The impact of hyperspectral infrared radiance observations on NWP forecasts

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with help from

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Introduction

- Introduction
- How to measure impact
- How are NWP centres using hyperspectral sounders?
- The impact of hyperspectral radiance assimilation in NWP
- The impact of atmospheric motion vector assimilation in NWP
- Final Thoughts

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Introduction

- Hyperspectral sonders have been used in NWP since the assimilation of AIRS radiances at ECMWF in 2003.
- Temperature, Humidity, Ozone, Surface and Cloud information are inferred in various NWP systems around the world.
- This presentation is an attempt to summarize the impact seen from these instruments

How Vincent Guidard summarized IASI impact in global NWP models at the 2016 IASI Conference

- What was said in IASI science plan (in the 1990's):
  - **IASI will improve forecasts by 1 day**
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  -
- What he said last year:
  - **No numbers !**

How Vincent Guidard summarized IASI impact in global NWP models at the 2016 IASI Conference

- What was said in IASI science plan (in the 1990's):

Obviously our models, data assimilation systems and number of observations being assimilated have improved greatly over the last 20 years.

We should take a short detour into how to measure impact.

Measuring Impact

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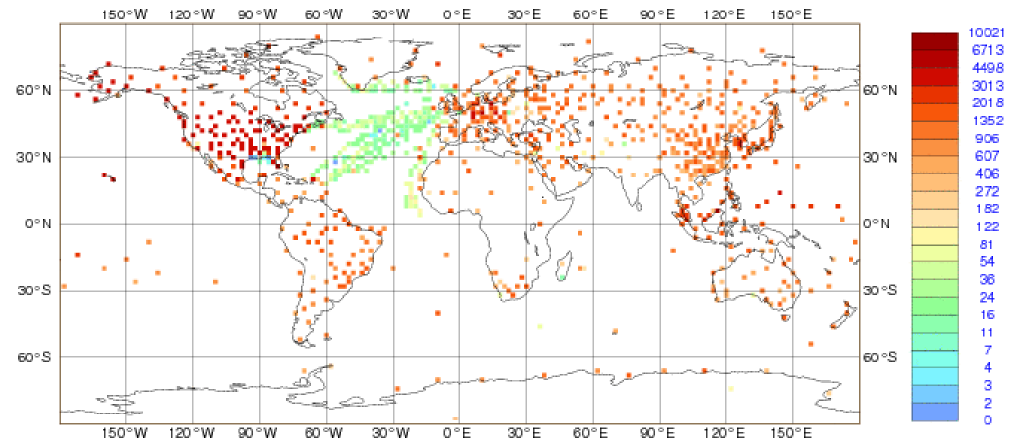
What is truth?

Observations?

Normally this means radiosondes (but also surface observations and aircraft are used). This means the statistics are biased towards densely populated regions in the northern temperate latitudes.



We should also (but usually don't) take account of the errors in the observations themselves

We can also use satellite observations (e.g., radiances) for verification as this would give more global sampling. However, comparisons in radiance space would be less intuitive.

What is truth?

Analyses?

The analysis should the best estimate of the atmospheric state through the combination of the information from the observations in the current and (through the forecast model) previous model cycles.

Also, given that the analysis does not suffer from the spatial sampling issues of conventional observations, the analysis seems to be the ideal "truth".

However, for forecast ranges of approximately three days or less it is found that forecast skill (and even the sign of that skill) is highly dependent on the verifying analysis (control, test, independent) used.

Also, for certain types of changes, if additional structure is added to the analysis fields this can be penalized in the usual forecast skill measures as it is easier to obtain a good fit to smooth rather than complex fields.

What is truth?

In practice, both observations and analyses are used in verifying forecast skill

Data Denial/Data Addition

- Data denial or Observation System Experiments (OSEs) are simply a way of investigating the impact of an observation or change by running full forecast experiments with and without the element to be tested.
- Alternatively can add instruments onto a data-poor system to see a more clear signal.
- OSEs are expensive to run, particularly at full operational resolution, and they need to be run for many forecast cycles (60 days is a typical number for global forecast systems) before statistically significant results are obtained.
- Individual case studies are generally not trusted as a way of demonstrating forecast impact because of the dominance of statistical fluctuations.
- Forecast impact scores are generally presented with error bars indicating statistical significance.
- Score are normally given in terms of differences between forecasts and “truth” in terms of RMS error or anomaly correlation coefficients (see next slide)

Forecast Sensitivity to Observations (FSO)

e **background**

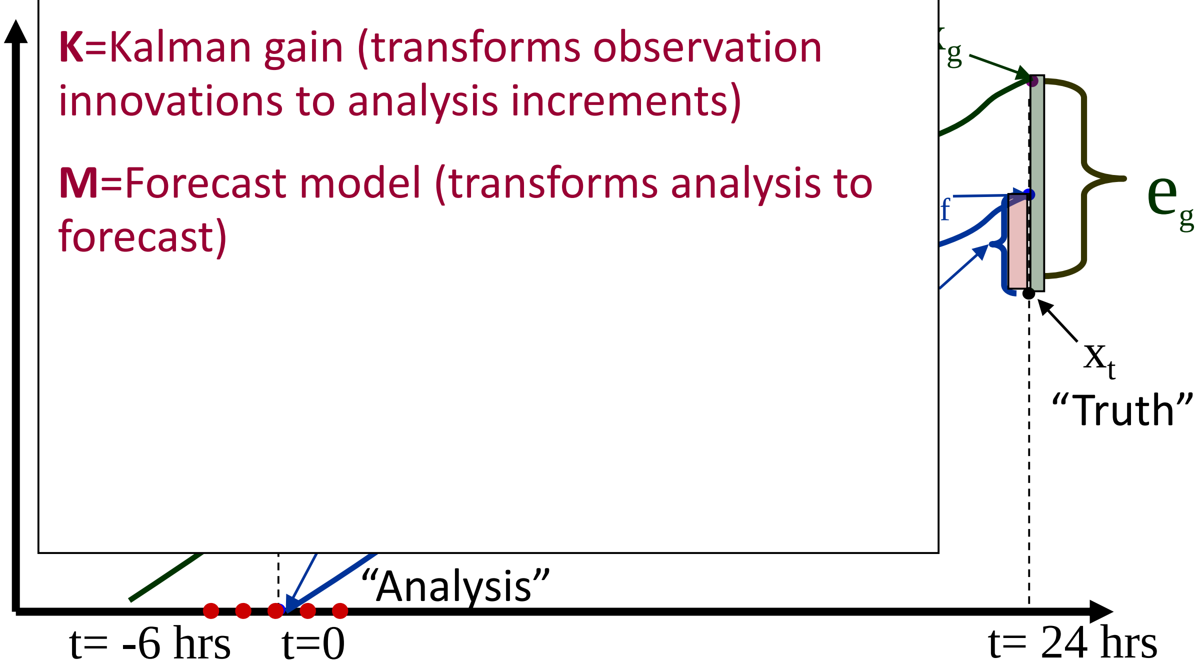
t **the new analysis**

$$(\mathbf{e}_f-\mathbf{e}_g)=\mathbf{M}\mathbf{k}\delta\mathbf{y}$$

$\delta\mathbf{y}$ = observation innovations ($\mathbf{y}-\mathbf{H}(\mathbf{x}_b)$)

K=Kalman gain (transforms observation innovations to analysis increments)

M=Forecast model (transforms analysis to forecast)



Langland and Baker (Tellus, 2004), Gelaro et al (2007), Morneau et al. (2006)

Forecast Sensitivity to Observations (FSO)

We want to get the sensitivity of the forecast to the observation increments so we apply the tangent linear model to

$\mathbf{C}(e_f - e_g) = \mathbf{CMK}\delta\mathbf{y}$:

$$\boldsymbol{\delta}\mathbf{e}_{f\text{-}g} = ½[\mathbf{MK}\boldsymbol{\delta}\mathbf{y}]^T\mathbf{C}(e_f - e_g) = ½\ \boldsymbol{\delta}\mathbf{y}^T\mathbf{M}^T\mathbf{K}^T\mathbf{C}(e_f - e_g)$$

Forecast Sensitivity to Observations (FSO)

We want to get the sensitivity of the forecast to the observation increments so we apply the tangent linear model to $\mathbf{C}(e_f - e_g) = \mathbf{CMK}\delta\mathbf{y}$:

$$\boldsymbol{\delta}\mathbf{e}_{f\text{-}g} = \tfrac{1}{2}[\mathbf{MK}\boldsymbol{\delta}\mathbf{y}]^T\mathbf{C}(e_f - e_g) = \tfrac{1}{2}\,\boldsymbol{\delta}\mathbf{y}^T\mathbf{M}^T\mathbf{K}^T\mathbf{C}(e_f - e_g)$$

Adjoint of linearized forecast model* ($\mathbf{M}^T$)

Adjoint of data assimilation scheme ($\mathbf{K}^T$)

Usually these both require approximations to be made (including linearity) and so this method is limited to forecast ranges of less than ~48 hours.

*Already required if running 4DVar

Forecast Sensitivity to Observations (FSO)

For Ensemble Kalman Filter (EnKF) data assimilation, this can be written as:

$$\boldsymbol{\delta e_{f\text{-}g} = \delta y^{T} R^{-1} (H X_a) X_f^{T} C (e_f - e_g)}$$

Where K is the number of ensembles, $\mathbf{X}_a$ and $\mathbf{X}_b$ are the ensemble perturbations of the analysis and forecast respectively and **H** is the linearized observation operator.
This therefore does not require an adjoint of the forecast model.

However for any reasonably-sized sample of ensembles, localization is required which also puts an approximate upper limit on the validity of this method at ~48hours.

Advantages and Disadvantages of FSO

- Advantages
  - Can infer the impact of observations to whatever level of detail is required (e.g. ob by ob, channel by channel) without having to re-run the full system repeatedly.
    - Useful for determining relative impact of observations and for quality control of bad observations.
  - Allows the impact of observations on the forecast to be monitored on a daily basis.
- Disadvantages
  - Limited to short-range forecasts
    - So there is sensitivity to the accuracy of the verifying analysis
  - Impact is always in the context of the total observing system as used
    - Forecast impacts of an observation type may change as other observations are added/removed.

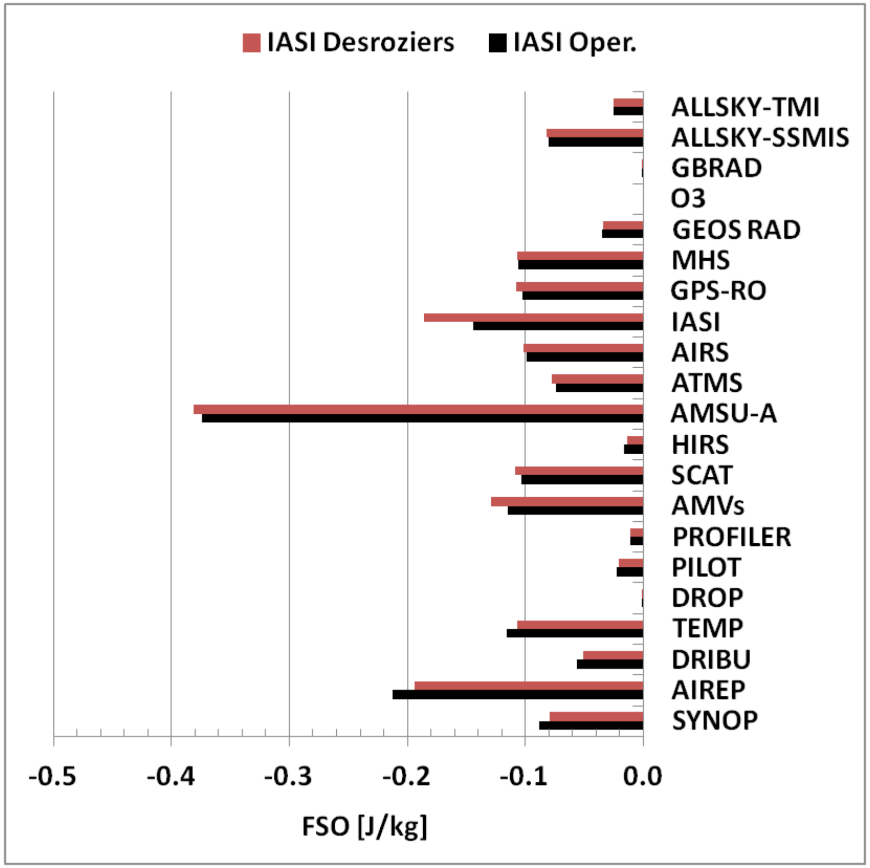
Every American Presentation should have a School Bus Analogy…

