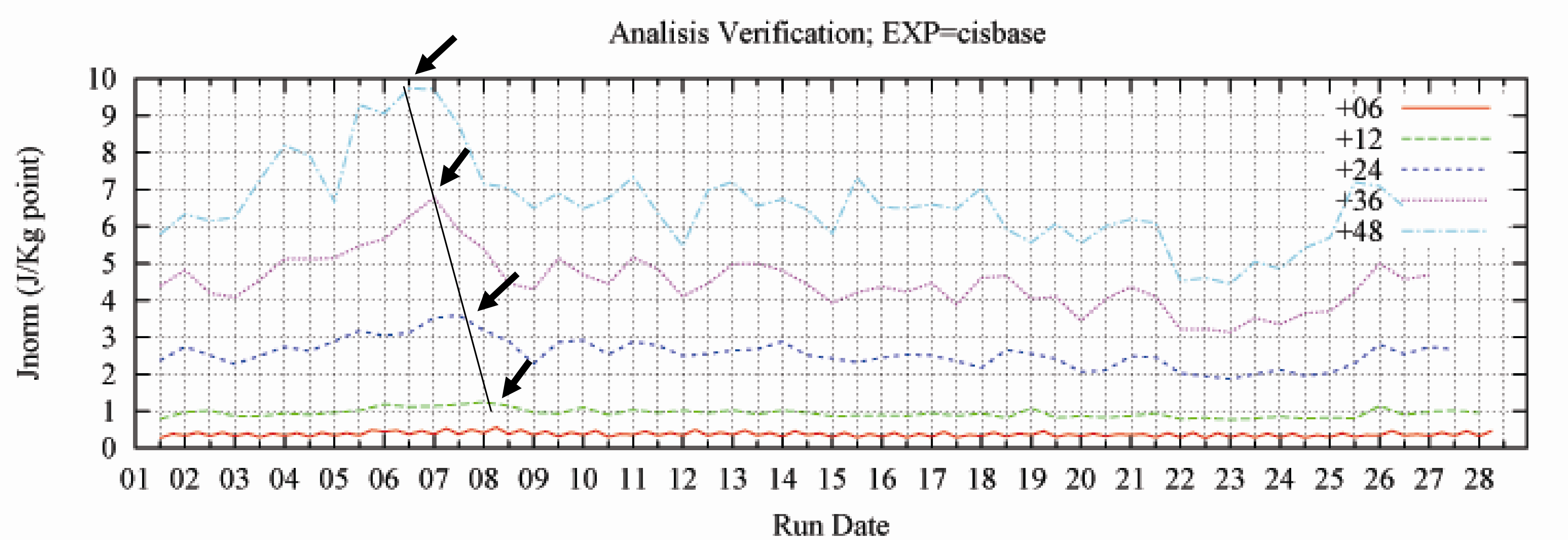
We studied the impact of these data over a <u>baseline configured with "in-situ" observations + AMSU-A data from NOAA15/16</u>, which is the current default configuration for versions below 7.2. We run some denial experiments too in an attempt to "rank" these observations types.

Let's go straight to some verification results. In the one-month experiment (February 2007) we found something interesting.



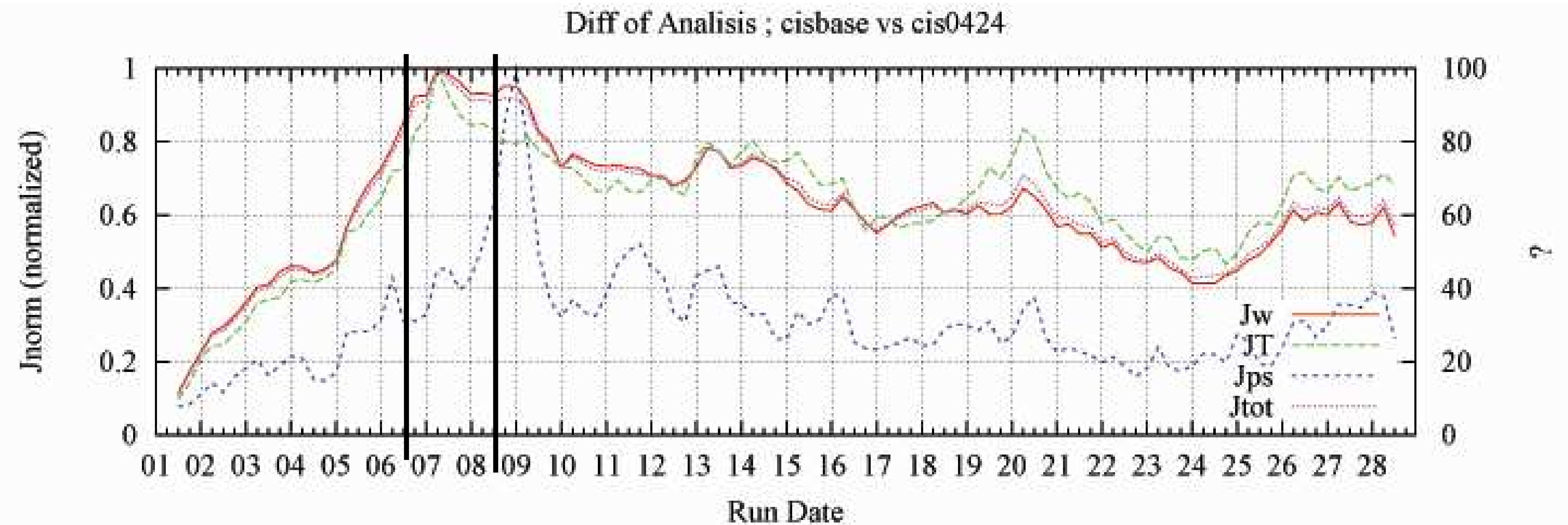

290 stations Area: EWGLAM
Surface pressure
At {00,06,12,18} + 00 06 12 18 24 30 36 42 48 Window: 6h
Dotted STDV; Dashed BIAS; Dashed grey is number of cases
cis0424
cis_noamsu
cis_exp
CIS_noMODIS
CISNGW
CISNSW
cisbase
cisconv
ALL
No AMSU-A
No AMSUB
No Modis
baseline
Only in-situ
hPa
Number of cases
FEB 2007

The “blast” in the forecasts for day 8 at 12 UTC can be clearly seen in the “field verification” as well. In the baseline experiment, all forecasts verifying at that time show anomalously big differences with the analysis.

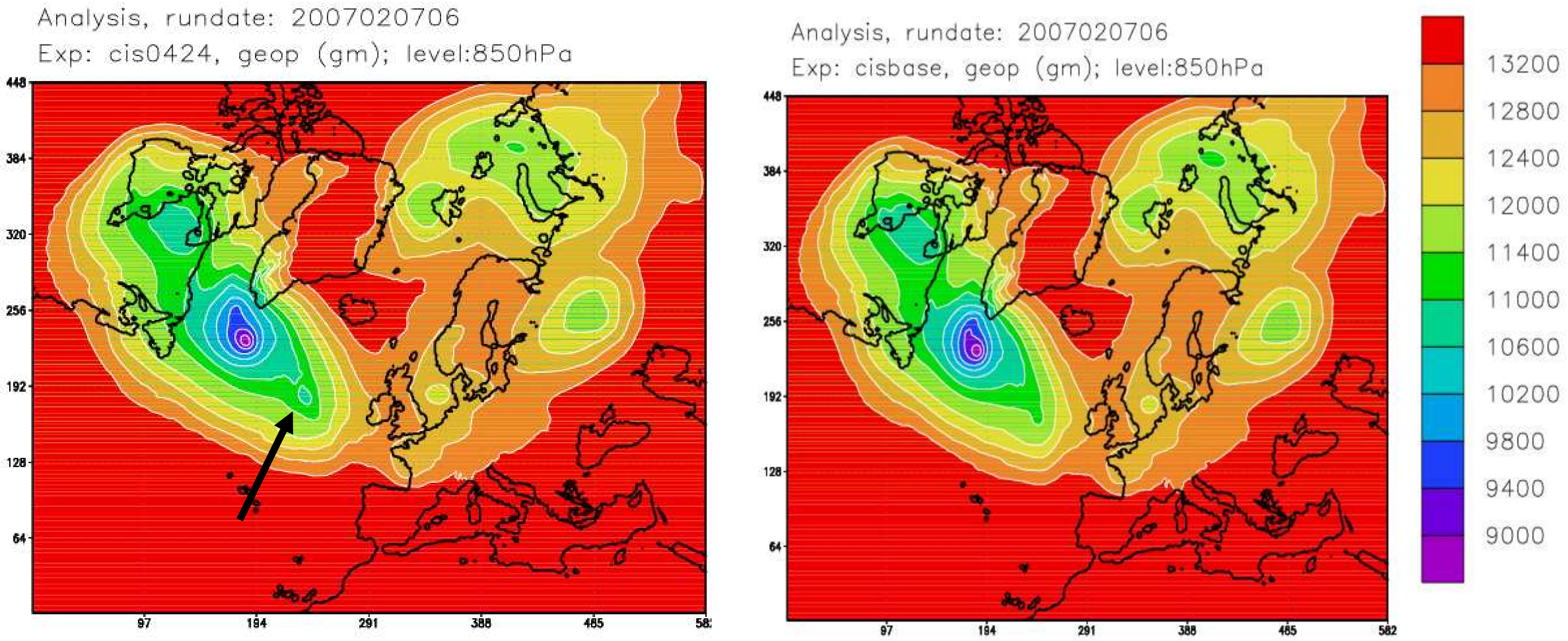


The norm used is $J = 1/N\ \Sigma_x \Sigma_y \Sigma_p\ [\ (\Delta u)^2 + (\Delta u)^2 + R_d T\ (\Delta \ln p_s)^2 + C_p/T_r\ (\Delta T)^2\ ]$ <u>over the whole domain</u>

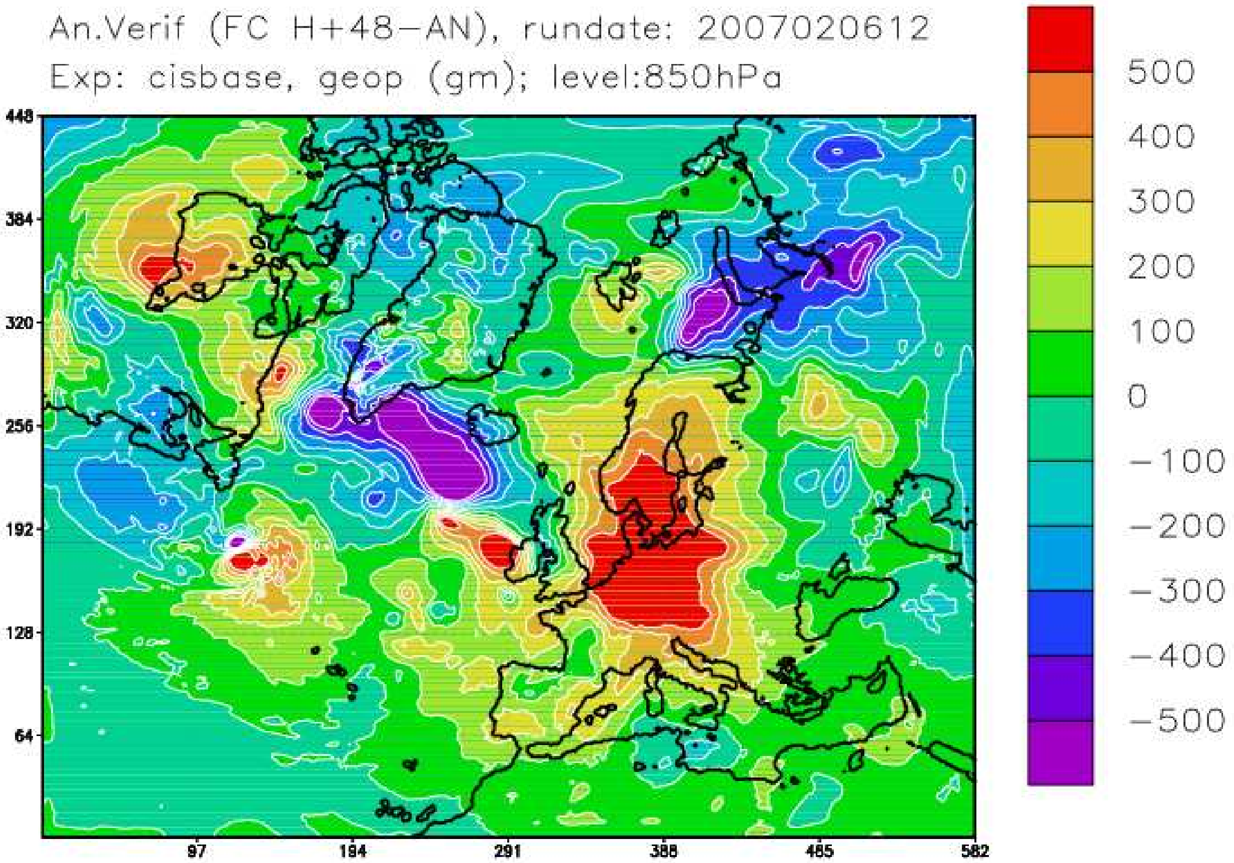
The “Allobs” and “baseline” analysis differ markedly for the runs 48 hours before the cycle in which the failure is detected. The max difference is for day 7 at 06 UTC, 30 hours before that date.



