Satellite impact to short-range global forecast using the adjoint-based Forecast Sensitivity to Observation (FSO) method

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Thanks to Ed Pavelin

Motivation

Recently, the volume of satellite data assimilated in an operational NWP system has increased dramatically with the help of advanced data assimilation methods and the advent of new satellite data (i.e. hyper-spectral sounders) and this trend will be continued.

Satellite data needs lots of resources to launch a new platform and the impact on NWP is huge but varies depending on the observing techniques and sensors. Therefore, it is required to evaluate the impact of the satellite data in the most recent NWP configurations to inform discussions on future satellite systems.

The volume of assimilated satellite data is increased, but only a small portion of satellite data is assimilated. It is still a challenge to assimilate more satellite information (i.e. over land and sea ice, cloudy radiance) in many operational centres.

Therefore it is necessary to check if any useful information of satellite data is not assimilated in a current NWP configuration and use all the beneficial satellite information without loss to reduce NWP error.

Works

1. The relative importance of satellite data is compared in terms of FSO depending on various subsets (i.e. platform, observation technique) in the recent Met Office global NWP system.

2. The impact of the daytime IASI data over land is evaluated and a new channel selection is proposed to make use of more information from IASI data without any changes in the current data assimilation system.

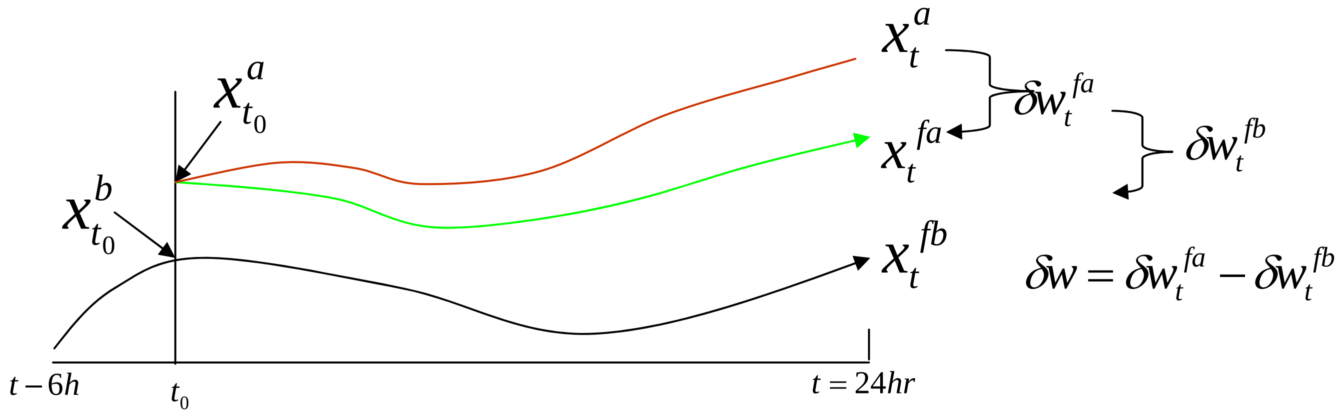
Contents

- Introduction to the adjoint-based FSO method
- FSO results of satellite data
- Channel selection of IASI data
- Summary & further works

Adjoint-based FSO method

Forecast Sensitivity to Observation (FSO) calculates an aspect of forecast error reduction due to analysis

(**Negative value** means error reduction and then it means a **good impact**)