Fitting an extra person (observation) on the bus will mean they get their share of the space (impact)…
… but the bus does (may) not get any bigger

FSO sensitivity to observation error

Impact measured using operational observation error model (values 0.4K to 2K)

Impact measured using unrealistic observation error model (unscaled Desrosier values)



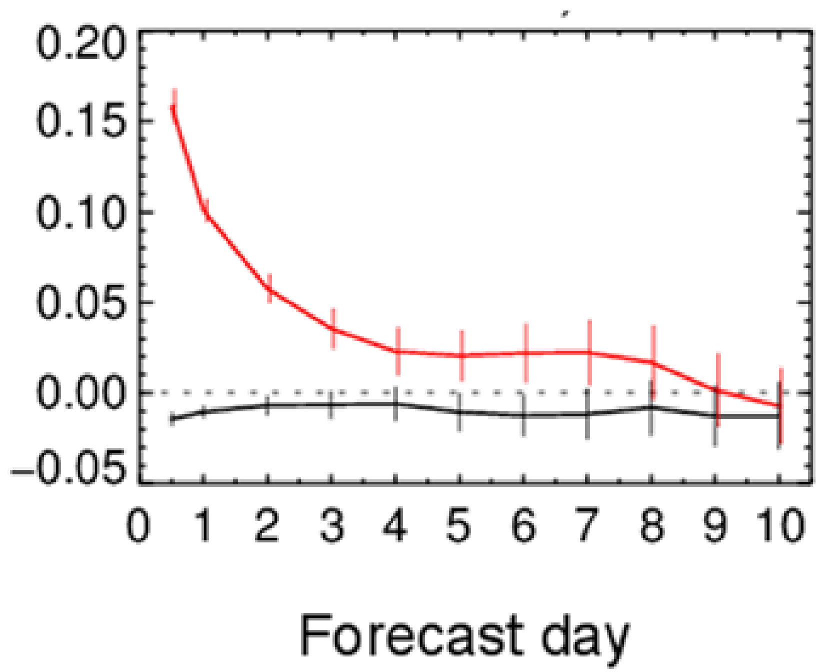
OSE sensitivity to observation error

Impact measured using operational observation error model (values 0.4K to 2K)

Impact measured using unrealistic observation error model (unscaled Desrosier values)

RMSE(IASI) minus RMSE(NO-IASI)

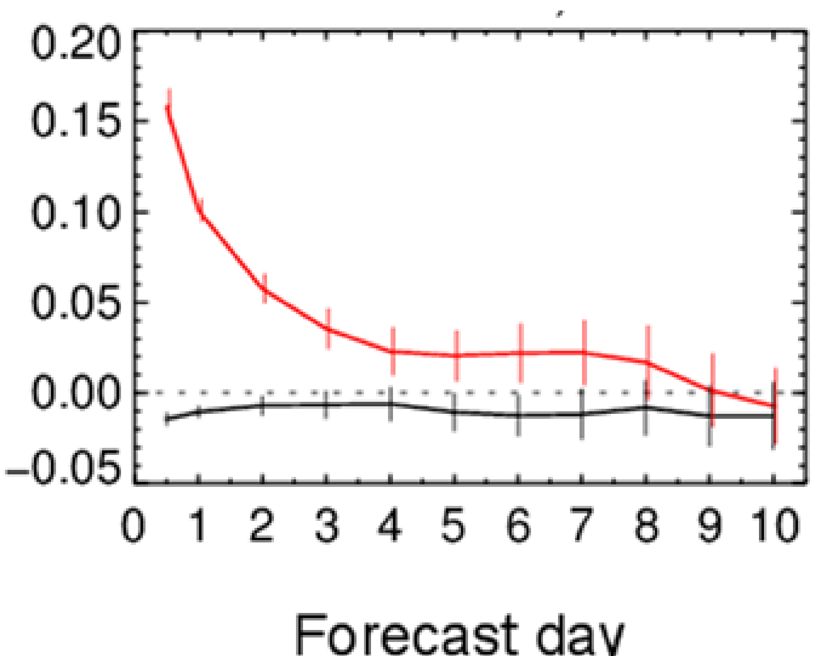
RMSE(IASI*) minus RMSE(NO-IASI)

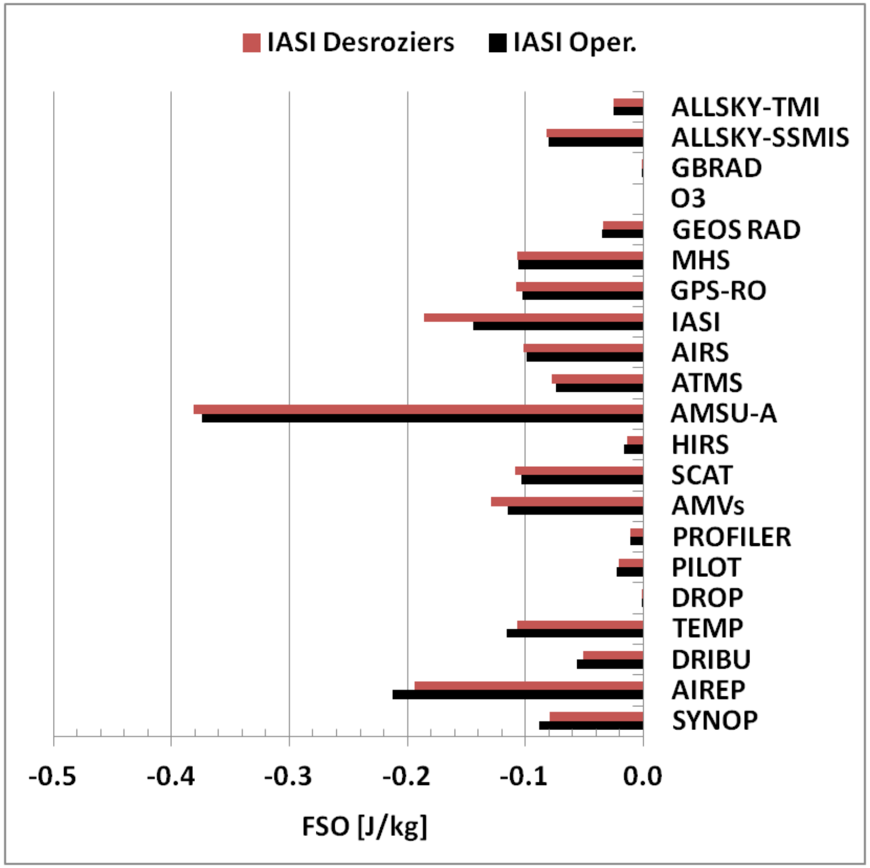


Do results of OSE and FSO disagree ?

RMSE(IASI) minus RMSE(NO-IASI)

RMSE(IASI*) minus RMSE(NO-IASI)





How do we use hyperspectral sounders

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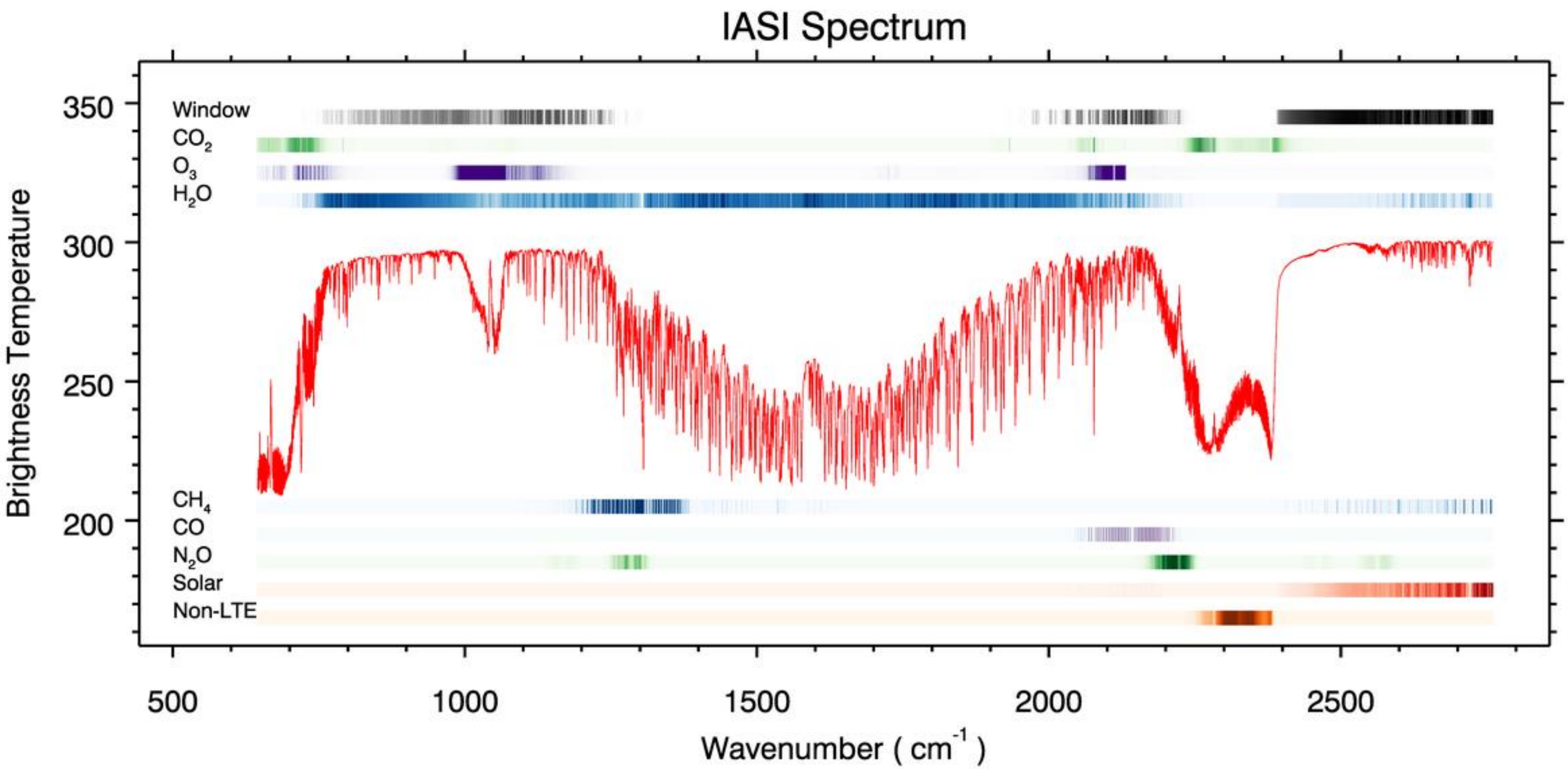
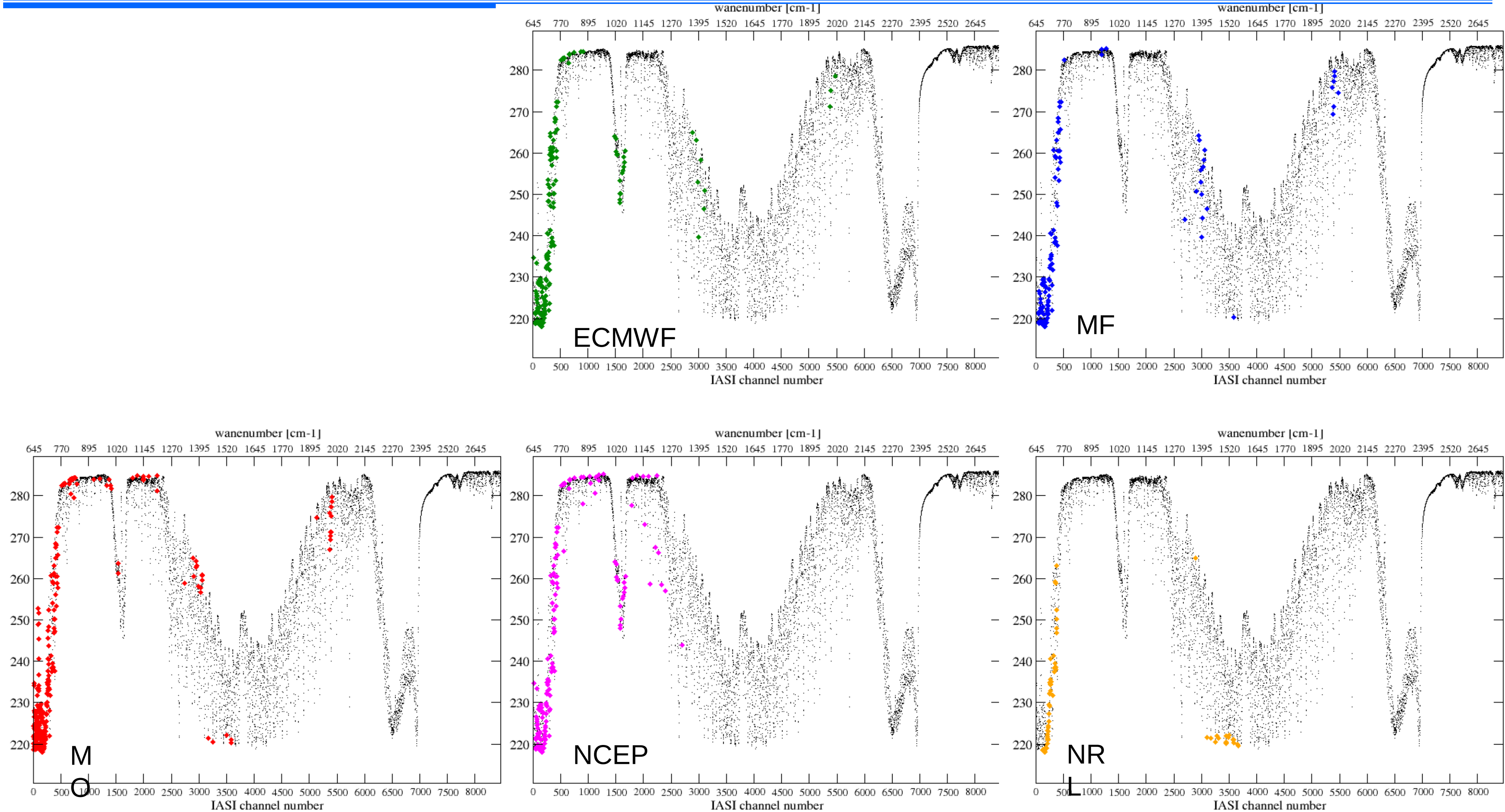
Hyperspectral spectrum