At bare eye the difference between the analyses seems not big …



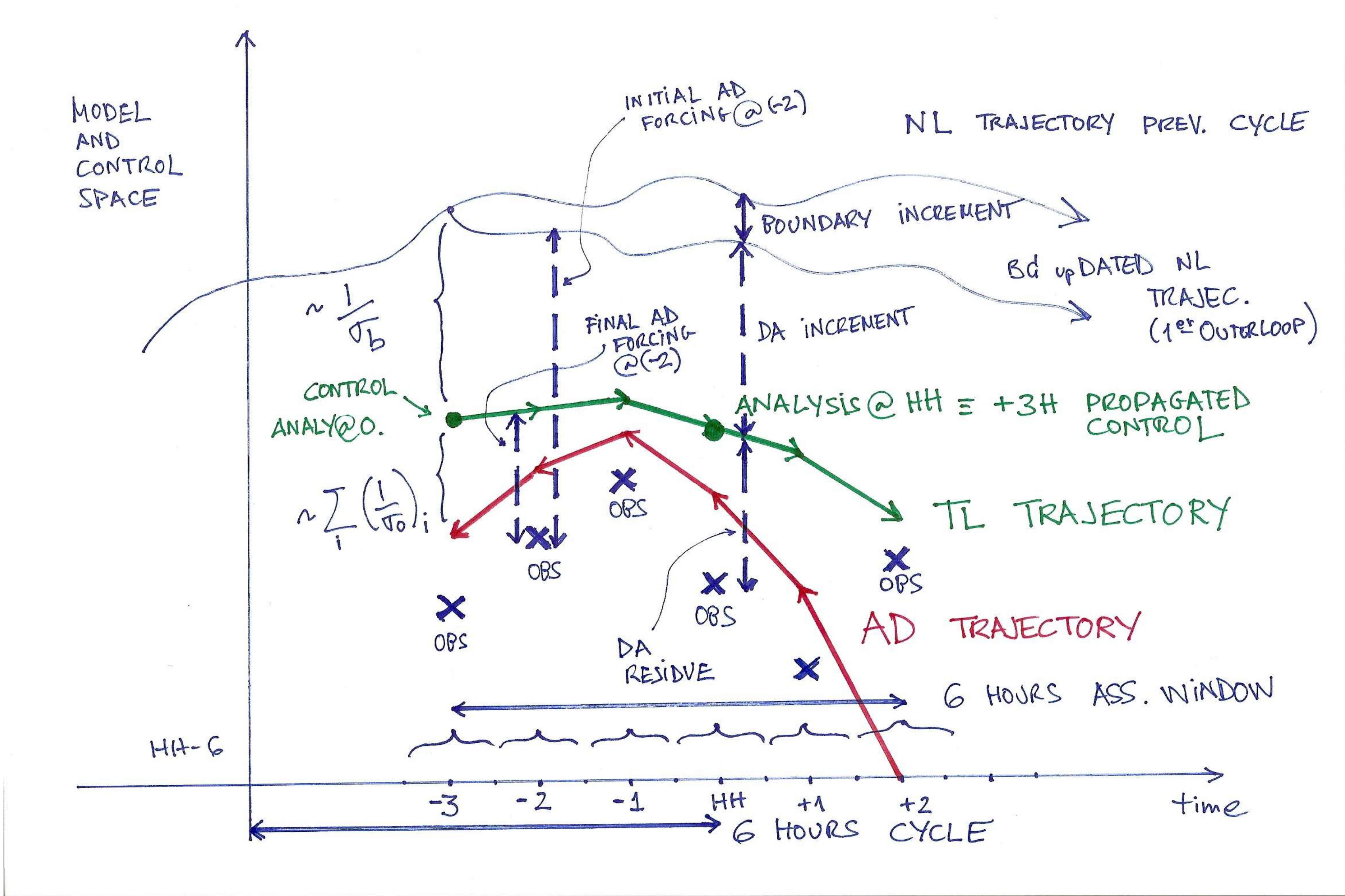
…but these differences may, as we know, grow fast



Now that the case has been documented, let´s focus on some DA aspects:

- The HIRLAM 4D-Var algorithm
- AMSU data and how is assimilated
- SEAWINDS data and how is assimilated
- AMV data and how is assimilated
- Sundries
- Conclusions

HIRLAM-4Dvar in a nutshell, (Nils gustafsson et al.)



HIRLAM-4Dvar in a nutshell

Boundary term. The boundary conditions are added to the control space. Specific to assimilation in LAMs. Not fully tested yet in HL and therefore <u>not considered in these CIS experiments</u>

Time dependent observation forcing term

$$J = J_b + \Sigma_i (J_o)_i + J_c + J_{boundary} + J_{largescale}$$

Constraint at the begining of DA window. Similar formulation to 3DVar, i.e SSI algorithm with multi-variate statistical balances

GW penalty term

Draws towards a given analysis for scales not well resolved by the LAM. Specific to LAMs.Implemented and tested but <u>not used in CIS</u>.

HIRLAM-4Dvar in a nutshell , extension to the boundaries

The 4D-Var algorithm stems from Optimal Control Theory. The linear version of the model is used as a "strong constraint" (perfect model assumption, a major weakness) in the minimization of J. It can be shown that the gradient of the forcing term(J_o) is given by the integration of the adjoint equation, that is:

$- \text{grad } J_o = \lambda \ (t=0)$; $- d\lambda/dt = M^{\dagger} \lambda - d$; $\lambda(t=T) = 0$

where λ is the lagrange multiplier, also known as adjoint variable. The boundary term, $J_{boundary}$, comes in when one wants to consider the "complete" definiton of a differential adjoint operator, that is, non vanishing contribution from the boundaries:

$$< M^{\dagger} \lambda , \delta x > = < \lambda, M \, \delta x > + B (\lambda_b , \delta x_b)$$

the functional variation of $B (\lambda_b , \delta x_b)$ with δx_b gives the BC for the adjoint equation and the expression for grad $J_{boundary}$

HIRLAM-4Dvar in a nutshell , CIS settings

• TL / AD integrations are carried out with simplified physics, in particular no moist physics is included

• They are performed with the spectral version, that is, over the extended domain we impose PBC ($B_{ext.}(\lambda_b, \delta x_b) = 0$, i.e., $J_{boundary} = 0$)

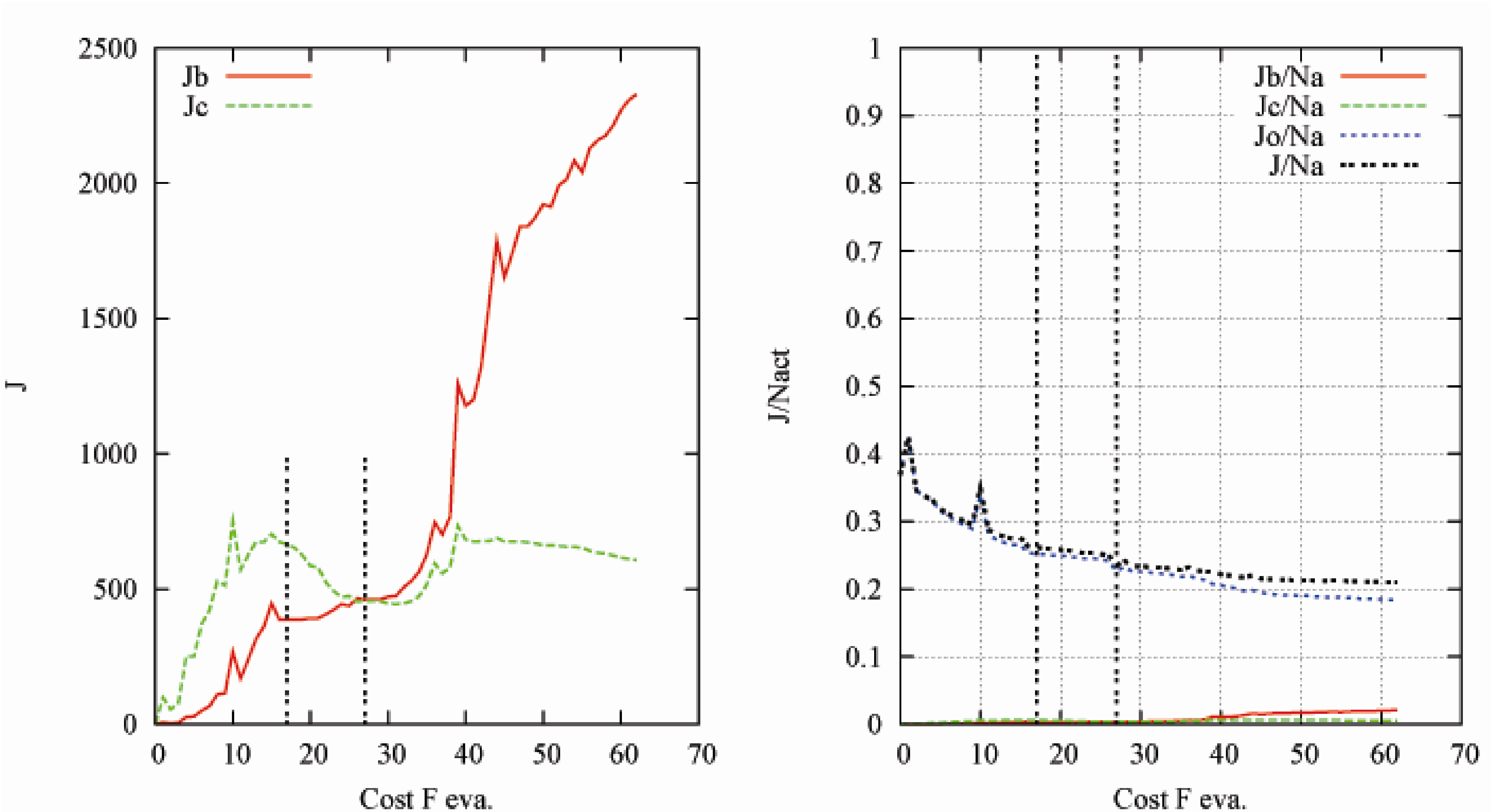
• Time step 1800 s, at 1/3 full model's horizontal resolution and full vertical resolution (60 levels)

• 1 outer loop and 60 iterations in the inner loop

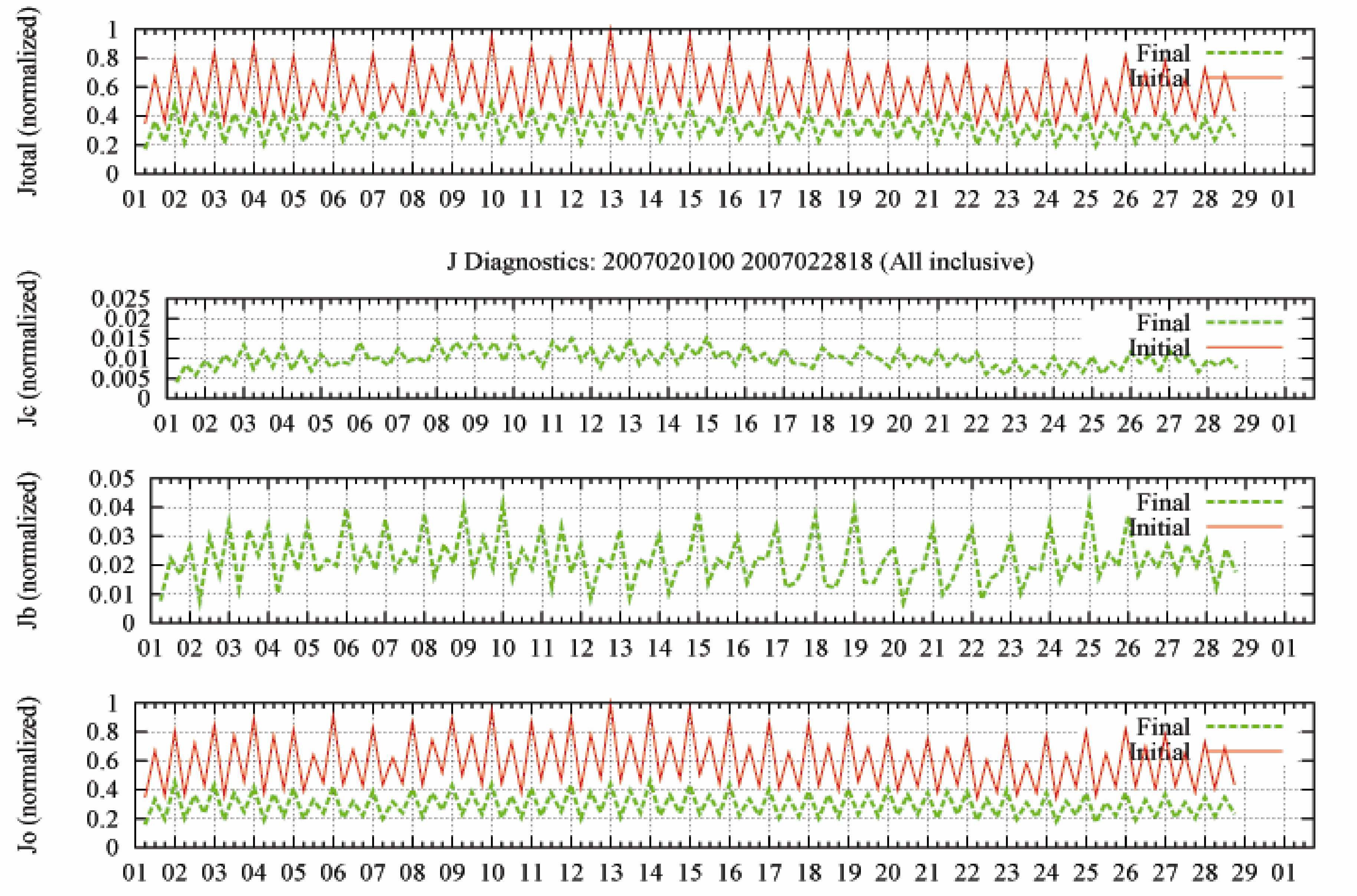
• VarQC between iterations 15 and 25

• 4 to 5 times more expensive in CPU time than 3DVar (on ECMWF hpce)

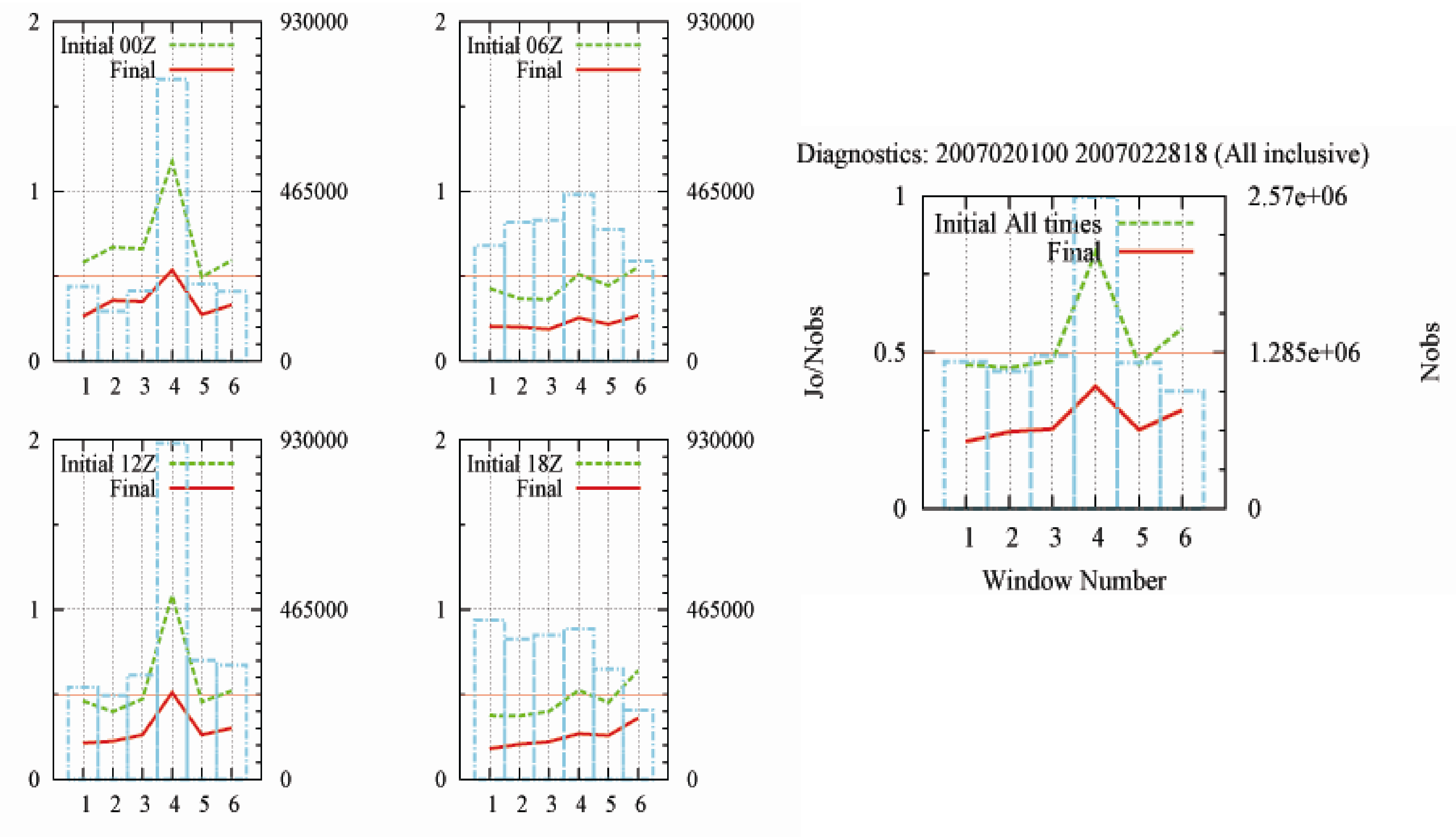
HIRLAM-4Dvar in a nutshell , Assimilation Diagnostics