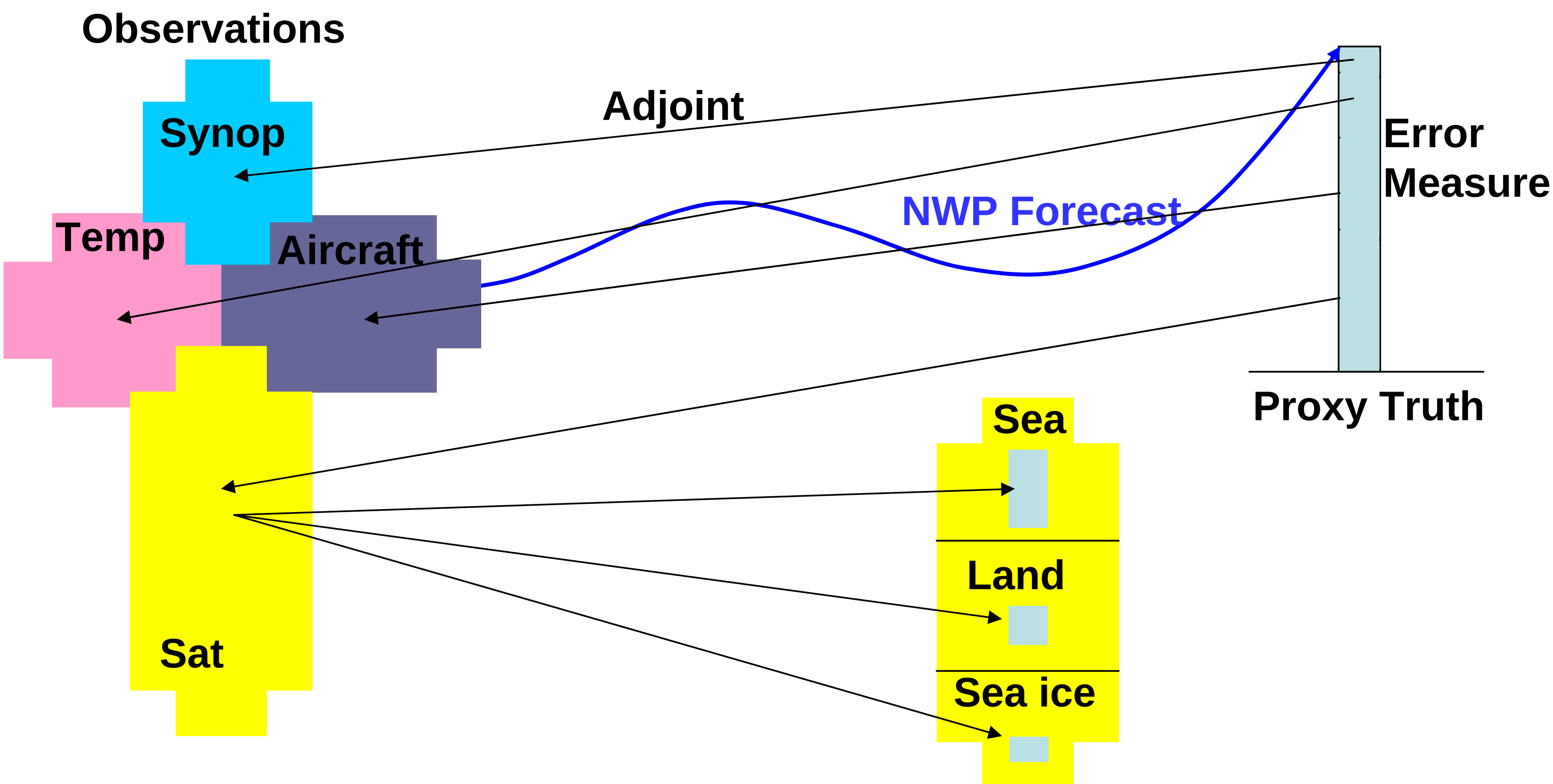


$$\delta J = (\delta w)^T \mathbf{C}\left(\delta w_t^{fa} - \delta w_t^{fb}\right) = \left(\delta y^o\right)^T \delta\hat{y}^o \qquad \delta w \approx \mathbf{MK}\delta y^o \qquad \delta\hat{y}^o = \mathbf{K}^T\mathbf{M}^T\mathbf{C}\left(\delta w_t^{fa} - \delta w_t^{fb}\right)$$

$\mathbf{M}$: Linear model $\mathbf{K}$: Karman Gain δy^o: innovation $\delta\hat{y}^o$: observation sensitivity
x^b: background x^a: analysis x^{fb} x^{fa} : forecast from background and analysis respectively
t_0: analysis time t : forecast time

δJ is a decrease of the global energy norm error(24hours) due to analysis and negative value means reduction of forecast error and better performance. (Reference : Met Office VSDP 63)

Benefit of Adjoint-based FSO method



- All impacts are produced simultaneously in FSO and so the method is efficient.
- Impacts can be easily aggregated making the method extremely useful for evaluating the impact of satellite data, which consists of many sub-types.