Channels used in Global NWP models



Use of IASI Varies Greatly

- Use of water vapor channels
- Use of ozone channels
- Surface emissivity characterization
- Correlated observation errors
- The use of a 1DVar pre-processor
- Use of cloudy scenes

Usage of Hyperspectral Sounders in NWP is summarized on the ITSC website

https://groups.ssec.wisc.edu/groups/itwg/nwp

NWP Survey http://www.emc.ncep.noaa.gov/gc_wmb/acollard/NWP_Survey.html

Use of Sounders in NWP Survey (Six Tables)

Click through all the tables using tabs at the bottom of the screen

NWP Survey

Table 5: Use of AIRS, IASI and CrIS Radiances in N

	AIRS						
	15 microns (1)		Window + O3 (2)		H2O (3)		Short W
Centre	Land	Ocean	Land	Ocean	Land	Ocean	Land
EC(Canada)	4	19	0	10	26	33	0
ECMWF (Europe)	48	81	0	32	0	7	0
met.no (Norway)							
FNMOC/NRL (USA)	30	50	0	0	0	11	0
DWD (Germany)	0	0	0	0	0	0	0
Met Office (UK)	46	72	0	19	0	45	0
DMI (Denmark)							
JMA (Japan)	0	76	0	0	0	0	0
Meteo France (France)	56	72	0	0	0	0	0
NCEP (USA)	75	75	11	11	20	20	14
BoM (Australia)	46	73	0	19	0	47	0
CPTEC/INPE(Brazil)							
SMHI (Sweden)							

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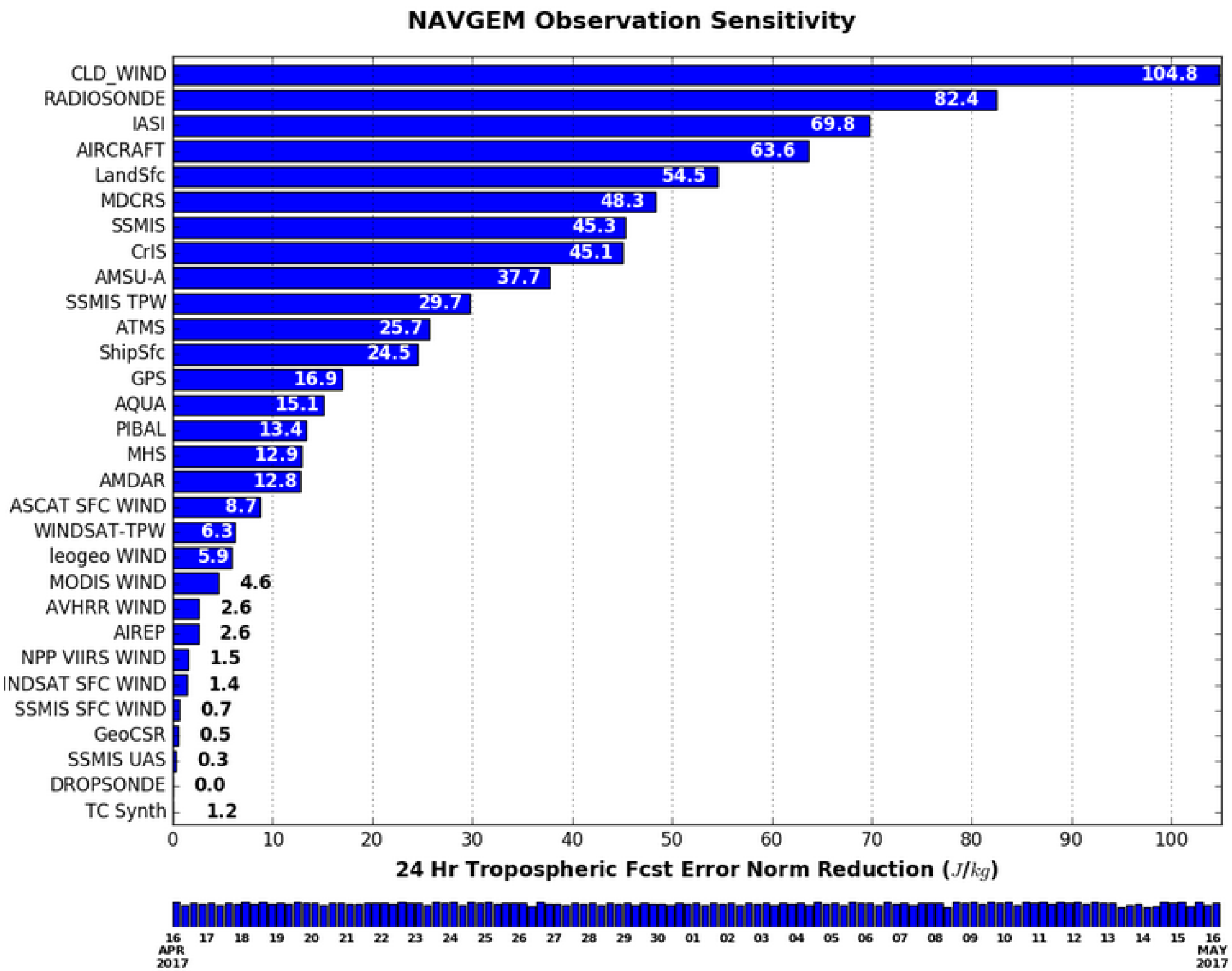
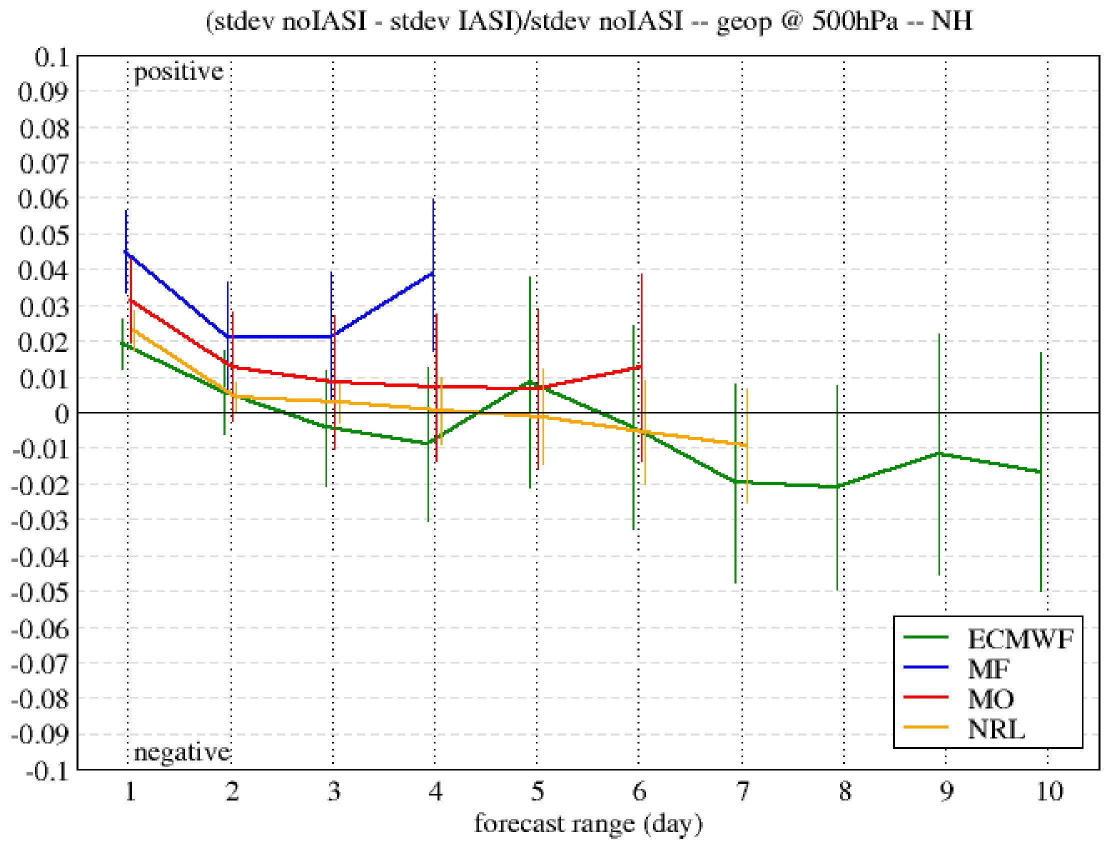
NRL FSO