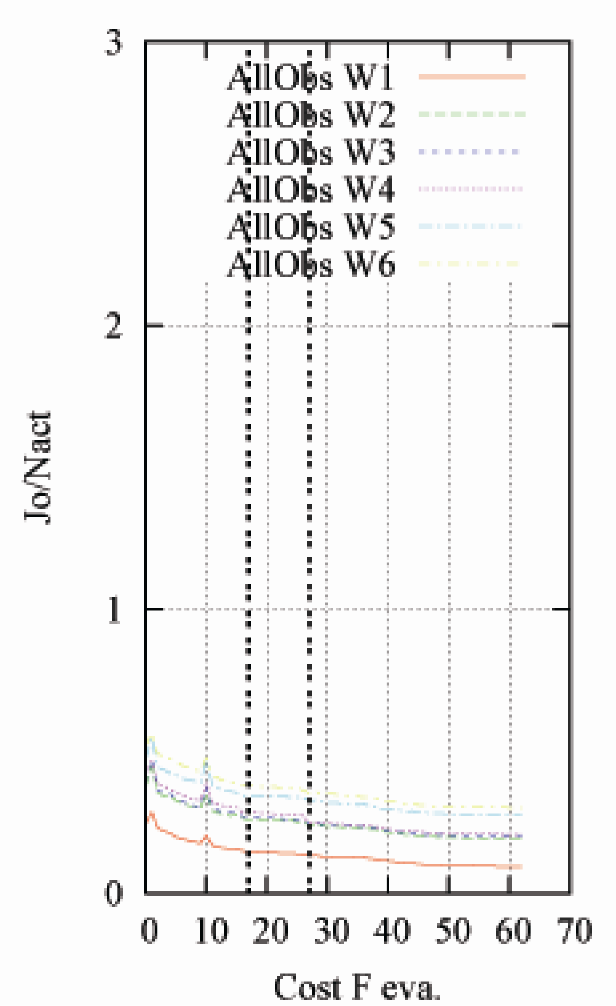
HIRLAM-4Dvar in a nutshell , Assimilation Diagnostics

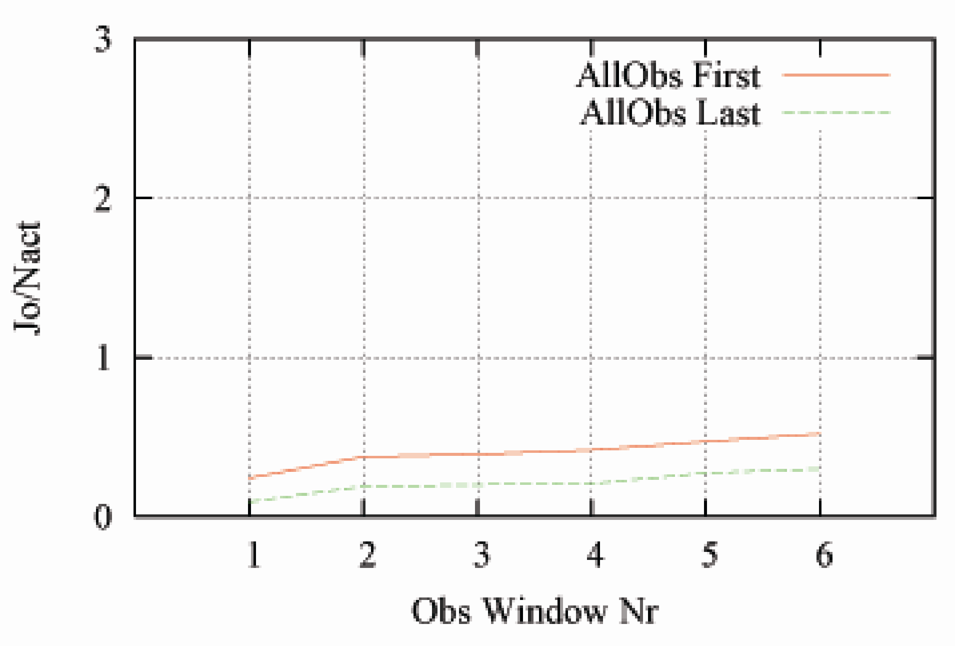


HIRLAM-4Dvar in a nutshell , Assimilation Diagnostics



HIRLAM-4Dvar in a nutshell , Assimilation Diagnostics





Microwave sounders data (CIS obs expert P. Dahlgren)

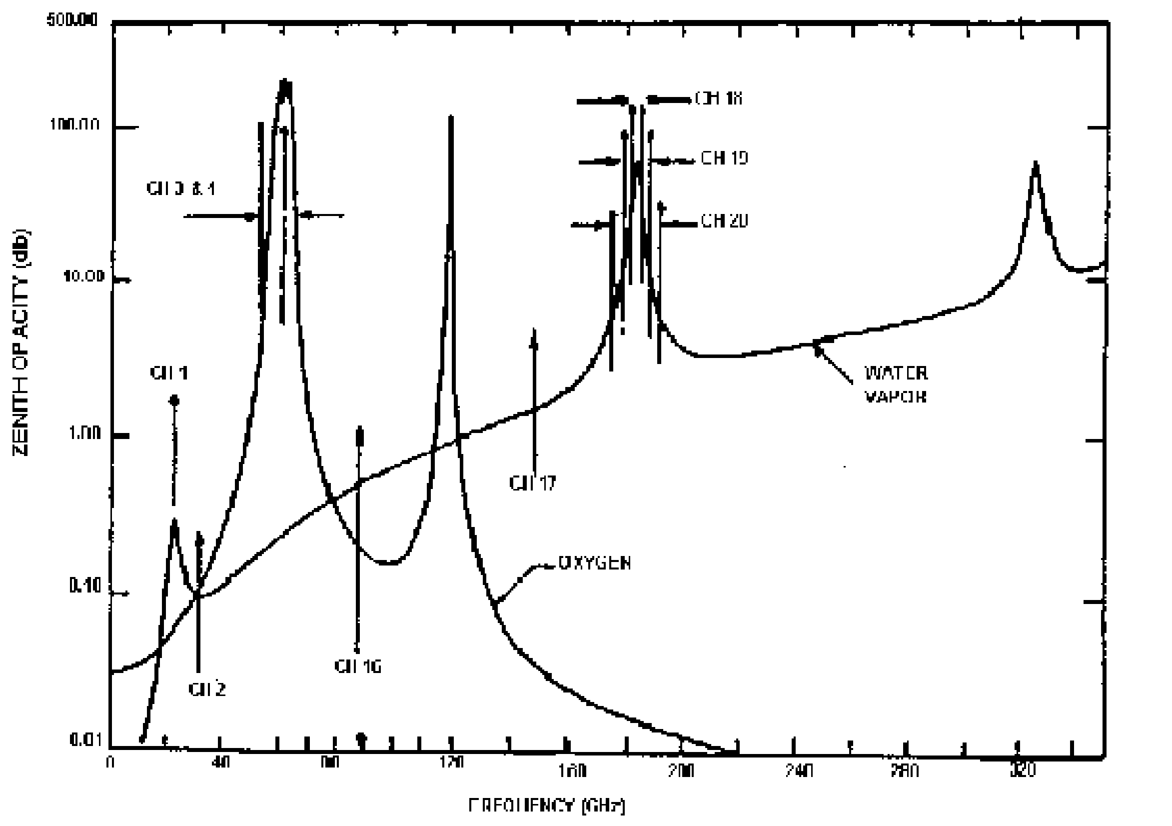
• The observation operator that has been used for CIS is RTTOV-8. This NWP-SAF product includes the FASTEM code for sea-surface emivissivity calculations. Currently no emissivity models for other surface types are used.

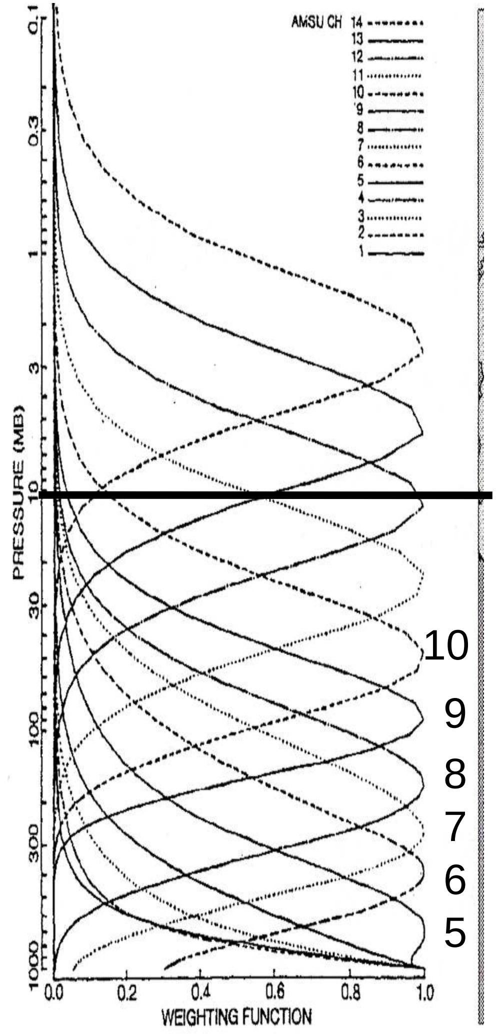
• For AMSU-A, all the "non stratospheric channels" (1-10) are used (HL-60L top at 10 hPa). The "water-burden" and "surface channels" (1-4) do not enter in the minimization, although they are used in QC. Over sea-ice and land, channel 5 is not considered in the minimization either.

• For AMSU-B and MHS, all channels in the 180 Ghz WaterVapour absorption band (i.e. 3-5) are used. The "auxiliary channels" (89GHz - 150 Ghz) do not force the analysis, although they are used in QC. In CIS, AMSU-B/MHS data has been considered only over sea surface.

Microwave sounders data

Figure 3.4.1-1. Microwave Characteristics of the Atmosphere.





Microwave sounders data

- Observations are corrected for estimated biases before the assimilation by means of statistical regressions with up to eleven predictors (no VarBC for the moment).

- Several screening checks are considered : high orography, cloud contamination, surface contamination (for sea-ice or land surface types), and rain clutter (for AMSU-B).

- A check on the difference with the BG is included. The check is performed on a channel-by-channel basis and the whole “profile” is rejected if the number of channels failing this test is bigger than a given threshold.

- Three thinning loops of increasing box-size are applied and preference is given to data closer to nominal obs window time and smaller scan angle.

- As for other observation types, a QC method based on Bayessian probability theory is embedded in the minimization (VarQC).

Microwave sounders data, Jacobians

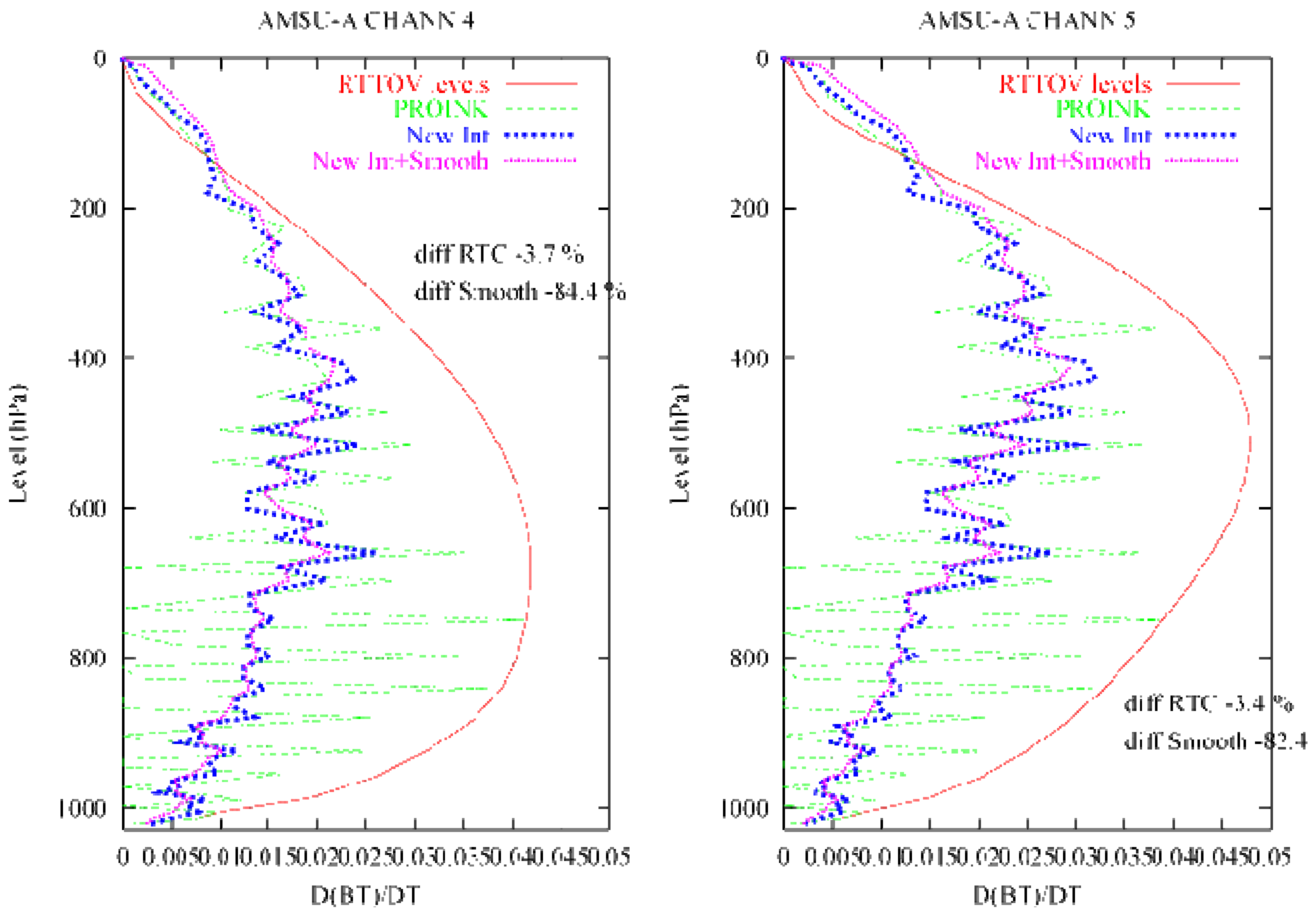
The original RTTOV Jacobian interpolation code has been improved (Nils) to avoid "blind levels" and to distribute the observation increments more evenly in the vertical

The problem arises from the fact that RTTOV levels and HIRLAM levels are different. The condition of equal values for the linear corrections to the radiances when one calculates these corrections on any of the two vertical grids, imposes a relation between the profile interpolation and the jaconbians interpolation schemes.