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Experiment Design

- Observation Impact measure:
  - Reduction in error variance of global moist energy norm
  - surface to ~150 hPa, 24-hour forecast
- NWP system:
  - Met Office global Unified Model (UM) with 4D-Var
  - version PS26 – operational from 16 March 2011
  - resolution: UM N320, 4D-Var N216
- Data period:
  - 6 hourly (00Z, 06Z,12Z,18Z)
  - 18Z on 22 Aug → 12Z on 18 Sept 2010
    - except 18Z on 30 Aug and 00Z, 06Z,12Z on 5 Sept

Satellite observations

Table 1. Satellite observation types used in this study and affected NWP variables

Observation Type	Satellite	NWP Variables
AMSU/MHS radiances	4 NOAA (15,17,18,19) + Metop-A	Temperature, humidity
HIRS clear radiances	2 NOAA (17,19)+ Metop-A	Temperature, humidity
IASI and AIRS clear,cloudy radiances	Metop-A + Aqua	Temperature, humidity
SSMIS radiances	DMSP(F16)	Temperature, humidity
Geo imager clear IR radiances	MSG(Meteosat-9) , GOES	Humidity
GPS RO bending angles	5 COSMIC, Metop-A/GRAS, GRACE-A	Temperature, humidity
AMVs-GEO	Meteosat-7, MSG(Meteosat-9), MTSAT, GOES-11, GOES-13	Wind
SEVIRI Clear sky radiances	MSG(Meteosat9)	Temperature, humidity
AMVs-MODIS and AVHRR	Aqua, Terra, NOAA	Wind
Scatterometer sea-surface wind	Metop-A/ASCAT	Surface wind
MW imager sea-surface wind	Coriolis/WINDSAT	Surface wind
Cloud-top height / amount	MSG/SEVIRI	Cloud
SSTs: AVHRR, AATSR	NOAA, Metop-A, ENVISAT, Aqua	Sea surface temperature
Soil Moisture: ASCAT	Metop-A	Soil moisture
Sea ice: SSMI, SSMIS	DMSP	Sea ice
Snow cover	Various	Snow cover

Note that some of these NWP variables – SST, sea-ice, snow cover and soil moisture – are initialised separately, and not as part of the 4D-Var process. Consequently, the impact of observations important for their analysis will not be measured by the FSO method.