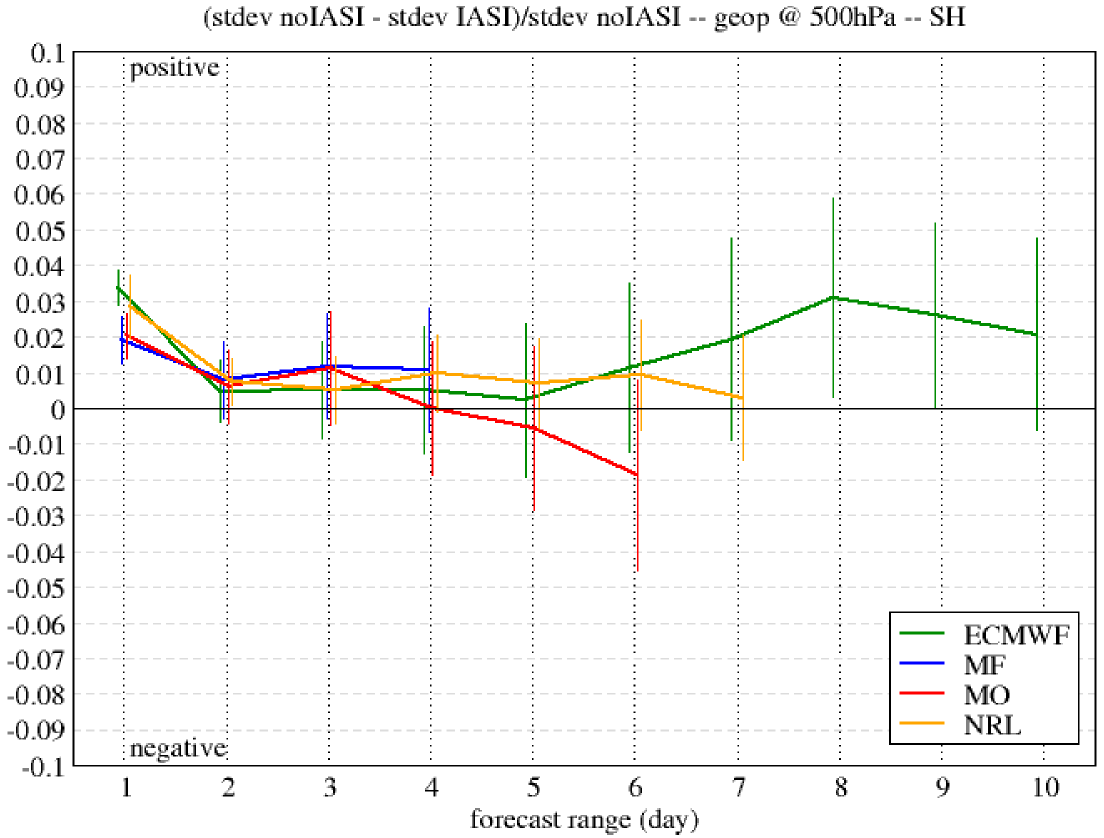


NAVGEM Observation Sensitivity
CLD_WIND 104.8
RADIOSONDE 82.4
IASI 69.8
AIRCRAFT 63.6
LandSfc 54.5
MDCRS 48.3
SSMIS 45.3
CrIS 45.1
AMSU-A 37.7
SSMIS TPW 29.7
ATMS 25.7
ShipSfc 24.5
GPS 16.9
AQUA 15.1
PIBAL 13.4
MHS 12.9
AMDAR 12.8
ASCAT SFC WIND 8.7
WINDSAT-TPW 6.3
leogeo WIND 5.9
MODIS WIND 4.6
AVHRR WIND 2.6
AIREP 2.6
NPP VIIRS WIND 1.5
INDSAT SFC WIND 1.4
SSMIS SFC WIND 0.7
GeoCSR 0.5
SSMIS UAS 0.3
DROPSONDE 0.0
TC Synth 1.2
0 10 20 30 40 50 60 70 80 90 100
24 Hr Tropospheric Fcst Error Norm Reduction (J/kg)
16 APR 2017
16 MAY 2017

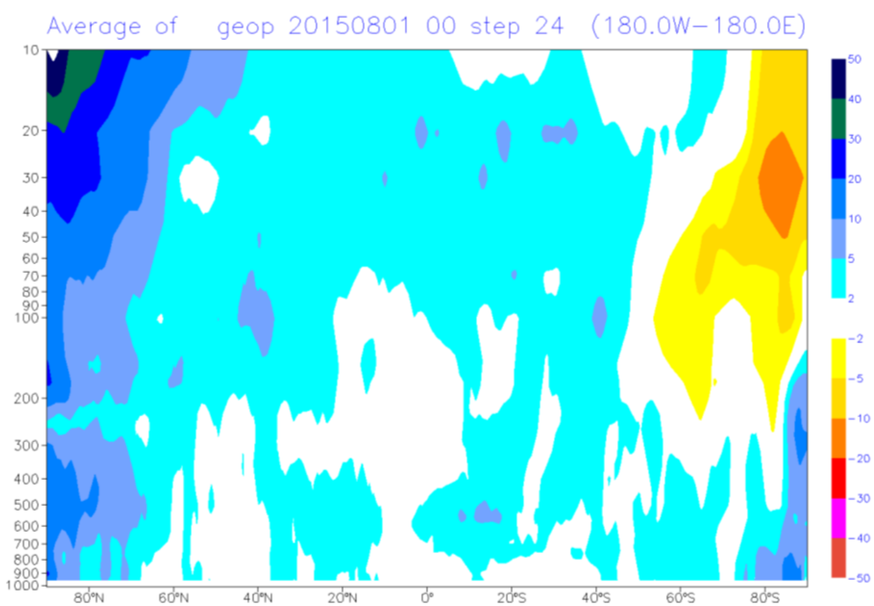
IASI Intercomparison:
Relative reduction of standard deviation wrt to control analysis – Z @ 500 hPa NH

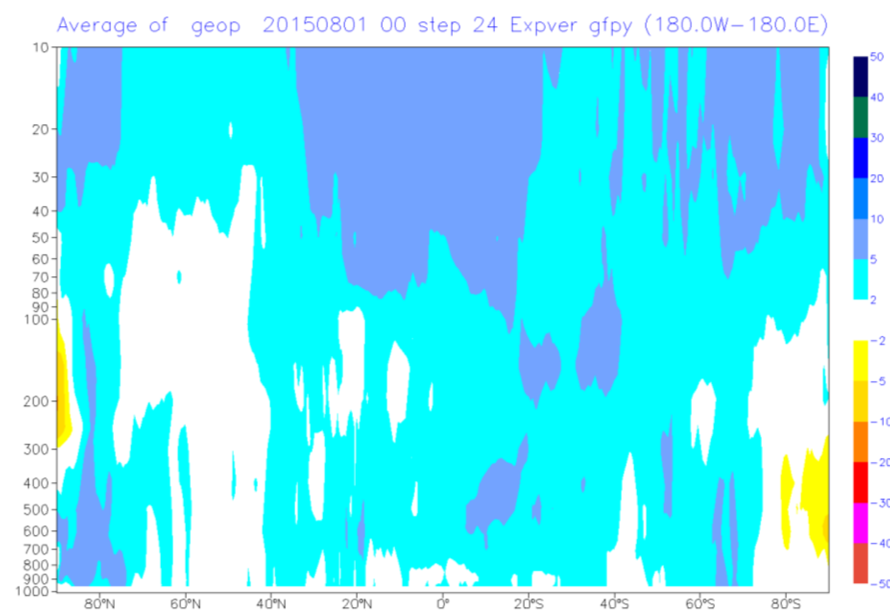


IASI Intercomparison: Relative reduction of standard deviation wrt to control analysis – Z @ 500 hPa SH



Relative reduction of standard deviation wrt to control analysis – Z – D+1 – zonal average

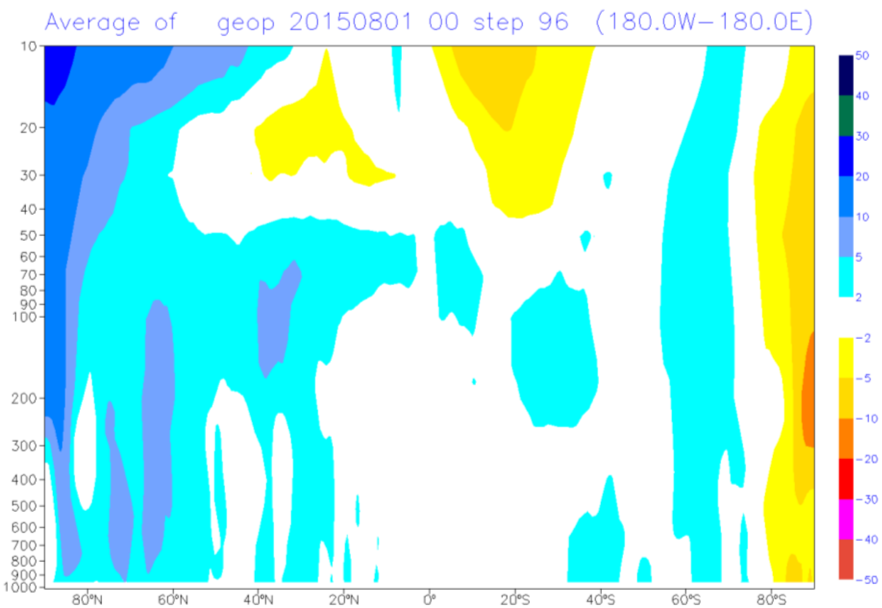




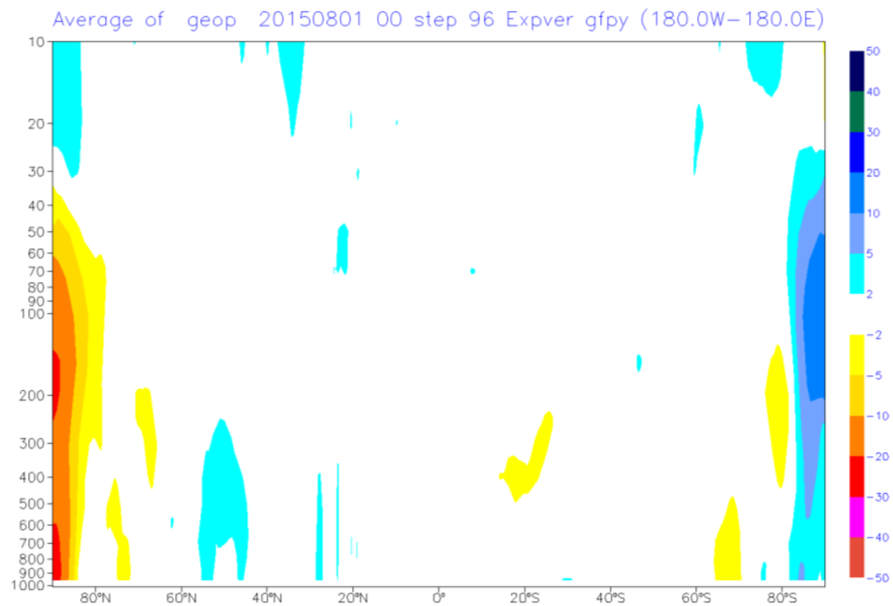
Meteo-France

ECMWF

Relative reduction of standard deviation wrt to control analysis – Z – D+4 – zonal average