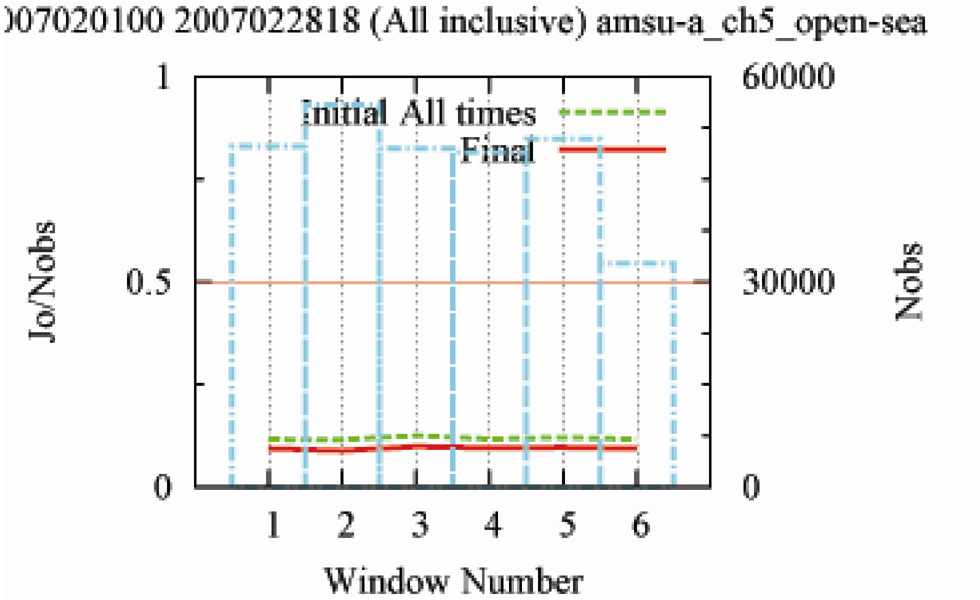
{ α } RTTOV-8 (41 levels), gives J_α but requires T_α
{ i } HIRLAM (60 levels), gives T_i but requires J_i
we seek for A and B so that $T_\alpha = \Sigma_i A_{\alpha i} T_i$ and $J_i = \Sigma_\alpha B_{i\alpha} J_\alpha$ with the condition That $\delta R = \Sigma_i J_i \delta T_i = \Sigma_\alpha J_\alpha \delta T_\alpha$. This gives inmediately that $B=A^T$.

A and B are rectangular, therefore smooth interpolation for the profiles can give unacceptable results for the jacobians and vice versa. A good solution depends on the distribution of levels in one grid with respect to the other.

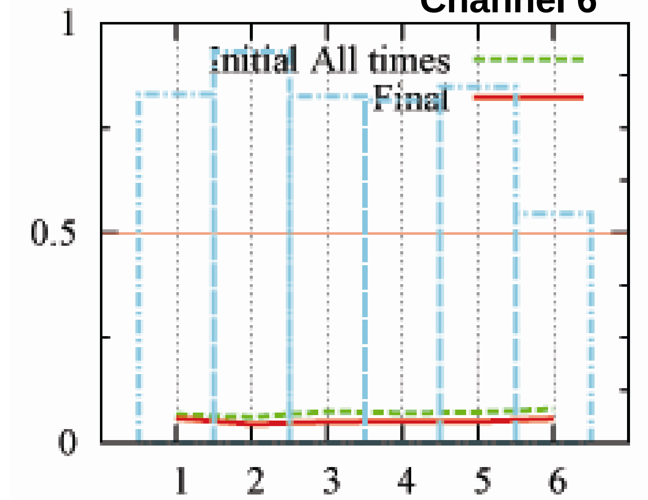
Microwave sounders data, Jacobians



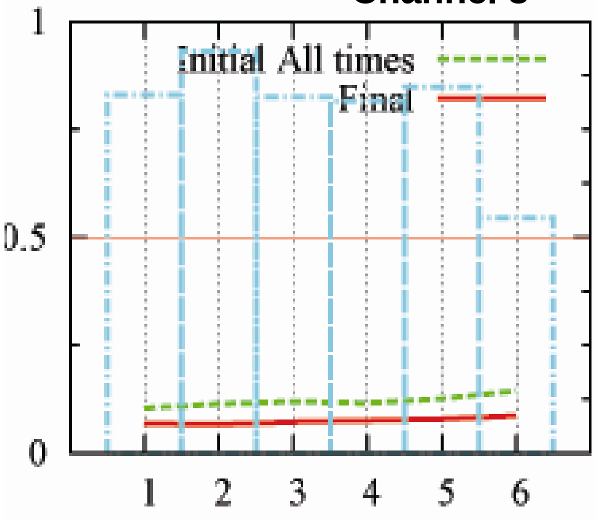
Microwave sounders data, assimilation diagnostics



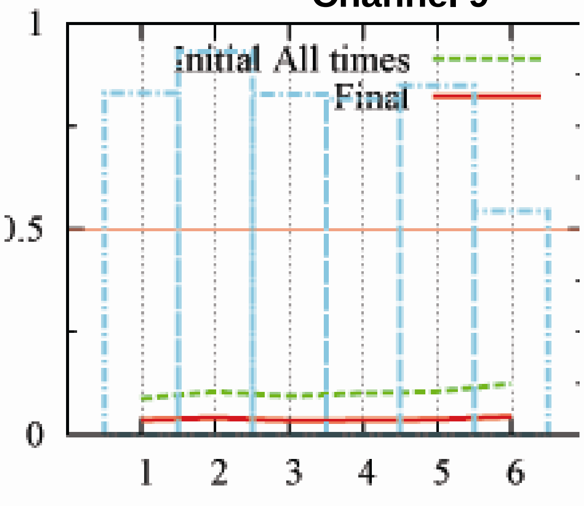
Channel 6



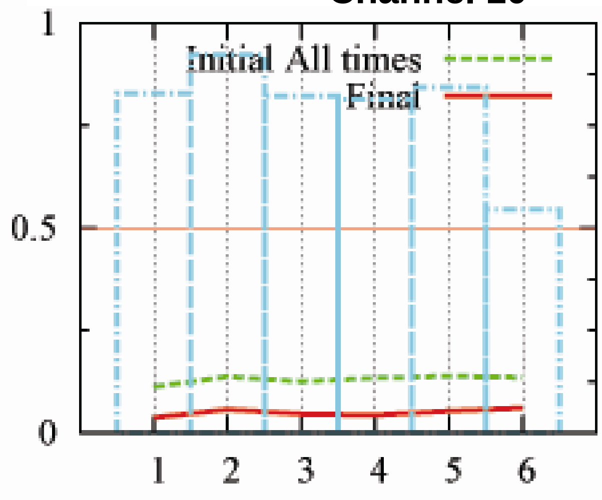
Channel 8



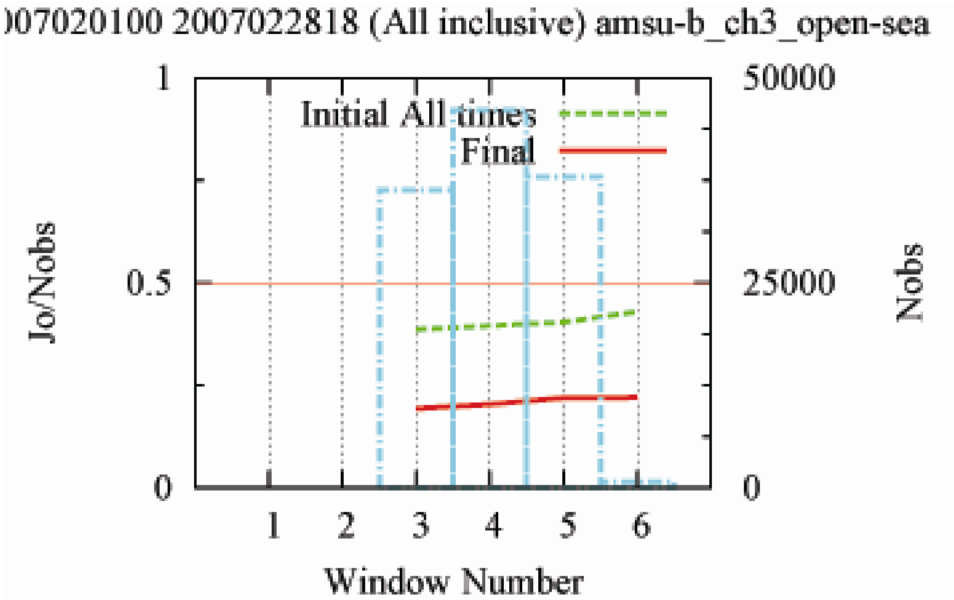
Channel 9



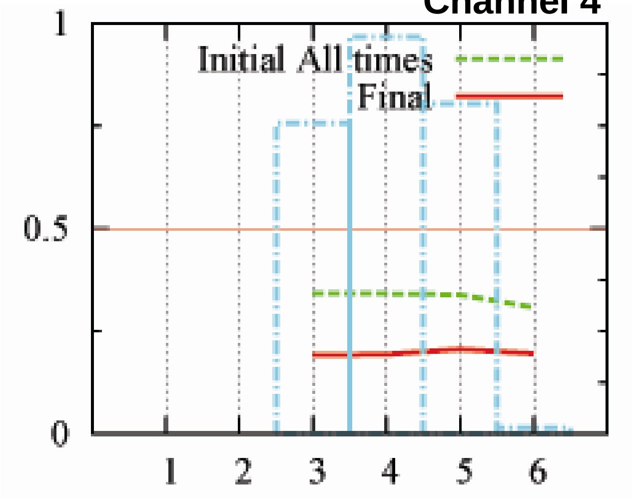
Channel 10



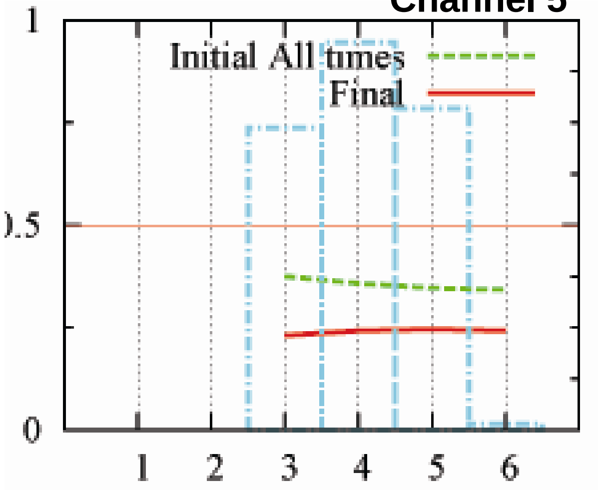
Microwave sounders data, assimilation diagnostics



Channel 4



Channel 5



SEAWINDS data (CIS obs expert J. De Vries)

• Seawinds 10m winds are produced by the SDP ("Seawinds Data Processor", SAF-NWP) at KNMI (The Netherlands) from measurements of the roughness of the sea surface at capillary-wave scales (cm). These measurements are obtained by the Seawinds scatterometer on board the QuikScat satellite (sun-synchronous, 14 orbits/day).

• Raw observations have a spatial resolution of 25 Km, but SDP delivers data with100 Km resolution and better S/N ratios. It provides too with a "solution probability" that is necessary in the ambiguity removal process that takes place during the minimization.

• No bias correction is applied to these data, and they do not pass a BG check either. The screening is based on a monitoring flag generated by SDP and the VarQC algorithm.

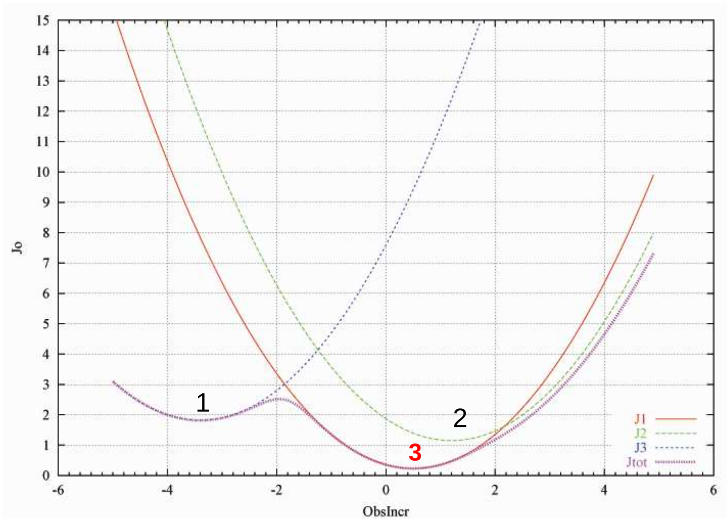
• Seawinds VarQC assigns a-priori probabilities of gross-error depending on the observation Wind Vector Cell (i.e., position of the "spot" in the swath).