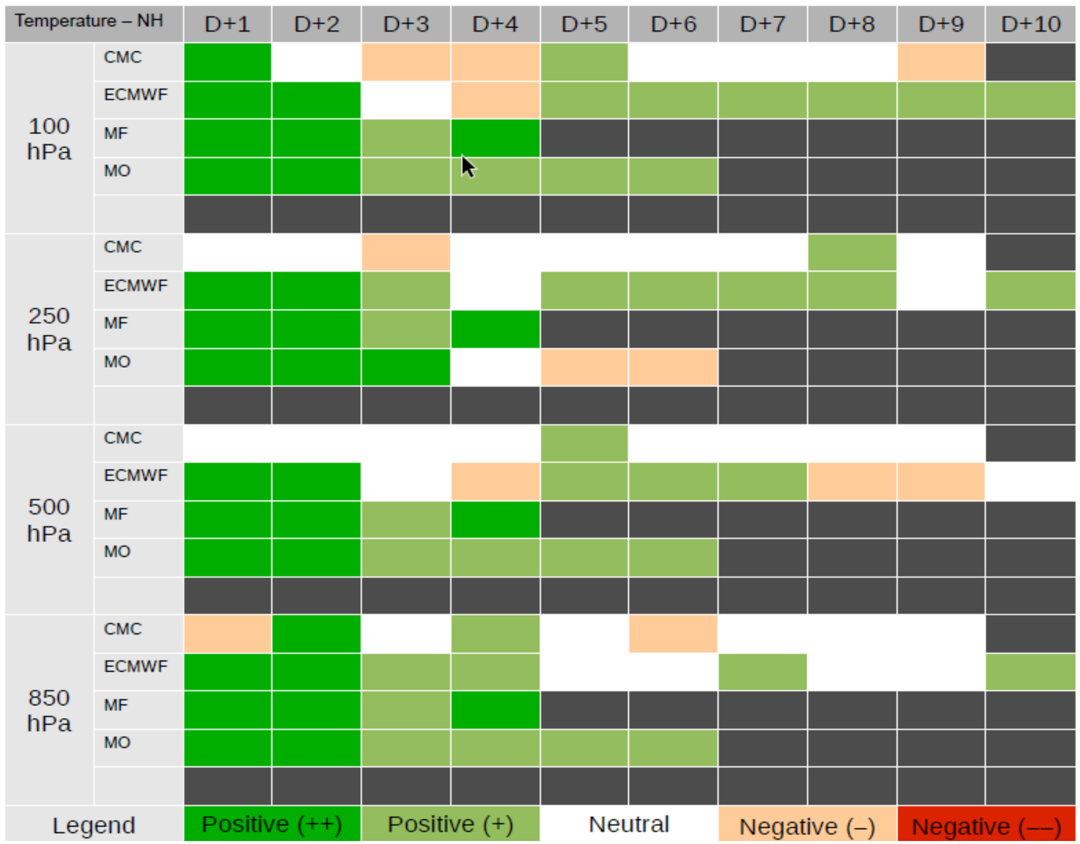


Meteo-France

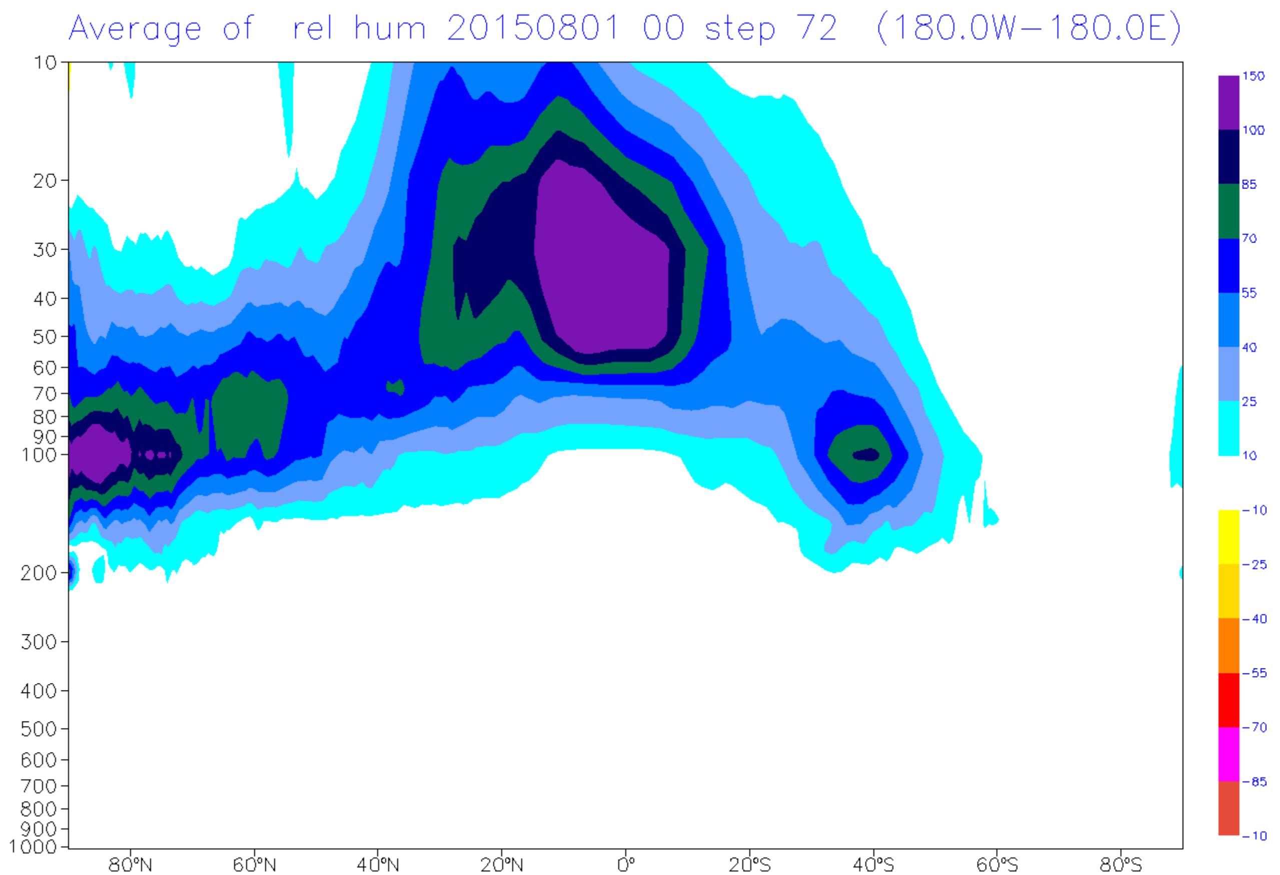


ECMWF

From Vincent's poster at the EUMETSAT conference



Relative reduction of standard deviation wrt to control analysis – RH – D+3 – zonal average



Meteo-France

JMA CrIS Impact

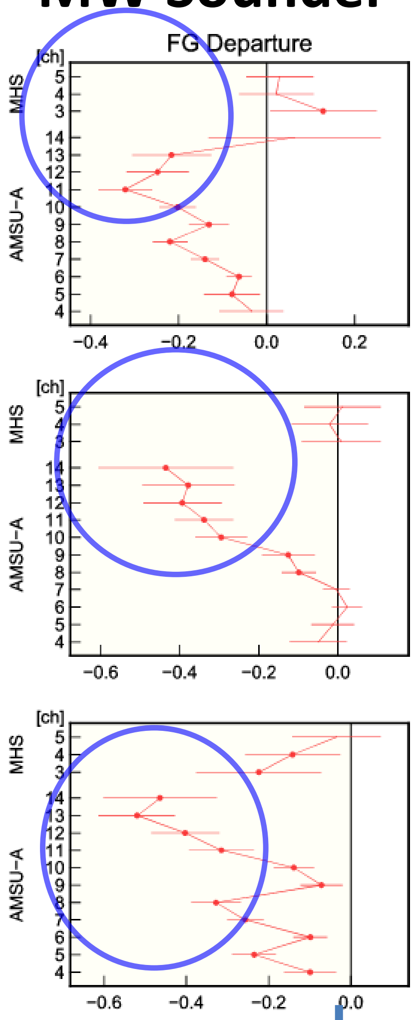
FG fit to observations on assimilating CrIS at JMA

MW Sounder

NH

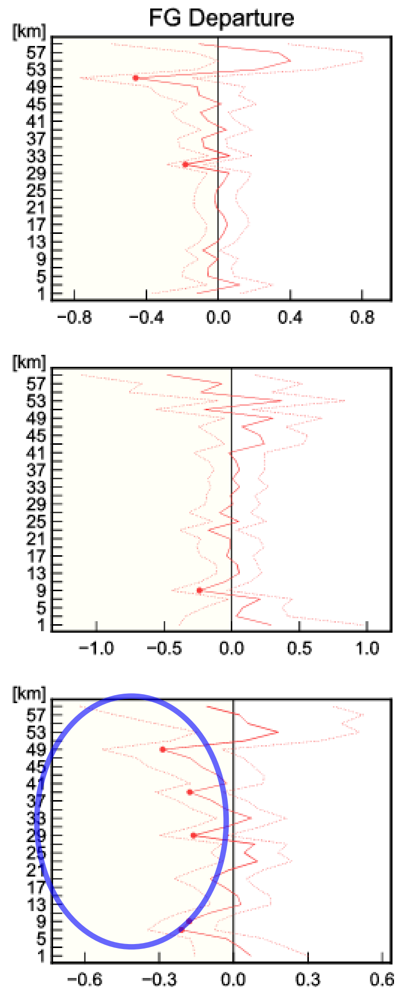
TR

SH



better

GNSS-RO



Changes of standard deviation of FG departure .

Improvement of temperature sensitive channels of AMSU-A (stratosphere and upper troposphere).

Large improvements of GNSS-RO in the South Hemisphere.

AMSU-A and GNSS-RO showed consistent positive results.

Negative value indicates improvements

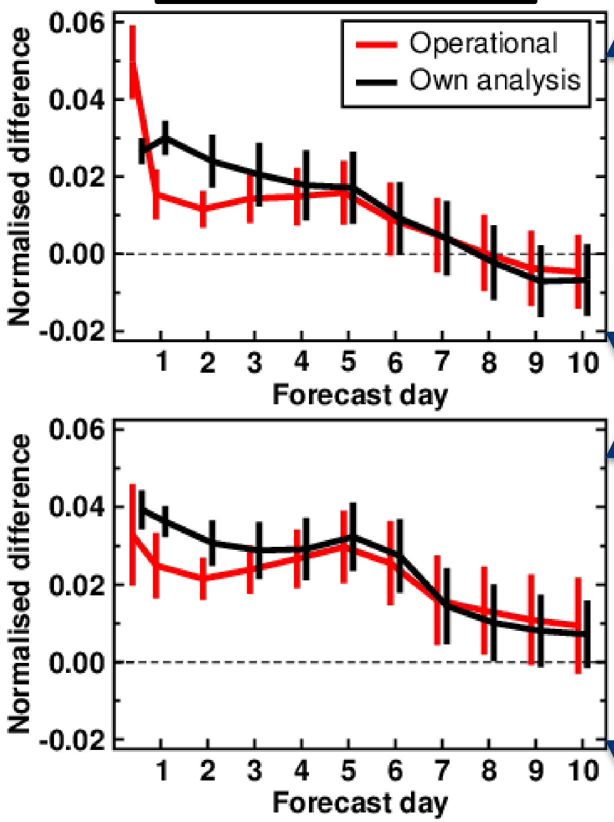
ECMWF Impacts

"No IR sounders" – "Full operational system" comparison at ECMWF

Z500 RMSE

N. Hem.

S. Hem.



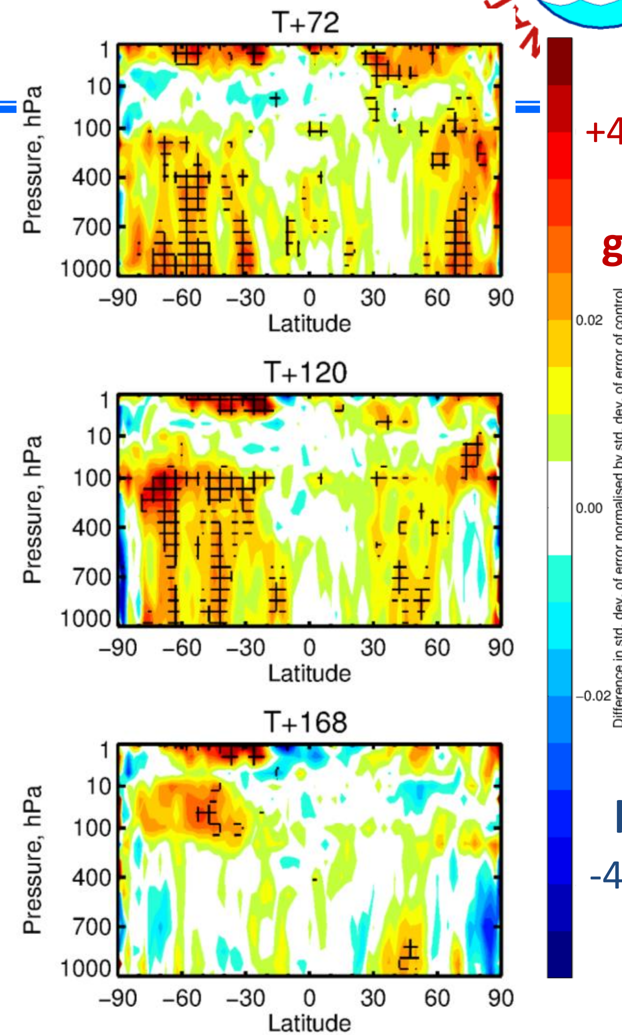
IR good

IR bad

IR good

IR bad

Vector wind error St.Dev.



+4%

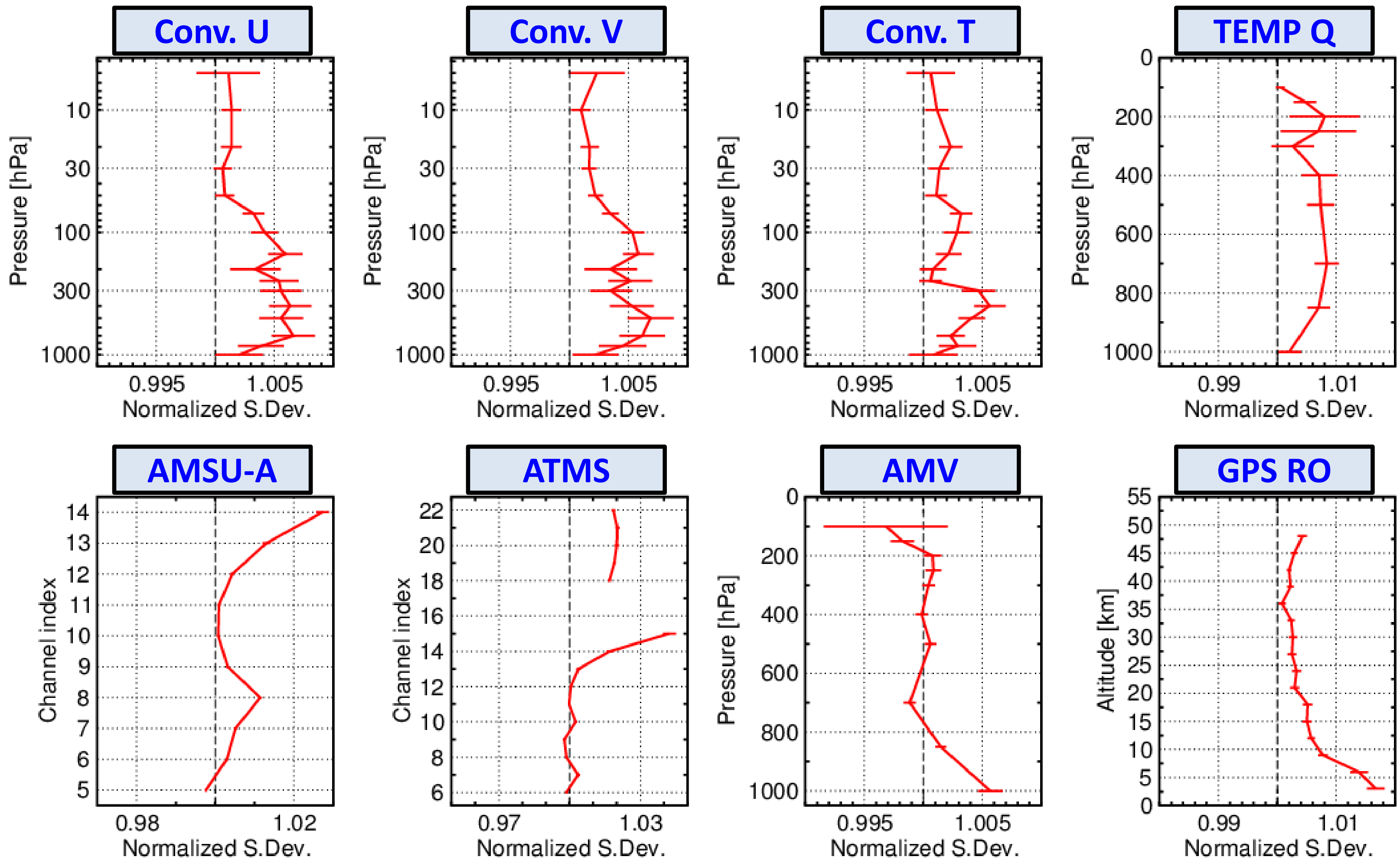
IR good

IR bad

-4%

Scores cover a total of 9 months in Nov 2015 – Sep 2016

Impact of removing all IR data on the background fits

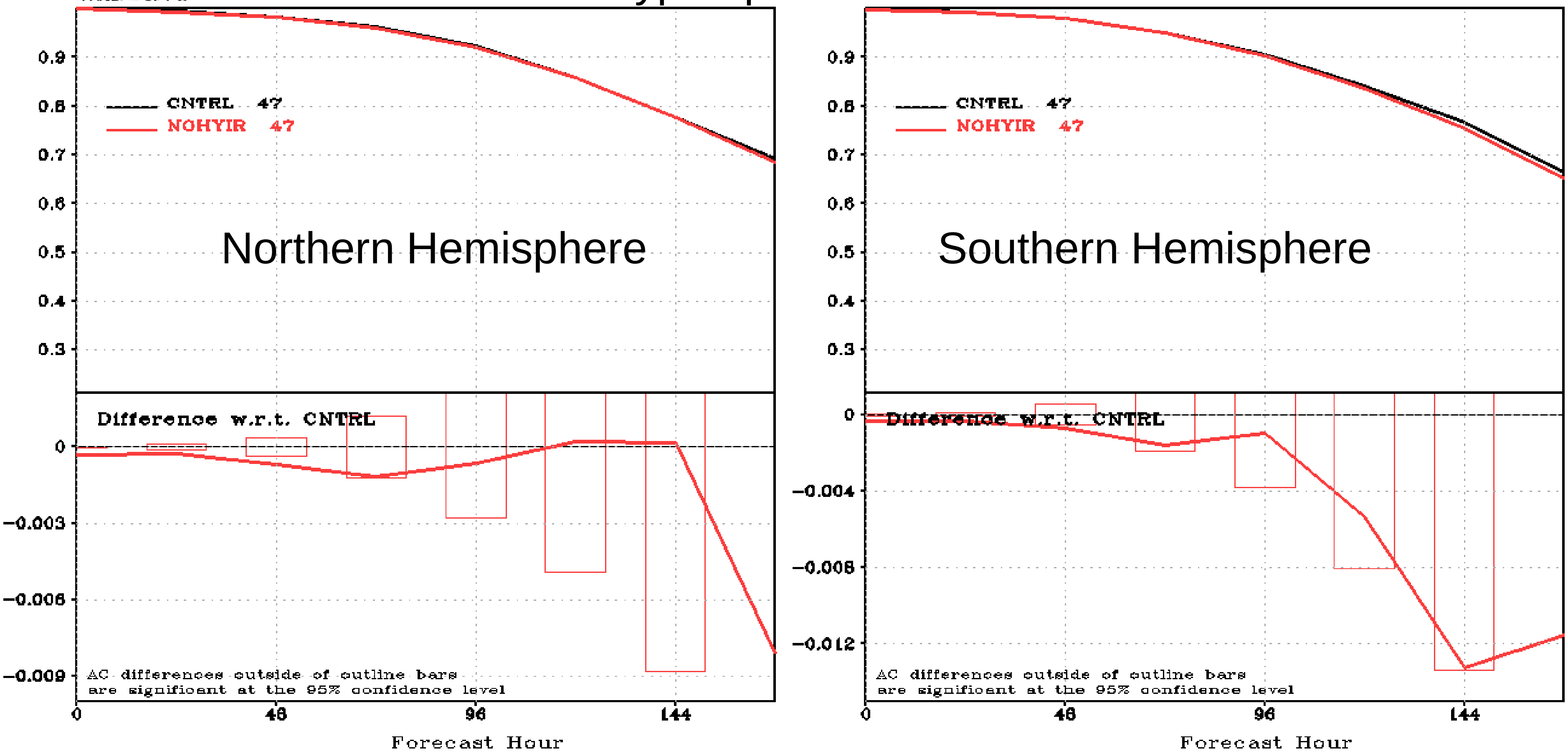


IR bad ⟵ ⟶ IR good

Scores cover a total of 9 months in Nov 2015 – Sep 2016

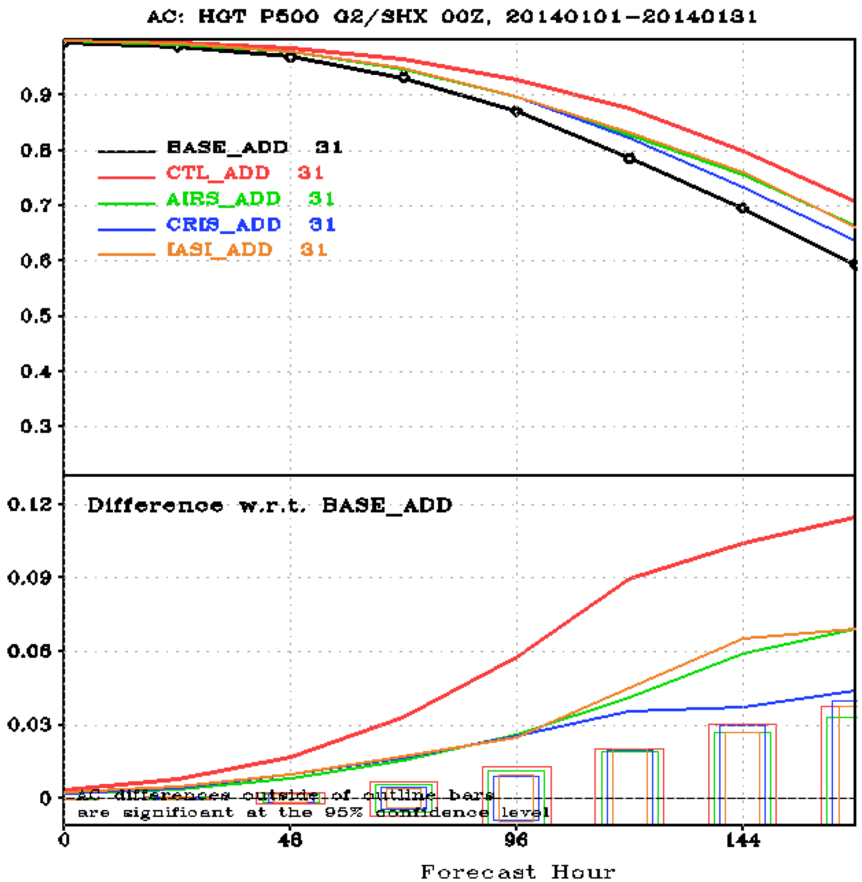
NCEP Data Denials

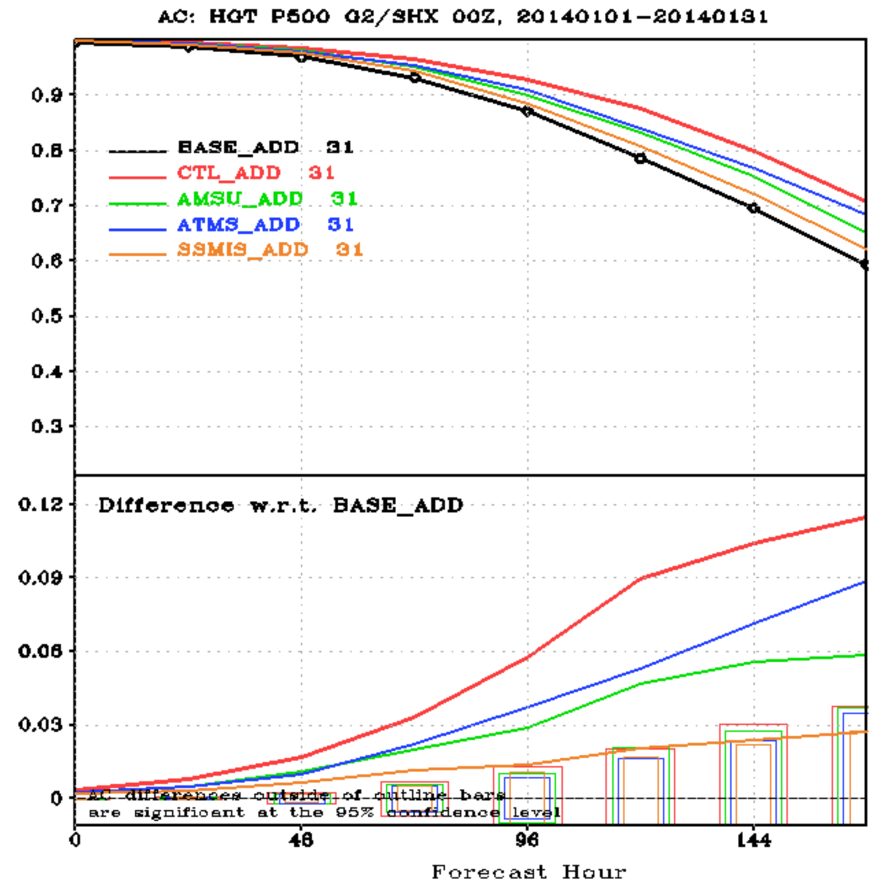
500 hPa Anomaly Correlations
15 Aug – 30 Sep 2010
No Hyperspectral Infrared