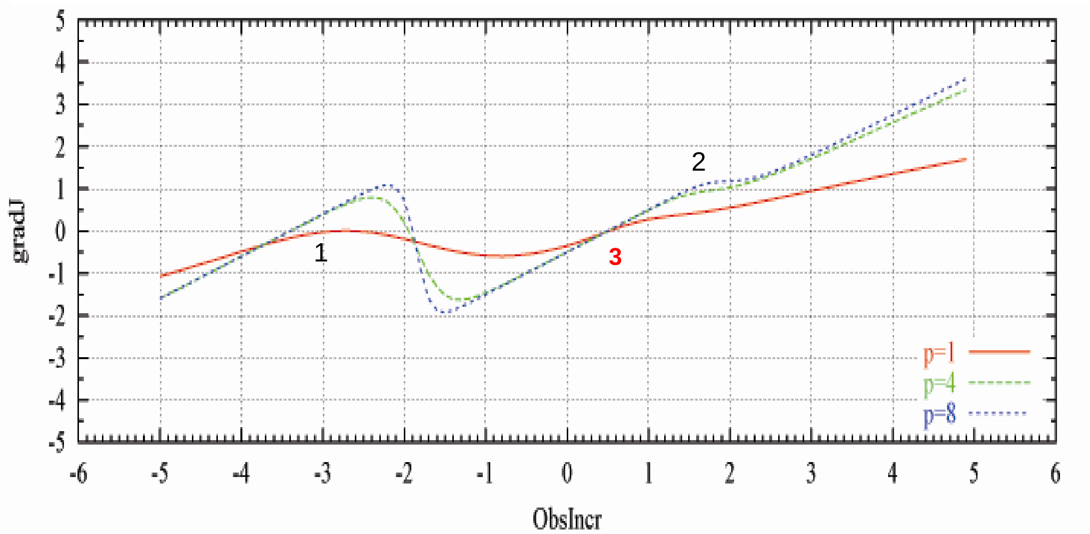
SEAWINDS data, **Ambiguity removal**

Seawinds observations are ambiguous in wind direction. The ambiguities are all presented to the minimization algorithm weighed with their corresponding “solution probability”, a parameter produced by SDP and calculated from the raw data (σ^os). The cost function for a single (ambiguous) observation has the form :

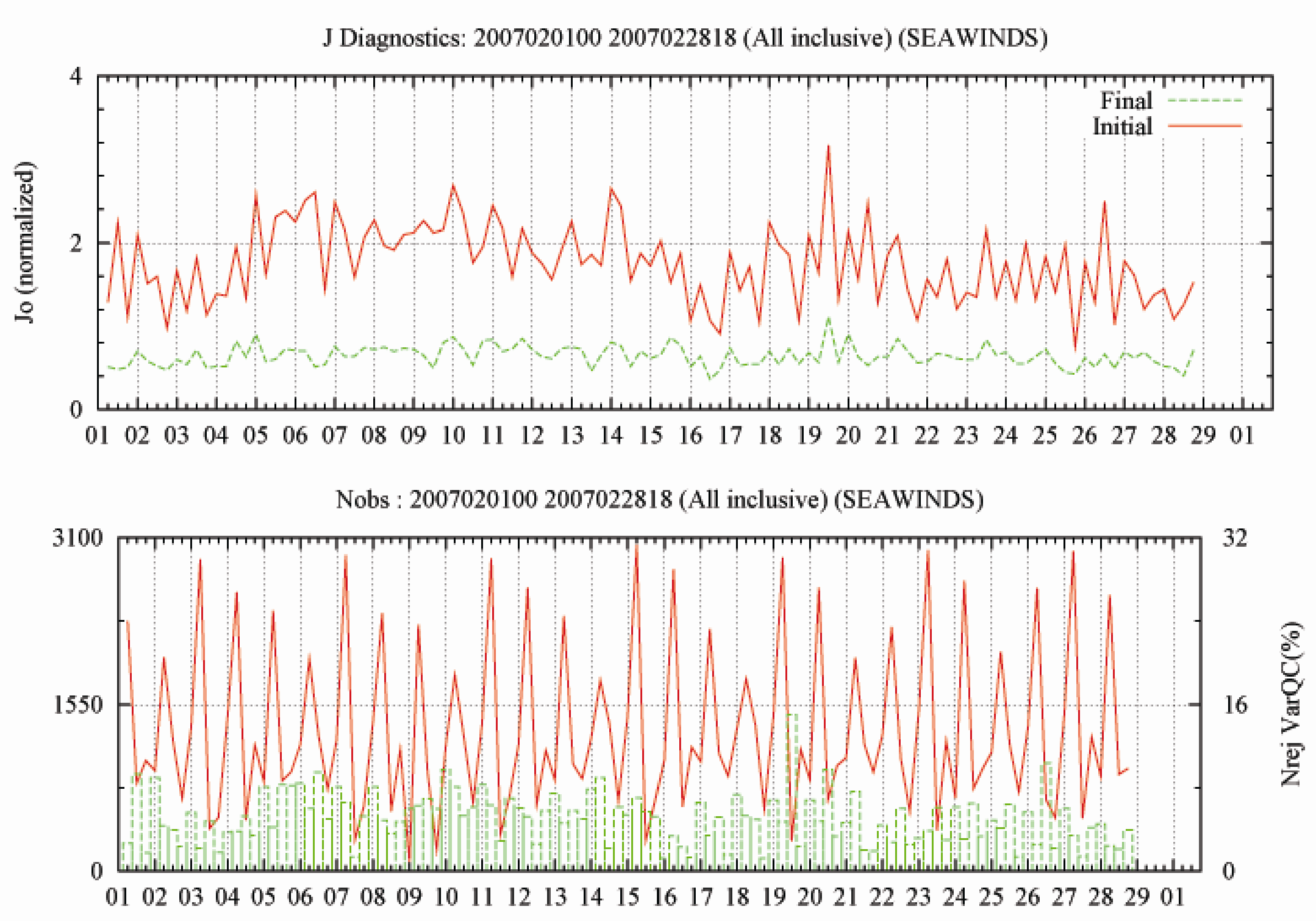
$$J = [\ \Sigma_{amb}\ J_i^{-p}\ ]^{-1/p} \quad ; \quad J_i = -\log [\ P_{sol}\ (i)\ \exp\ (\ -z_i^{\ 2} / 2\ )] \quad ; \quad Z_i = \text{ObsIncr} + \text{control}$$

where the parameter p (=4) is useful to improve convergence.





SEAWINDS, assimilation diagnostics



SEAWINDS, assimilation diagnostics

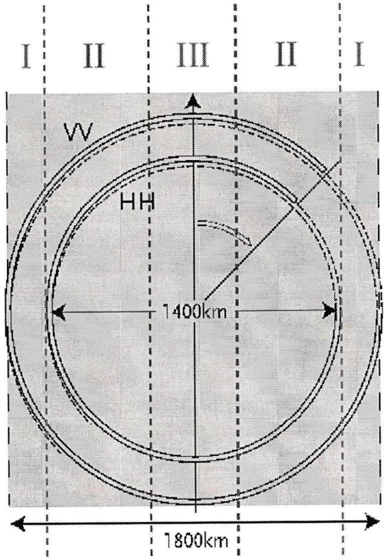
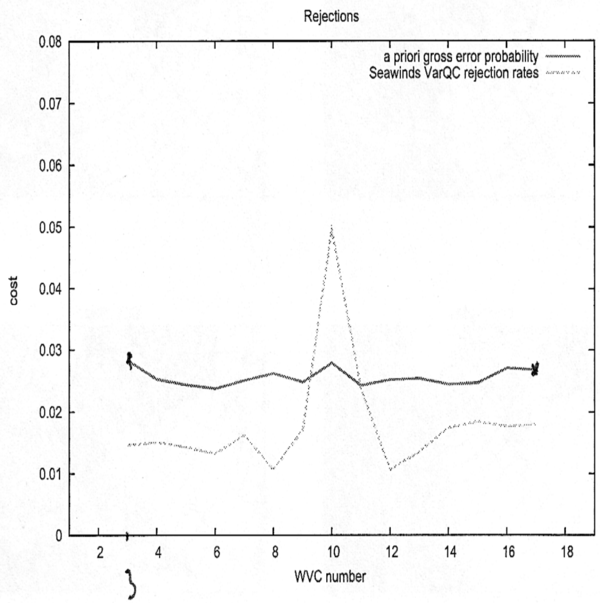
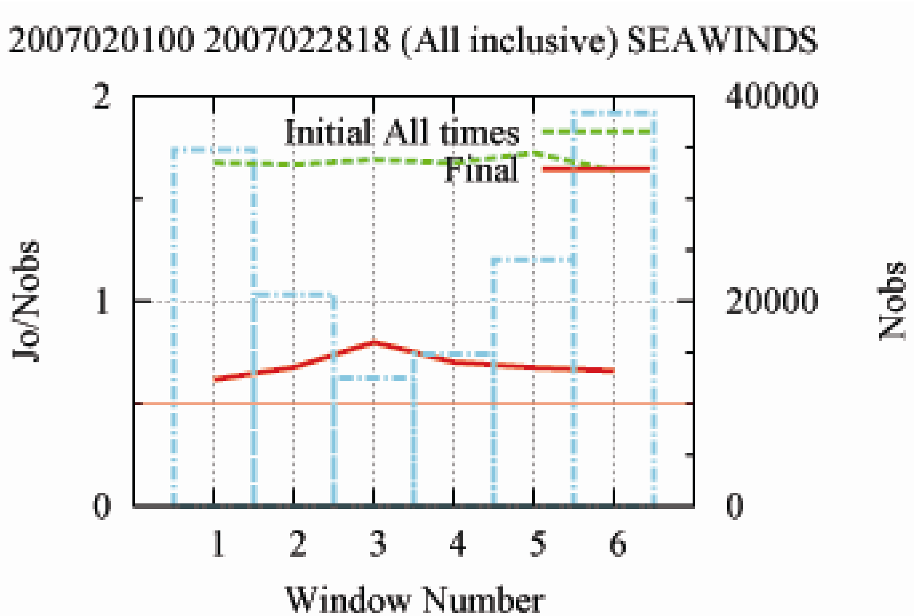
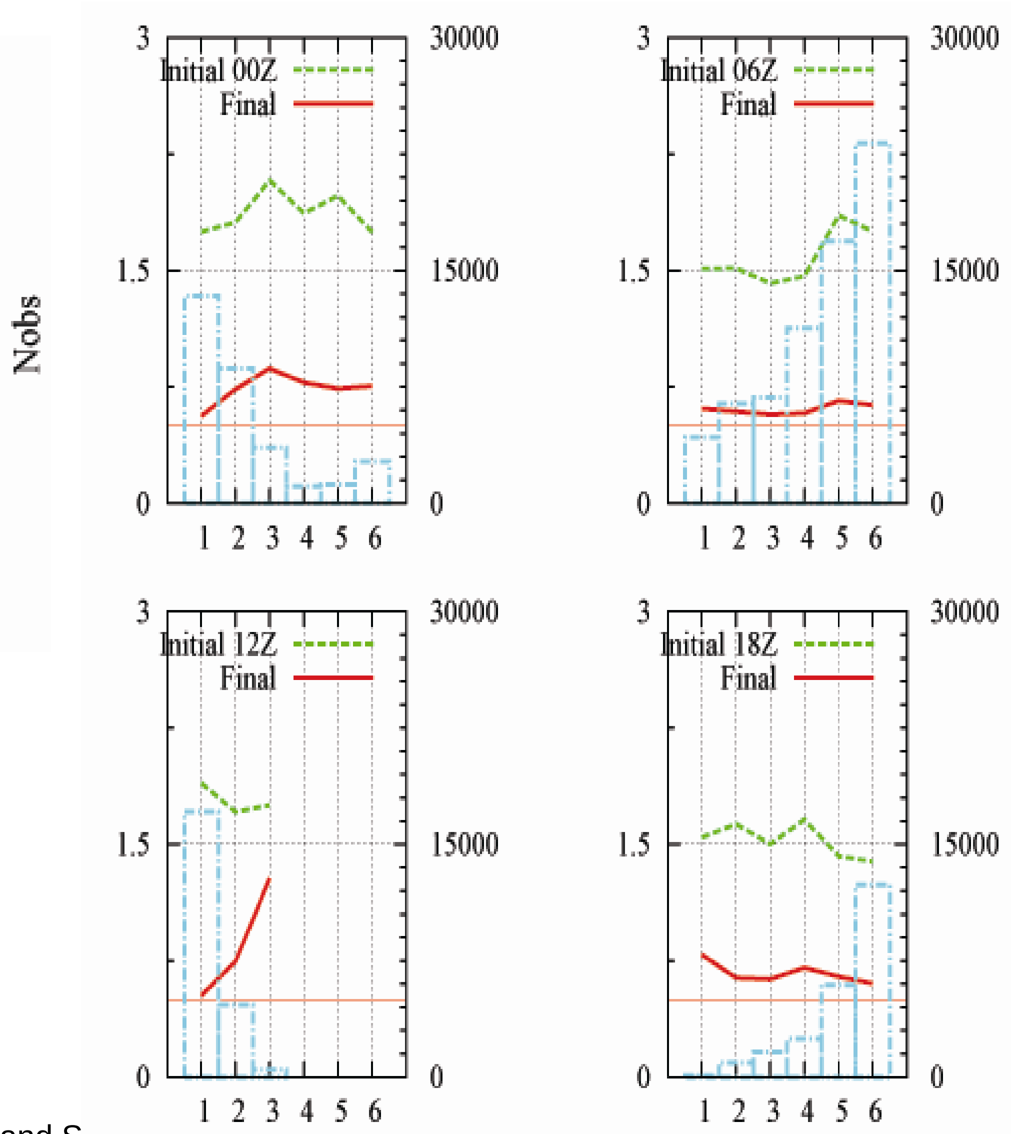


Figure 1: The Seawinds swath.



SEAWINDS, assimilation diagnostics





AMV data (SEVIRI and MODIS winds) (CIS obs expert C. Geijo)

• For SEVIRI AMV data, all the types of vectors available have been considered:
VI (low (72Km) and high(32Km)spatial resolution), IR, WV1 and WV2 (no CSK).
These data (except VI data) have a regular hourly production period, and measure the mean atmospheric motion over that time (RS-AMV data not tried in these experiments).

• For MODIS AMV data, just two vector types , IR and WV, have to be considered.
They have more irregular production period, somewhat between 30 and 70 min (2 sun-synchronous satellites orbit -> one pass every ~45 min), and represent the mean atmospheric motion over the time elapsed in the acquisition of three consecutive images.