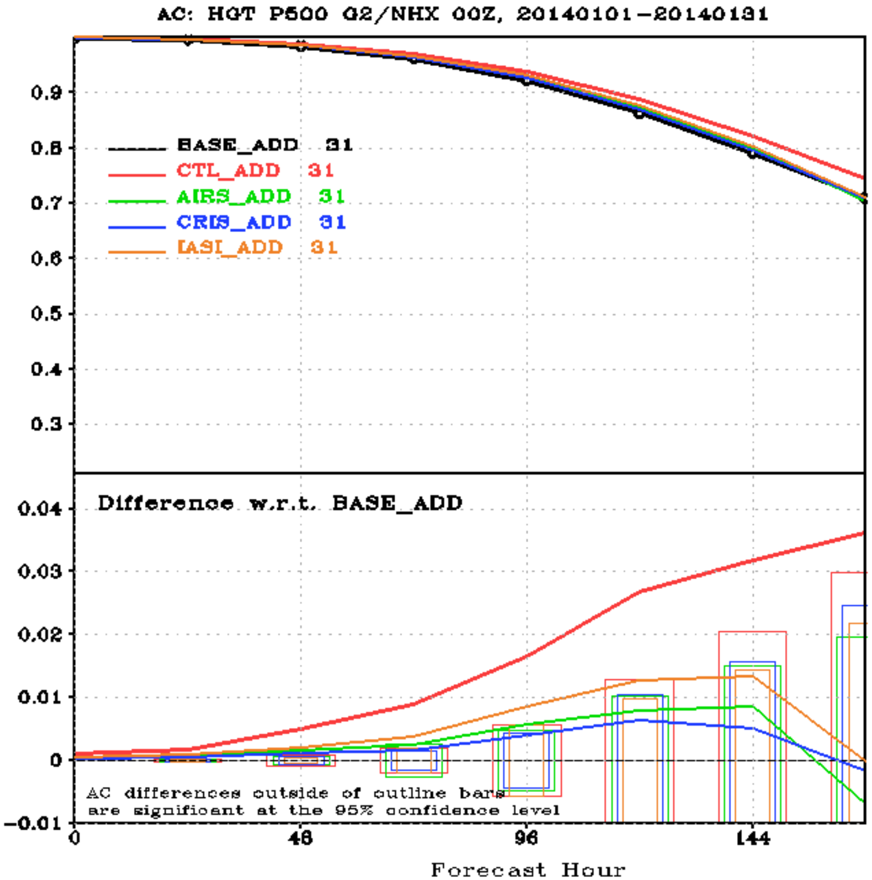
NCEP Data Additions

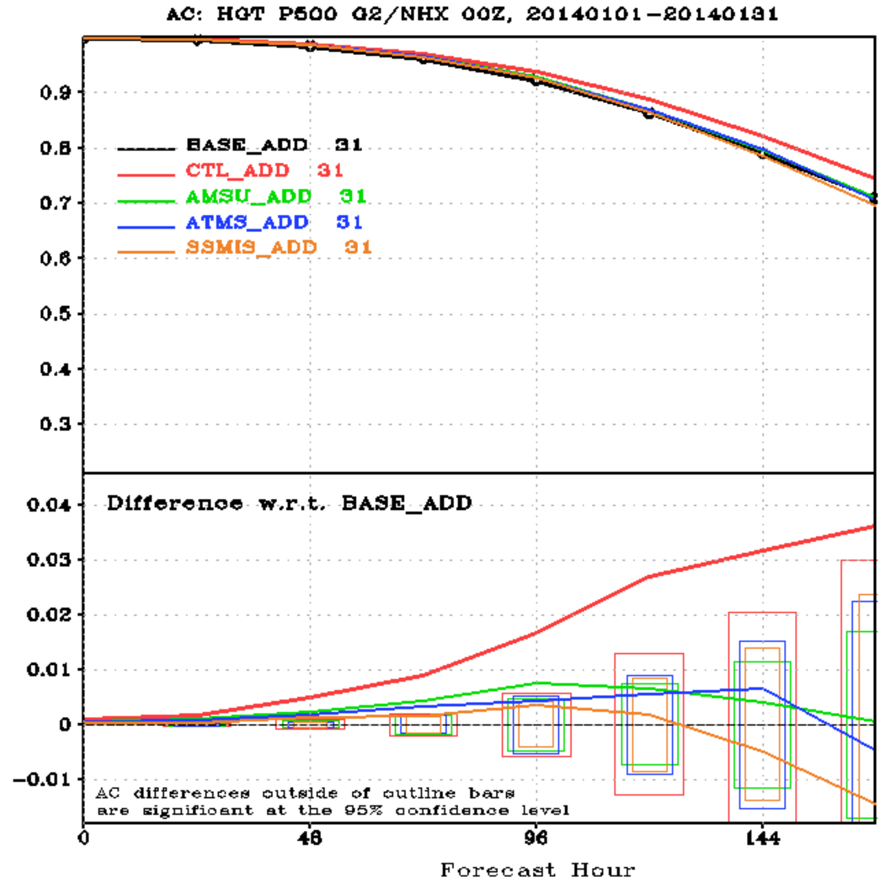
500 hPa Southern Hemisphere AC scores for 20140101 – 20140131 00Z





500 hPa Northern Hemisphere AC scores for 20140101 – 20140131 00Z





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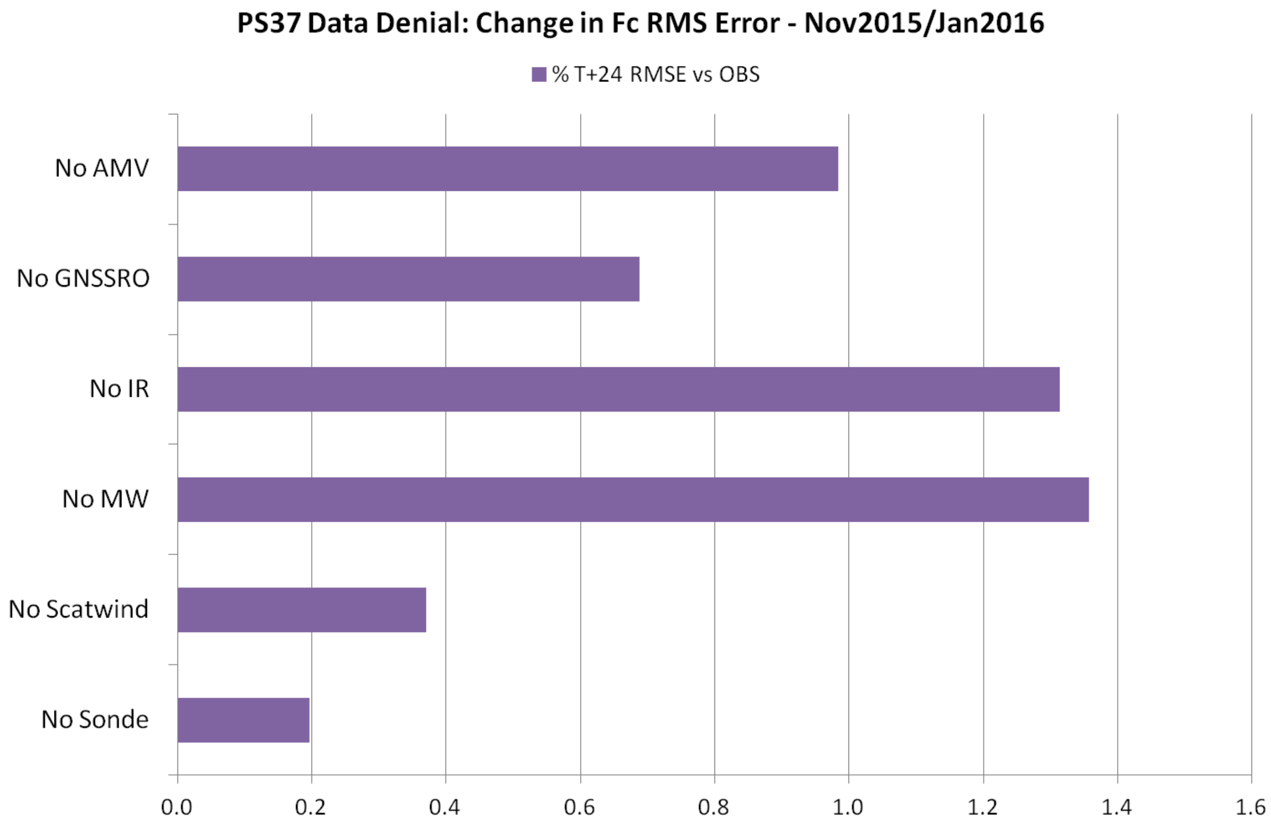
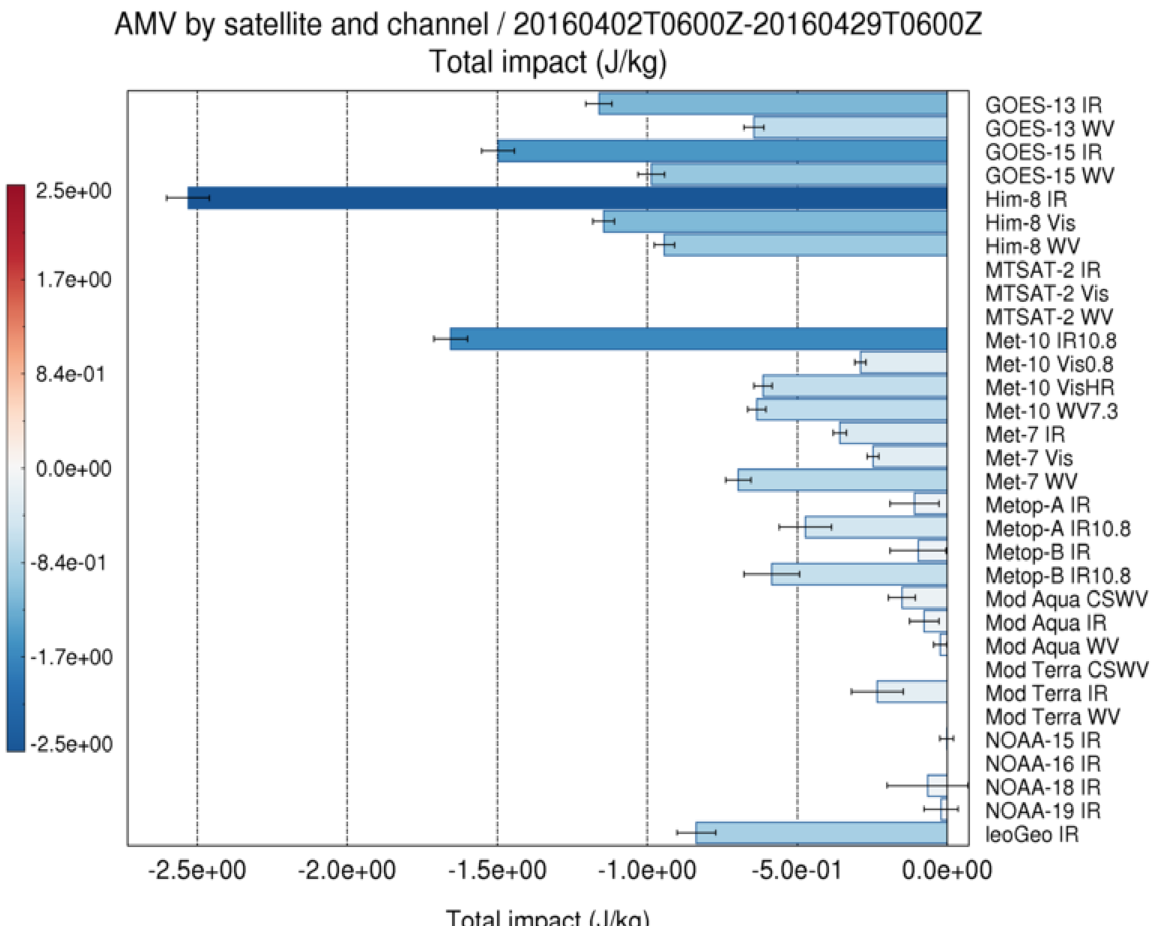
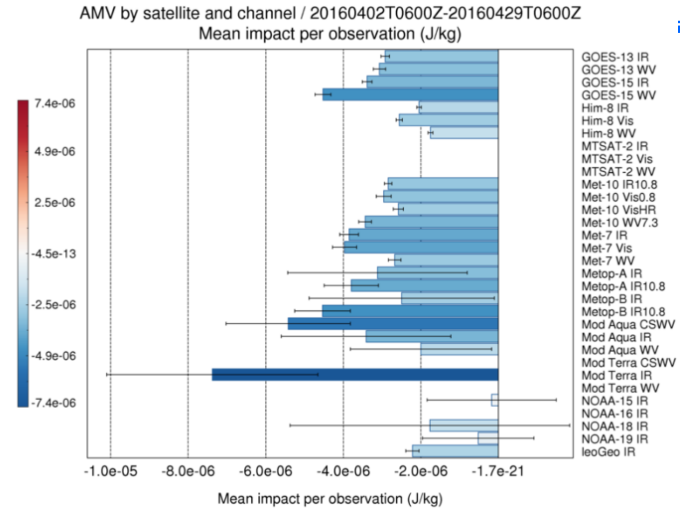
Met OfficeDenial T+24 RMSE vs OBS