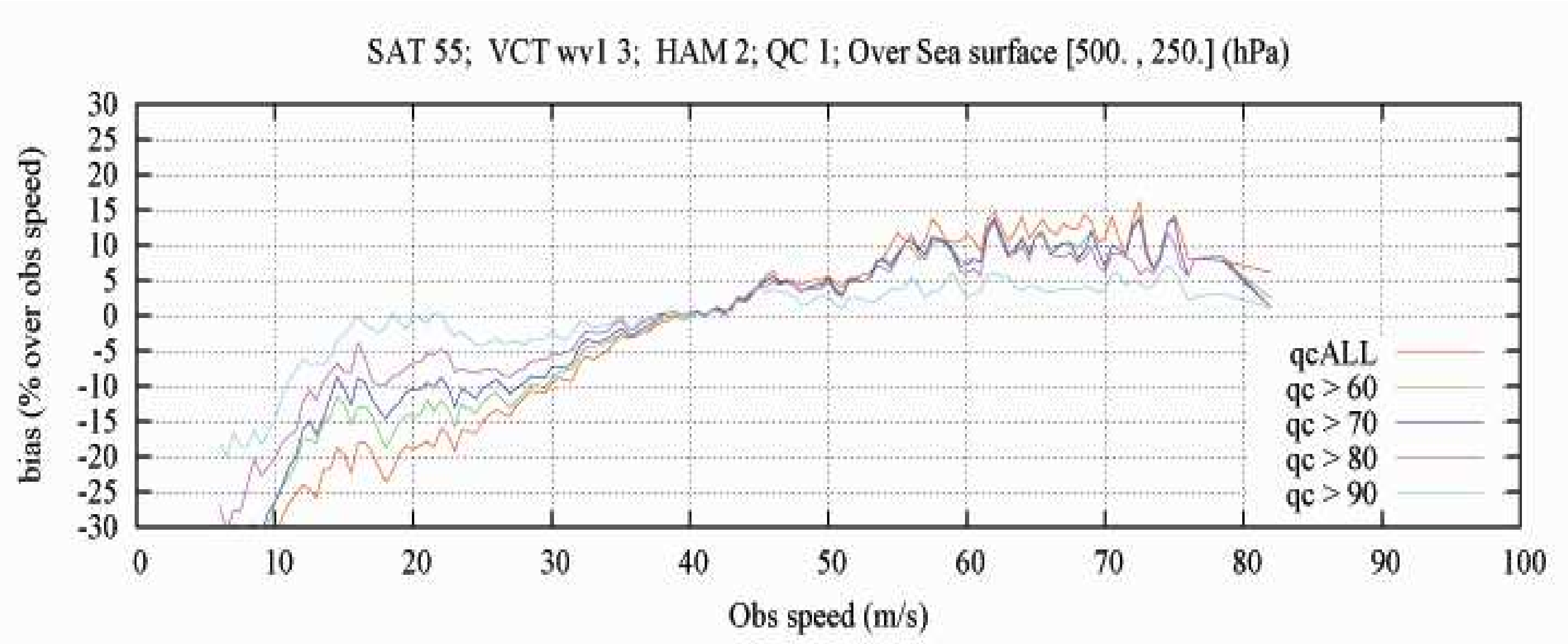
• Both are handled by the assimilation process in much the same way. They are treated as single level observations (no sophisticated Obs Operator for these data). Possible horizontal structure in the errors not considered either.

• The BC and screening step is somewhat more elaborated though, it takes into account: height assignment technique employed (EBBT, WV-IR intercept or CO2 slicing), surface type underneath, height range, speed range and DP QC index.

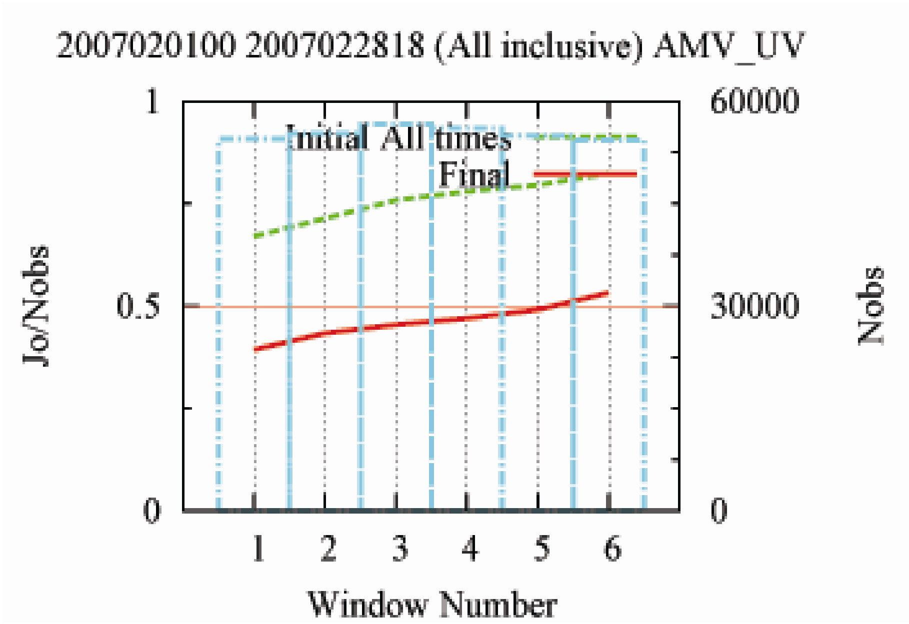
• The data go through a check on the difference with the BG. The data density is thinned down to ~100 Km retaining vectors closer to nominal data window time and better QC Index. VarQC applied during minimization.

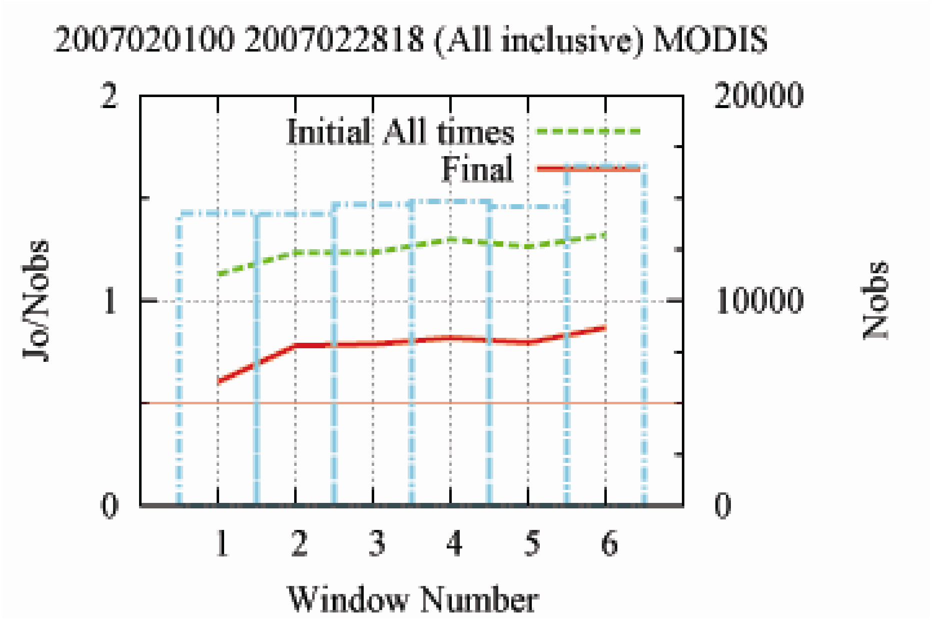
AMV data (SEVIRI and MODIS winds), Bias Correction

It was found that a convenient way to characterize the bias is by plotting relative speed difference vs obs speed. The correction then is very close to linear. <u>The data has more vertical shear than the model for all cases analyzed</u>. For SEVIRI AMVs it was found that one of the QCindexes (presumably that including a FG check) discriminate fairly well the cases strongly biased from those weakly biased.

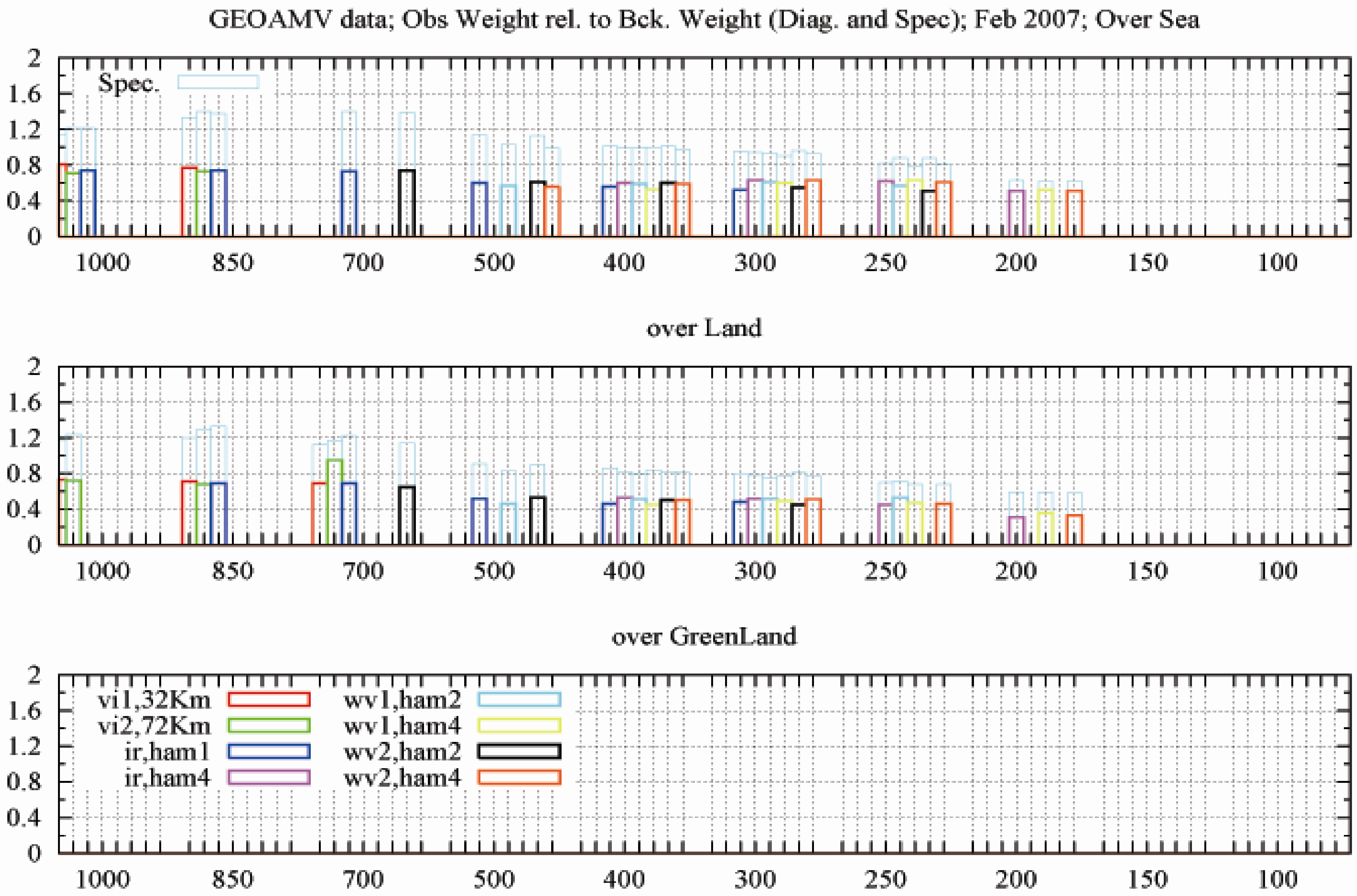


AMV data (SEVIRI and MODIS winds), Assimilation Diagnostics

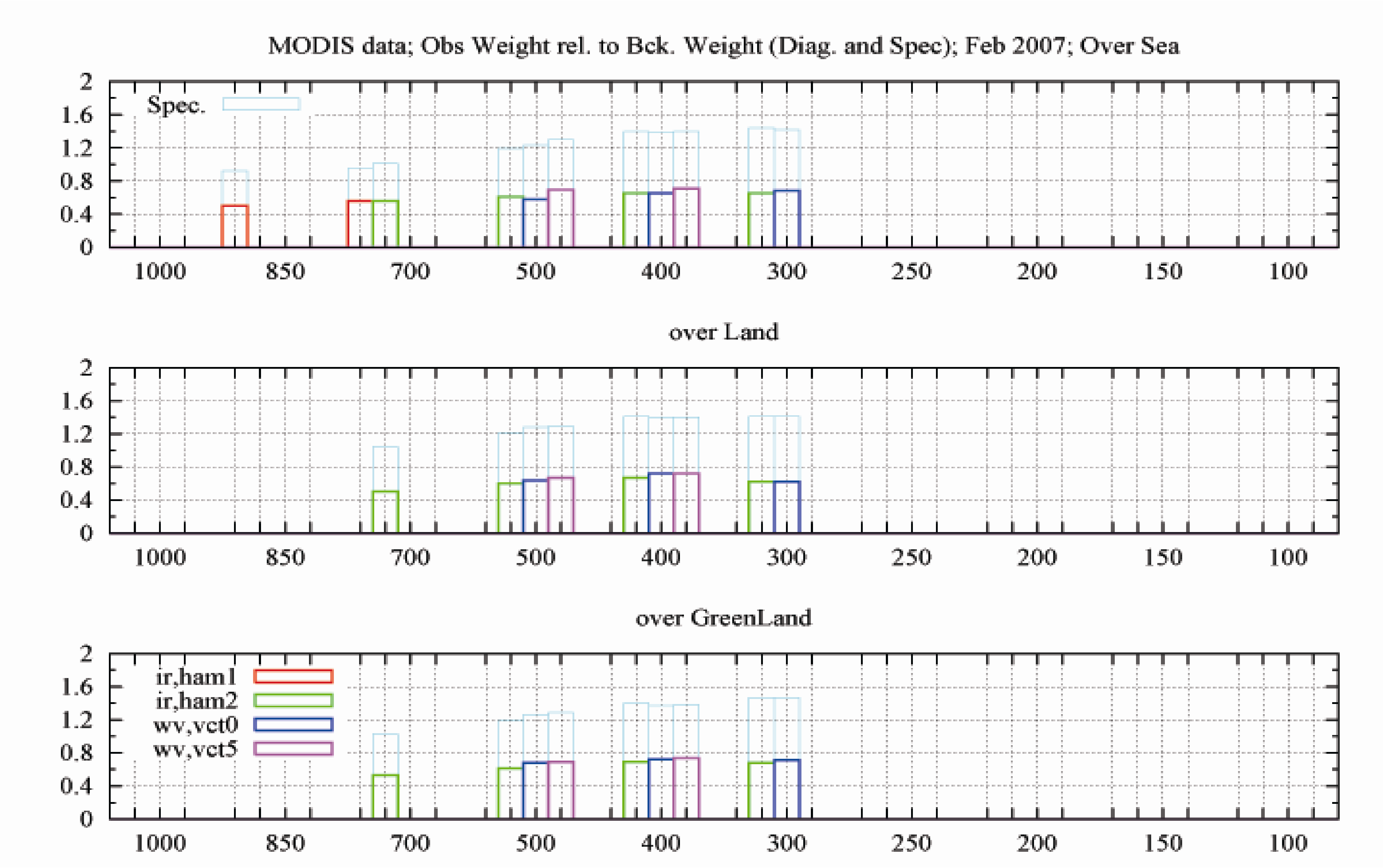




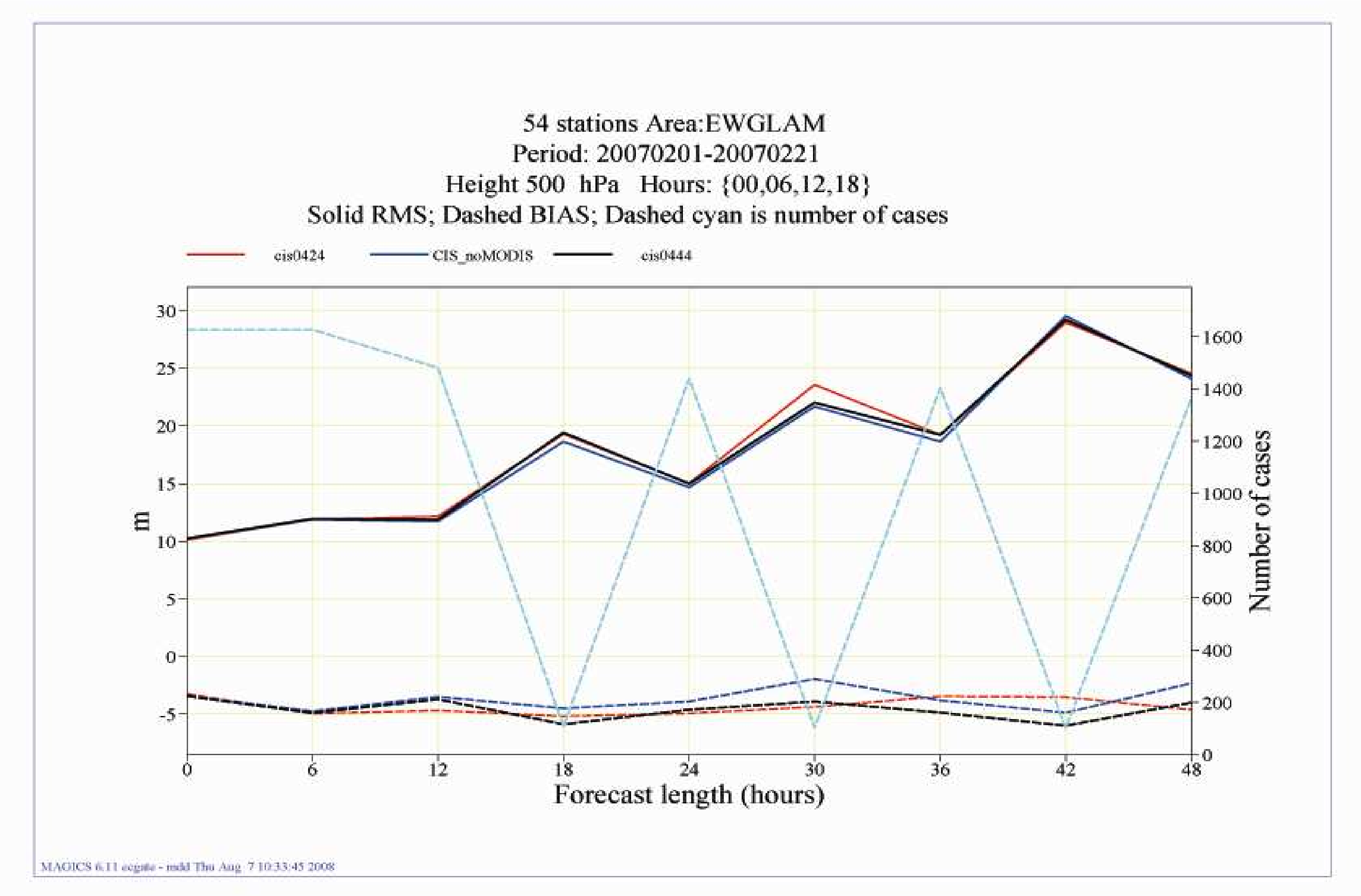
AMV data (SEVIRI and MODIS winds), Assimilation Diagnostics



AMV data (SEVIRI and MODIS winds), Assimilation Diagnostics



AMV data (SEVIRI and MODIS winds), Algorithm calibration



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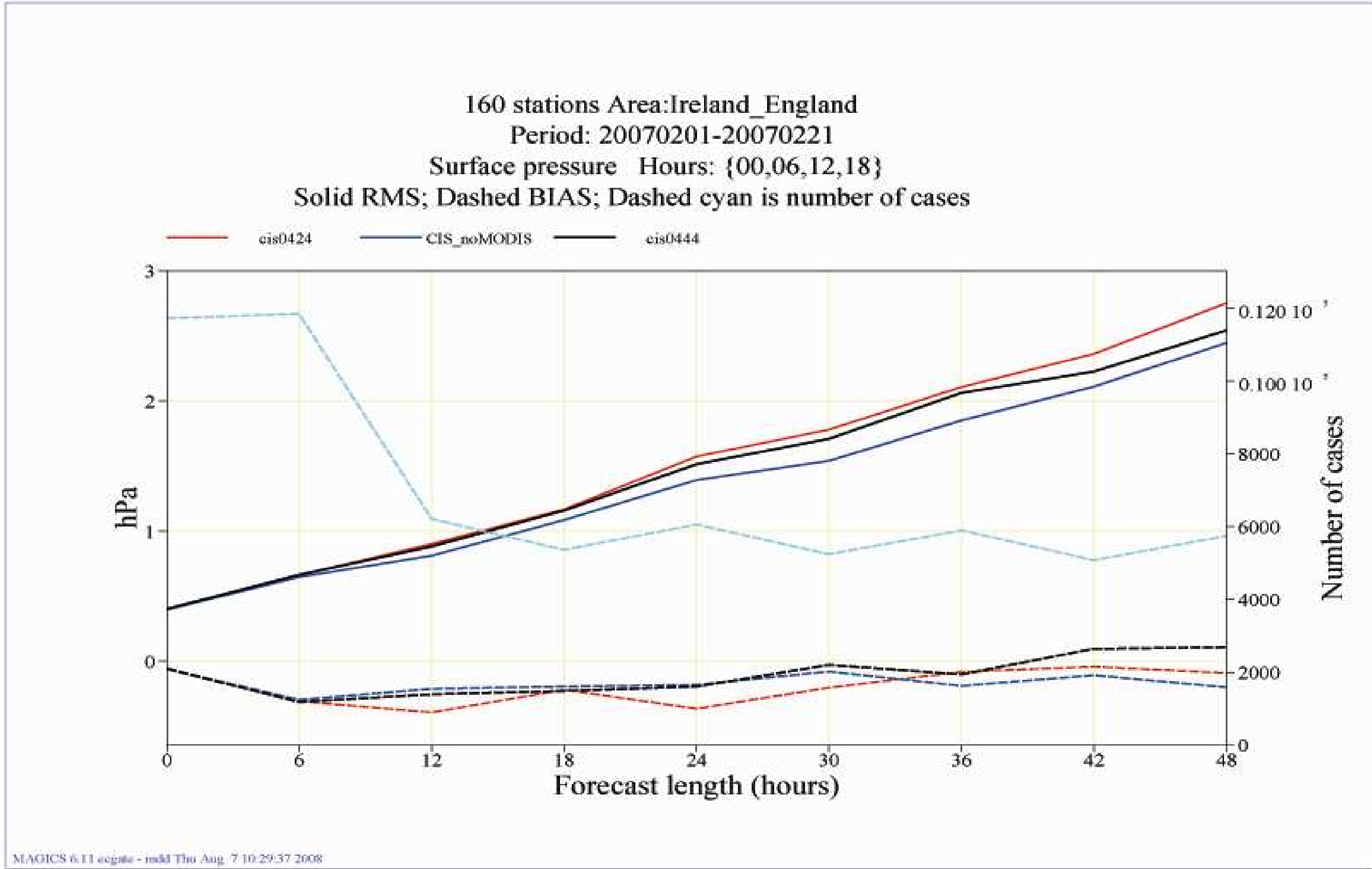
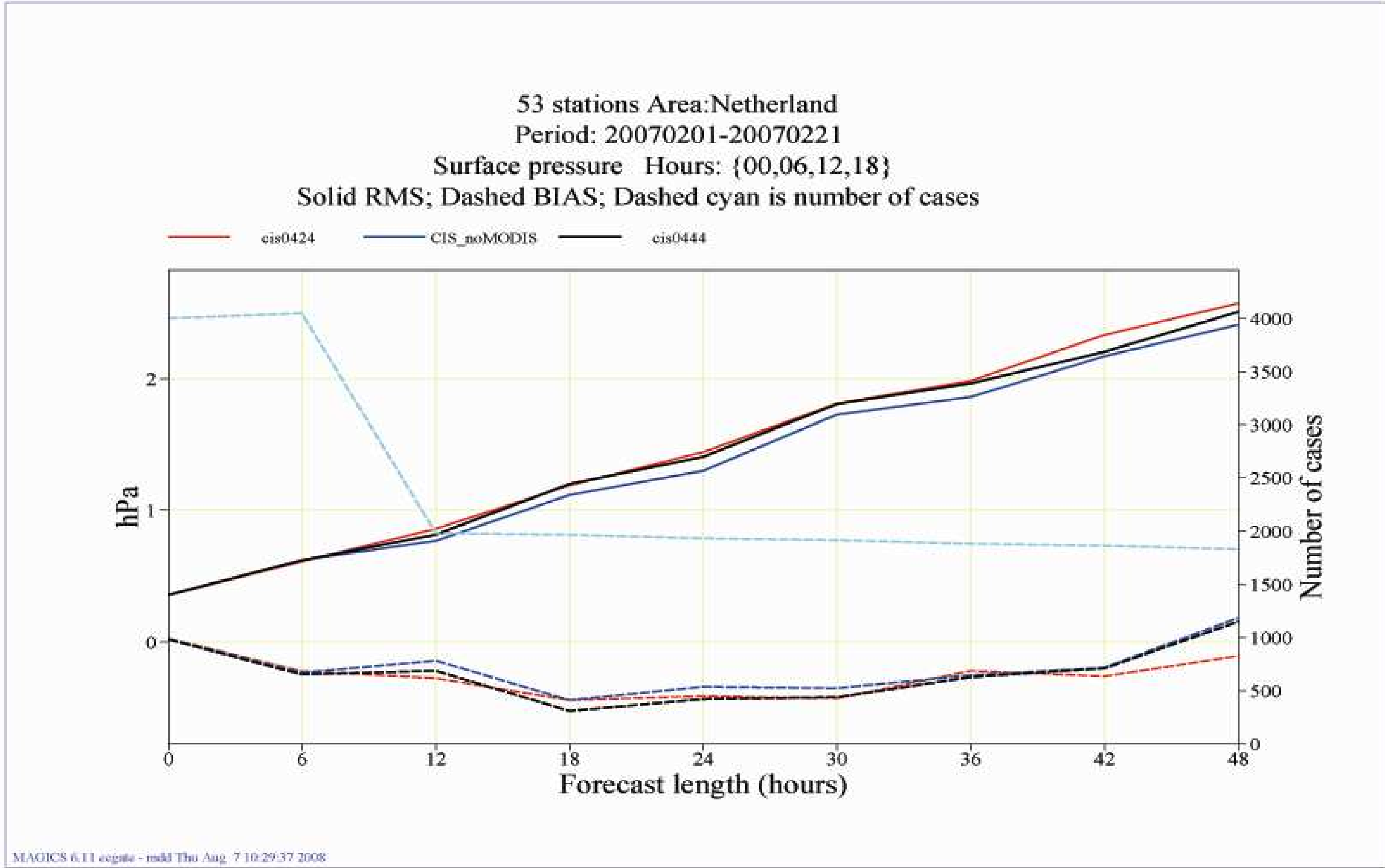
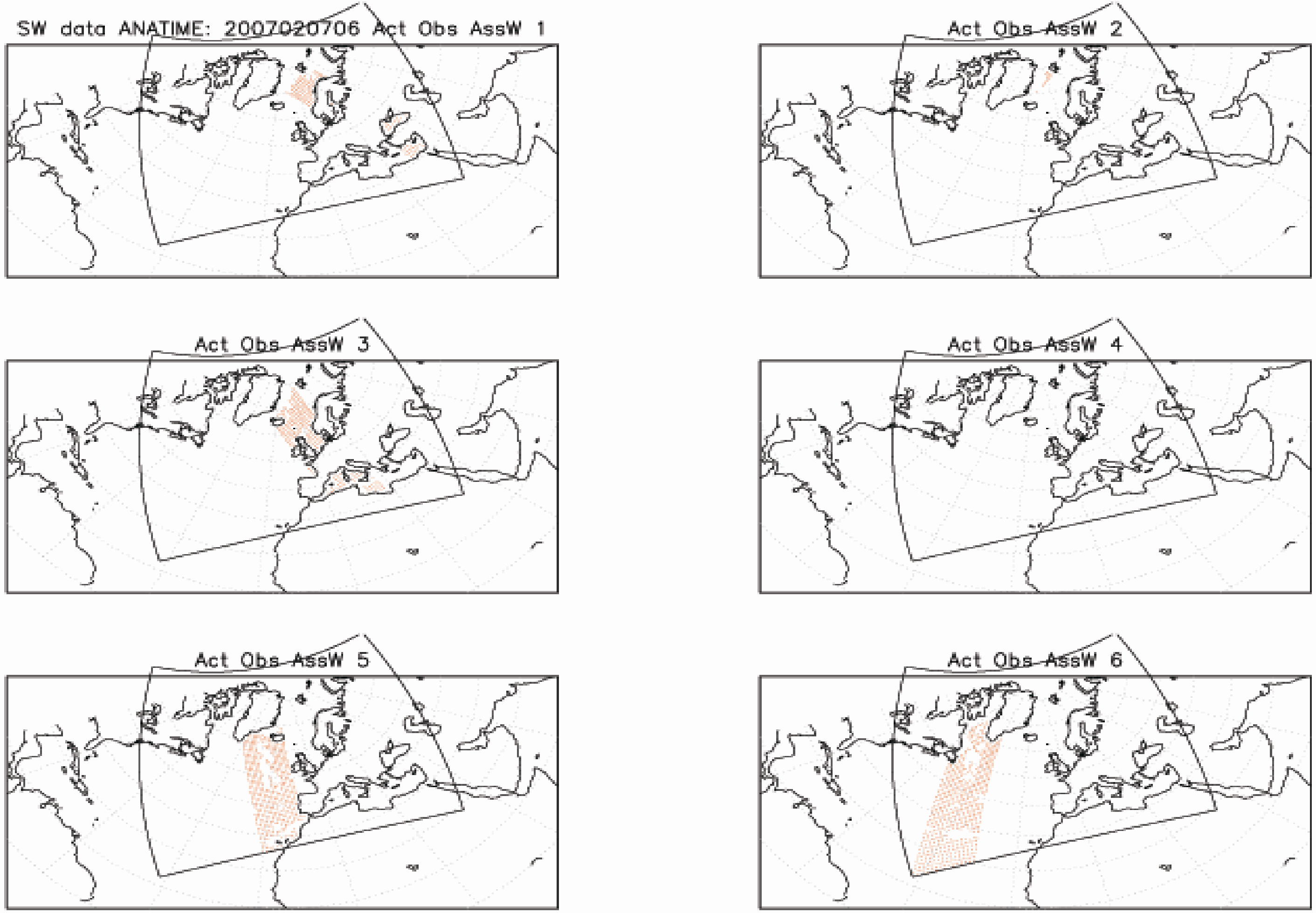