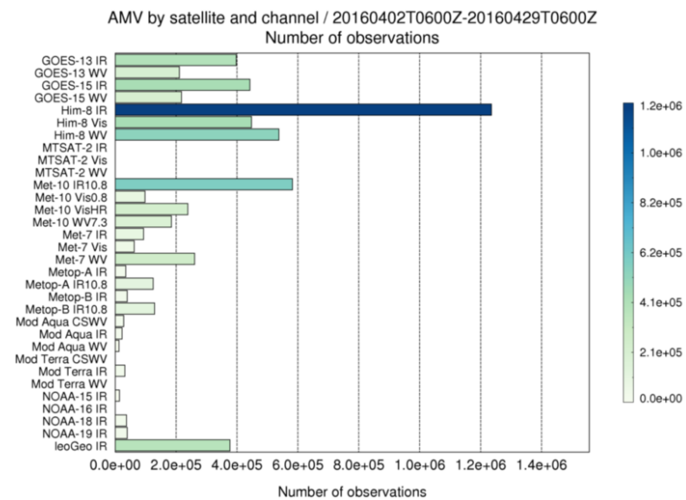


Met Office

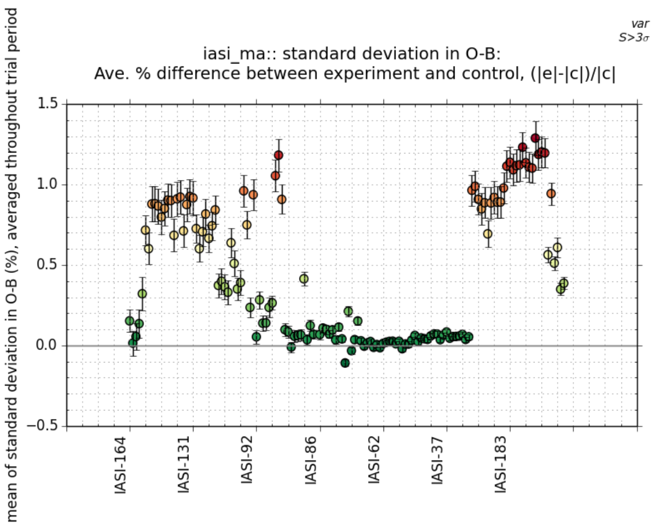
FSOI by Satellite-channel – Apr 2016

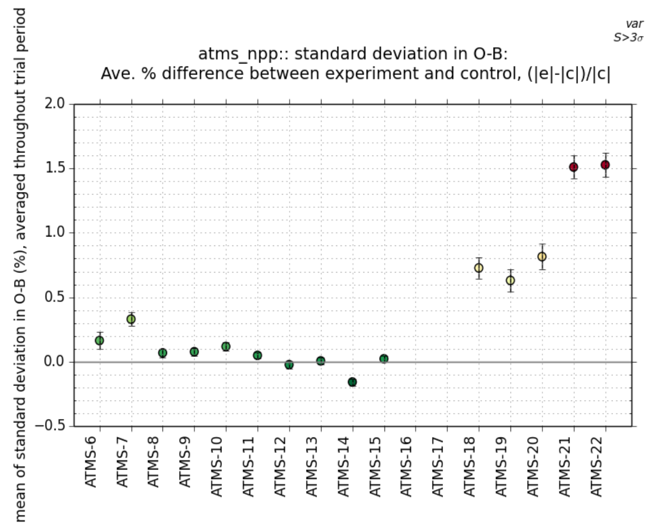






Met Office





The AMV denial trial showed degraded fits of the background to other observations, including the humidity sensitive hyperspectral IR and microwave radiance channels and tropospheric temperature sensitive hyperspectral IR channels

Met Office

All AMV except CA WV

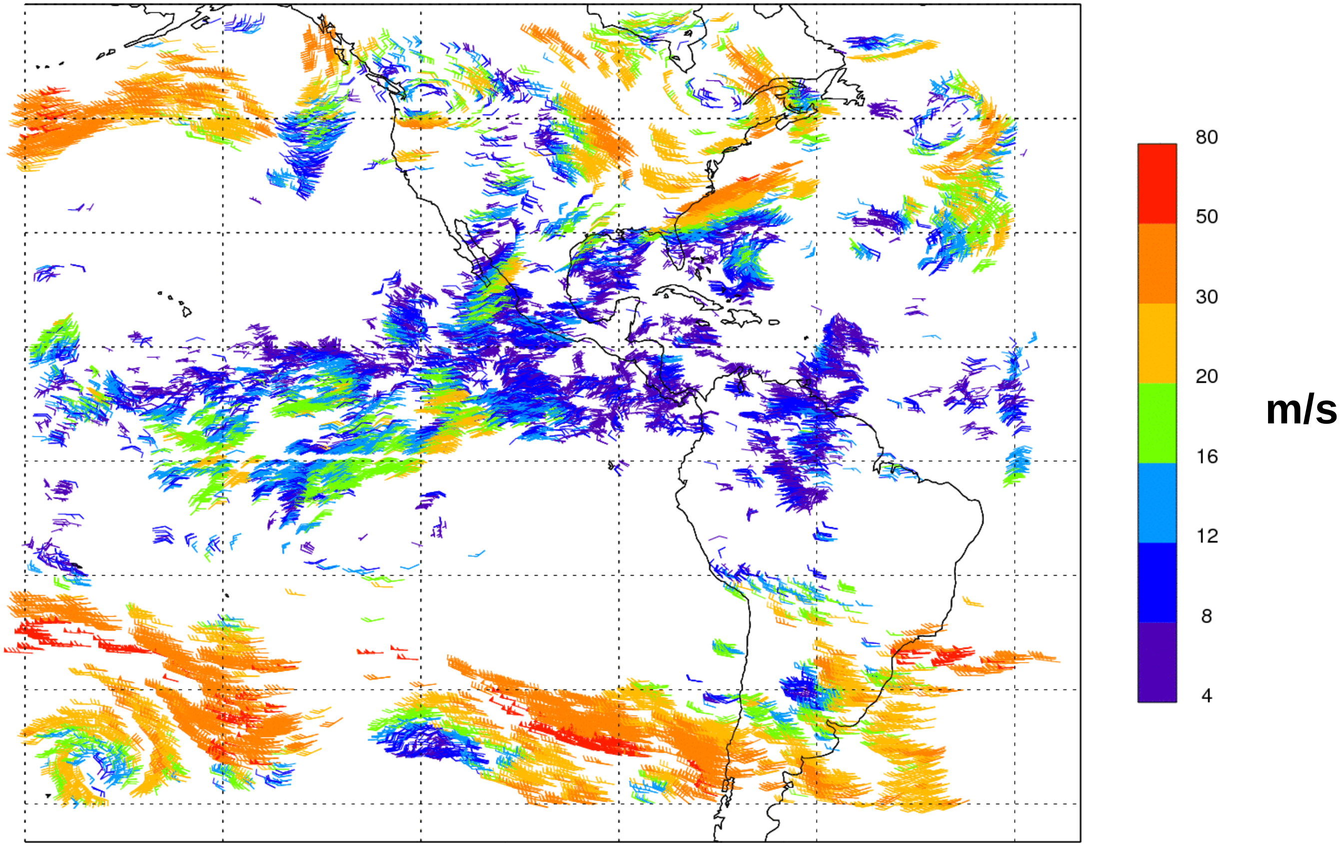
Results for 2014081518 to 2014081518

Motivation for using clear sky WV AMVs:

Improve data coverage in the tropics

GOES IR & Cloud Top WV AMV above 500 hPa

No Clear Air WV AMVs



Univ. of Wisconsin

18Z 15 Aug 2014

All AMV

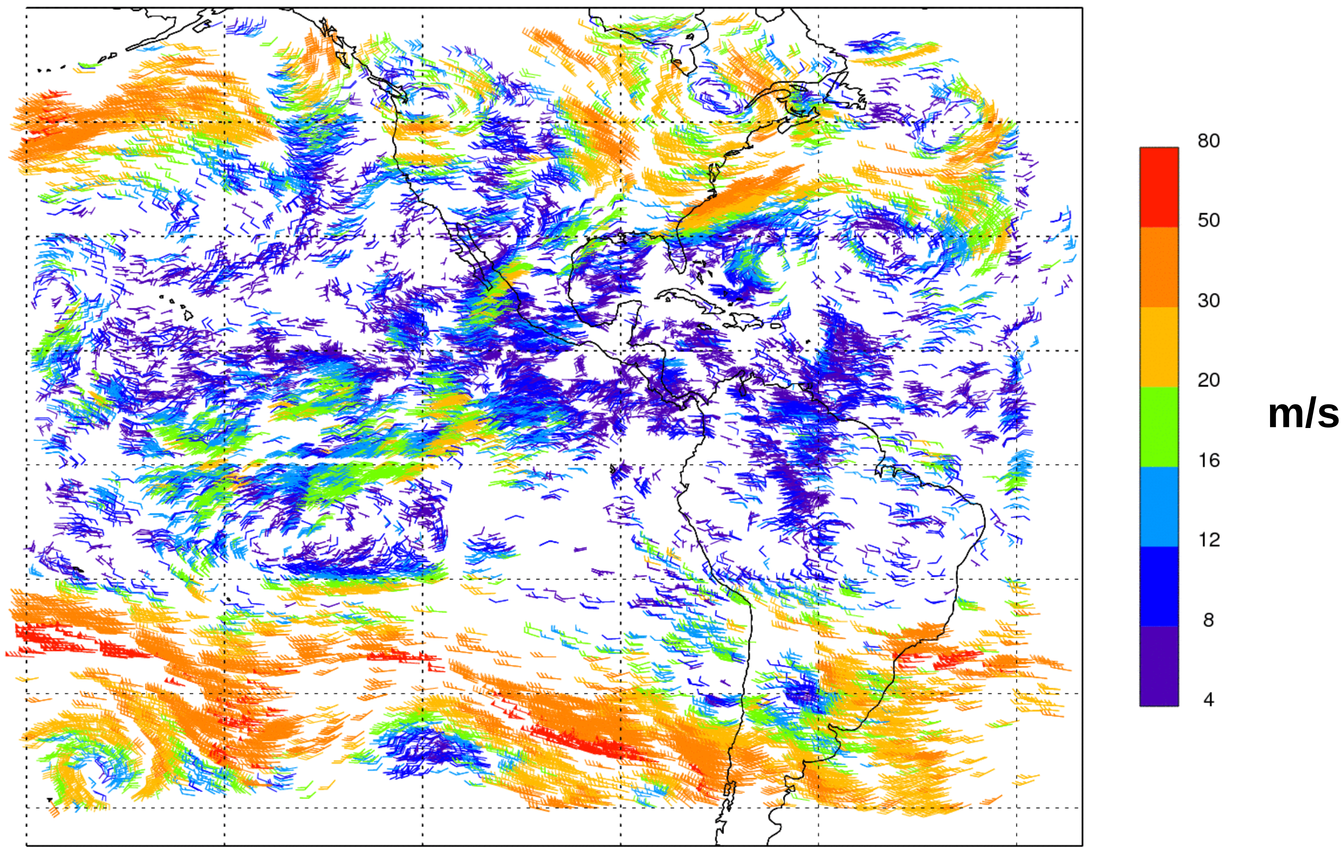
Results for 2014081518 to 2014081518

Motivation for using clear sky WV AMVs:

Improve data coverage in the tropics

GOES IR & Cloud Top WV AMV above 500 hPa

With Clear Air WV AMVs



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Final Thoughts

- Hyperspectral IR sounders show a consistent positive impact across all NWP centres.
- The size of the impact is limited by the quality of the initial conditions and the influence of the other data on the analysis
- AMVs also have a significant impact on NWP systems and it remains to be seem whether the derived products from MTG-IRS (including maybe better height assignments that current AMVs?) will provide the bigger initial impact from these data.