AMV data (SEVIRI and MODIS winds), Algorithm calibration



Other Facts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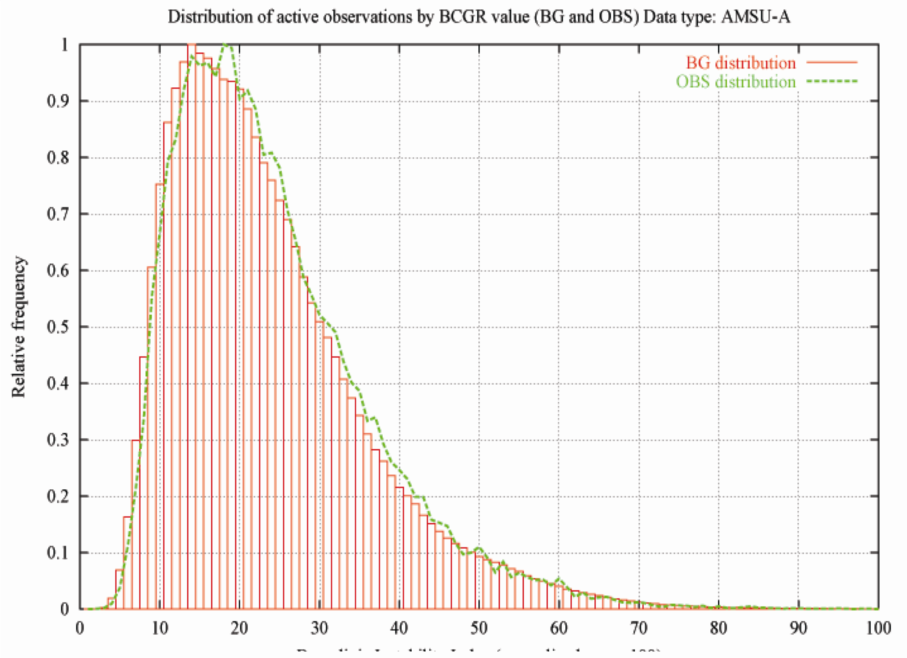
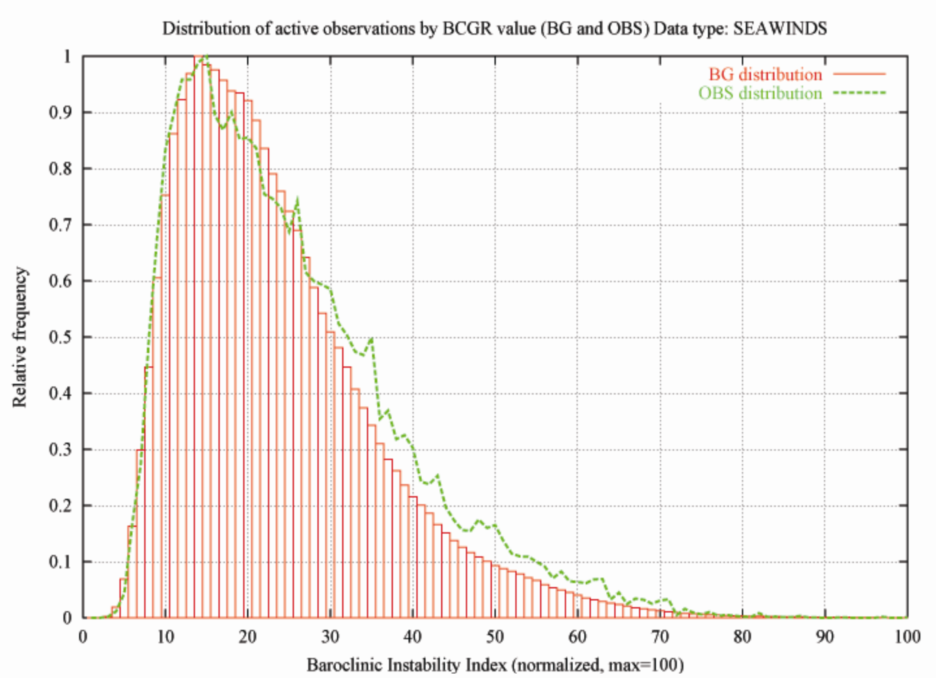
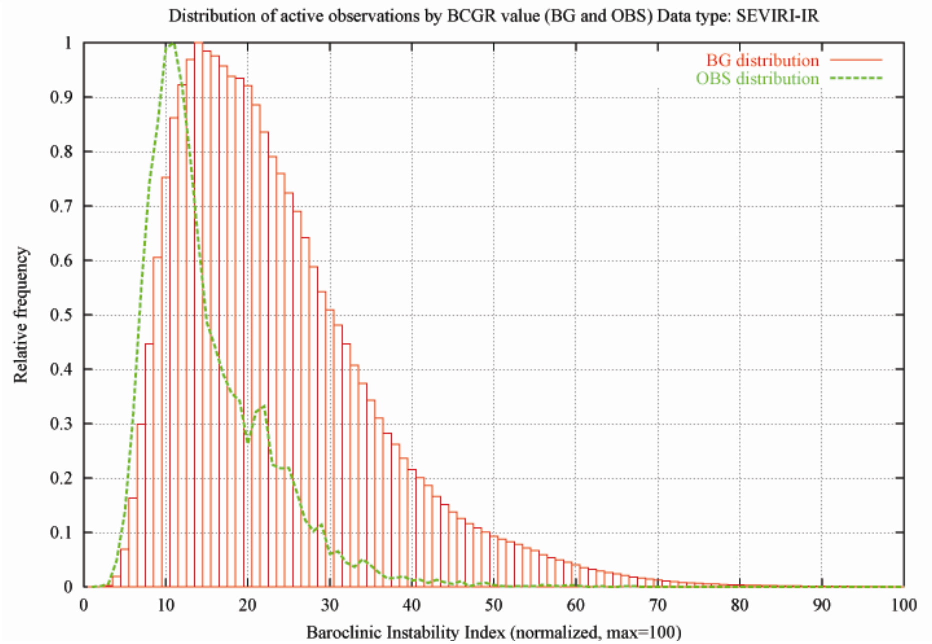
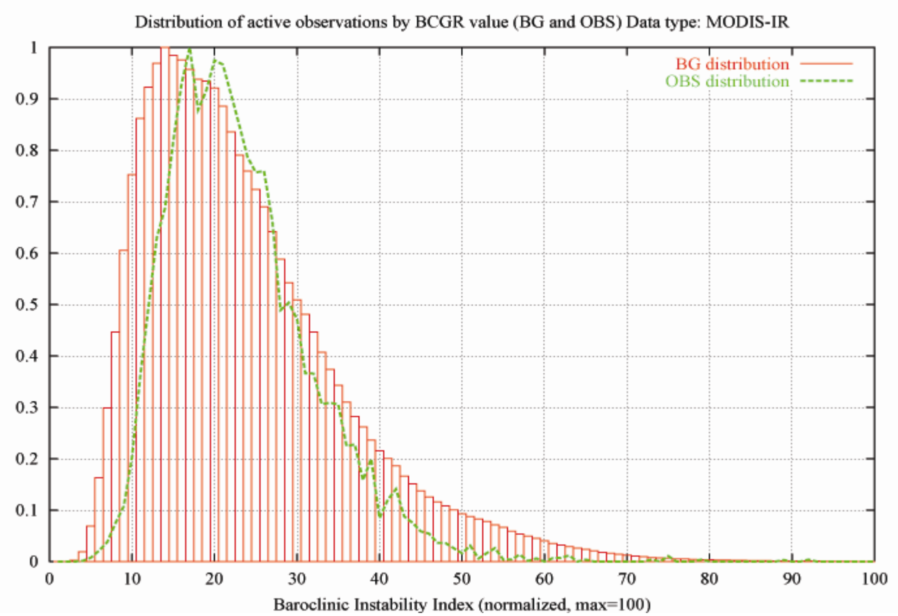
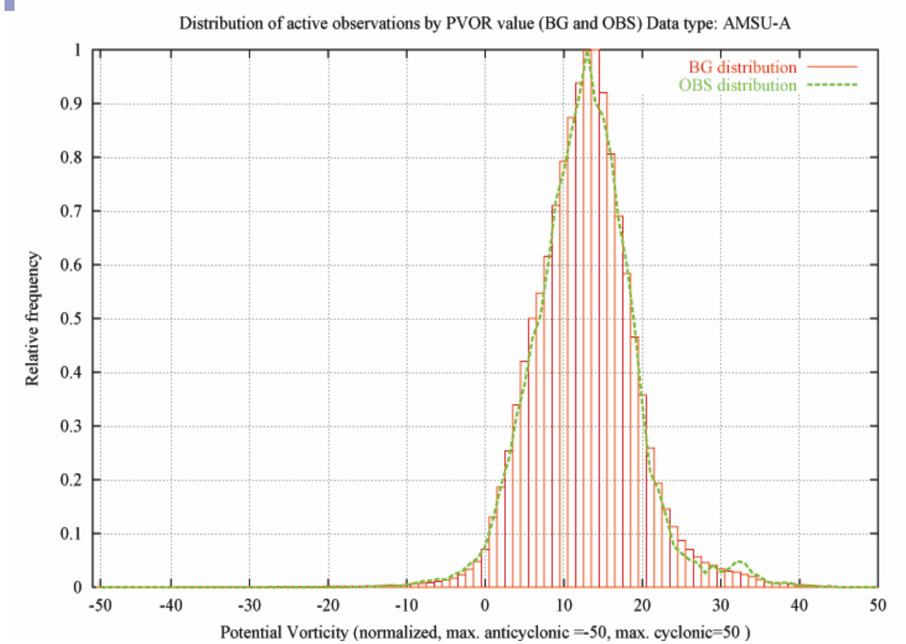
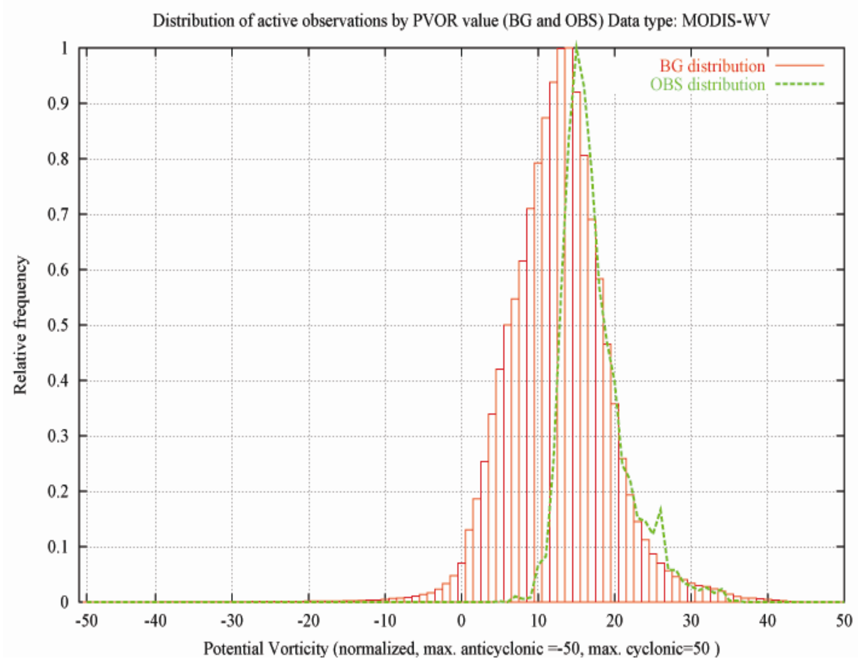

Distribution of active observations by BCGR value (BG and OBS) Data type: AMSU-A
BG distribution
OBS distribution
Relative frequency

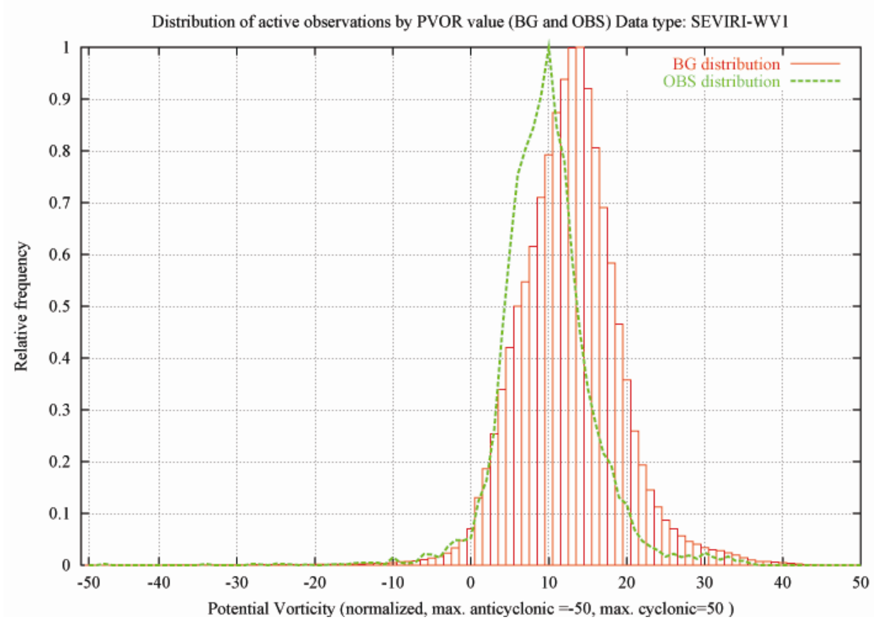

Distribution of active observations by BCGR value (BG and OBS) Data type: SEAWINDS
BG distribution
OBS distribution
Relative frequency
Baroclinic Instability Index (normalized, max=100)


Distribution of active observations by BCGR value (BG and OBS) Data type: SEVIRI-IR
BG distribution
OBS distribution
Relative frequency
Baroclinic Instability Index (normalized, max=100)


Distribution of active observations by BCGR value (BG and OBS) Data type: MODIS-IR
BG distribution
OBS distribution
Baroclinic Instability Index (normalized, max=100)


Distribution of active observations by PVOR value (BG and OBS) Data type: AMSU-A
BG distribution
OBS distribution
Relative frequency
Potential Vorticity (normalized, max. anticyclonic =-50, max. cyclonic=50)


Distribution of active observations by PVOR value (BG and OBS) Data type: MODIS-WV
BG distribution
OBS distribution
Relative frequency
Potential Vorticity (normalized, max. anticyclonic =-50, max. cyclonic=50)


Distribution of active observations by PVOR value (BG and OBS) Data type: SEVIRI-WV1
BG distribution
OBS distribution
Relative frequency
Potential Vorticity (normalized, max. anticyclonic =-50, max. cyclonic=50)

Some conclusions and prospects

• Even for a short period of one month, chosen at random, we have detected a serious failure in the forecast that must be attributed to poor use, or not use at all, of easily available and reliable satellite observations.

• All satellite observation types considered here contribute to avoid the bad performance. This is easy to understand because the analysis-forecast cycle makes the system auto-regressive and all observations help to avoid accumulation of errors. A minimum optimal set of observations is, of course, a different issue.

• Fine-tunning of the DA algorithm counts, at least for deterministic forecasts.

• There are several interesting lines of work and research in DA: flow-dependent methods, ensambles, etc ... but it is not clear to see how they can circumvent the problems that can arise from an inadequate use of observations.

• For the coming mesoscale DA systems, it will be very necessary to make an effort to bring other RS Observation systems, in particualr ground-based systems, to the same standards as those already reached by satellite systems.