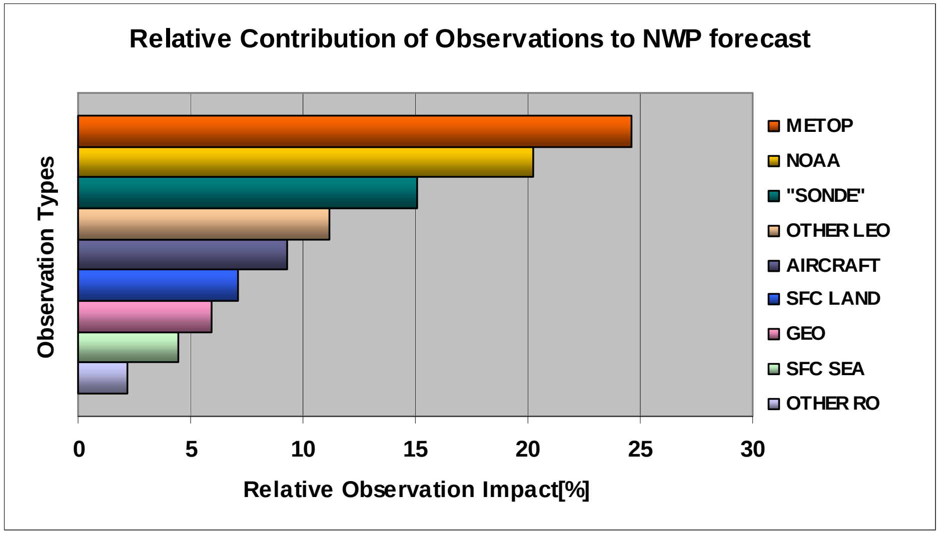
Subtypes in FSO results

Table 3. Detailed observations for each subset compared

Observation \ Subset name	Sub-type	Platform	Technique
Metop-A/IASI	Metop	Metop-A	IRS
Metop-A/AMSU-A	Metop	Metop-A	MWS
Metop-A/MHS	Metop	Metop-A	MWS
Metop-A/HIRS	Metop	Metop-A	IRS
Metop-A/ASCAT	Metop	Metop-A	SCAT
Metop-A/GRAS	GPSRO	Metop-A	GPSRO
NOAA-15/AMSU-A	NOAA	NOAA-15	MWS
NOAA-15/AVHRR	NOAA	NOAA-15	Imager/AMV
NOAA-16/AVHRR	NOAA	NOAA-16	Imager/AMV
NOAA-17/HIRS	NOAA	NOAA-17	IRS
NOAA-17/AVHRR	NOAA	NOAA-17	Imager/AMV
NOAA-18/AMSU-A	NOAA	NOAA-18	MWS
NOAA-18/MHS	NOAA	NOAA-18	MWS
NOAA-18/AVHRR	NOAA	NOAA-18	Imager/AMV
NOAA-19/HIRS	NOAA	NOAA-19	IRS
NOAA-19/AMSU-A	NOAA	NOAA-19	MWS
NOAA-19/AVHRR	NOAA	NOAA-19	Imager/AMV
EOS-Aqua/AIRS	Other LEO	Aqua	IRS
EOS-Aqua/MODIS	Other LEO	Aqua	Imager/AMV
EOS-Terra/MODIS	Other LEO	Terra	Imager/AMV

Observation \ Subset name	Sub-type	Platform	Technique
DMSP F-16/SSMIS	Other LEO	DMSP F-16	MWI
ERS2/AMI	Other LEO	ERS-2	SCAT
Coriolis/WindSat	Other LEO	Coriolis	MWI
GOES/AMVs	GEO	GOES	Imager/AMV
MTSAT/AMVs	GEO	MTSAT	Imager/AMV
Meteosat/AMVs	GEO	Meteosat	Imager/AMV
Meteosat/SEVIRI CLR	GEO	Meteosat	Imager/AMV
COSMIC	GPSRO	Other RO	GPSRO
GRACE	GPSRO	Other RO	GPSRO
AMDAR	AIRCRAFT	N/A	N/A
AIREP	AIRCRAFT	N/A	N/A
PILOT	"SONDE"	N/A	N/A
TEMP	"SONDE"	N/A	N/A
DROP SONDE	"SONDE"	N/A	N/A
Wind Profiler	"SONDE"	N/A	N/A
SYNOP	SFC LAND	N/A	N/A
BOGUS	SFC LAND	N/A	N/A
TCBOGUS	SFC SEA	N/A	N/A
BUOY	SFC SEA	N/A	N/A
SHIP	SFC SEA	N/A	N/A

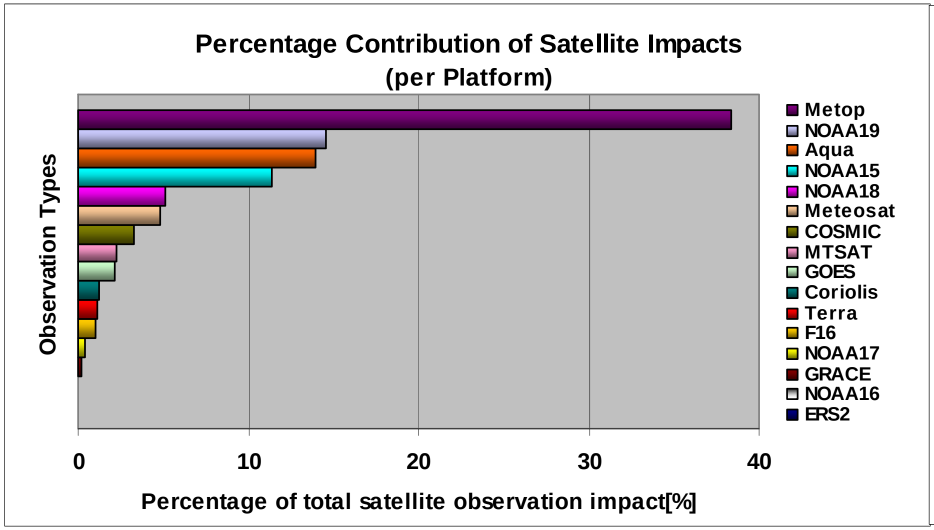
Satellite vs in-situ data

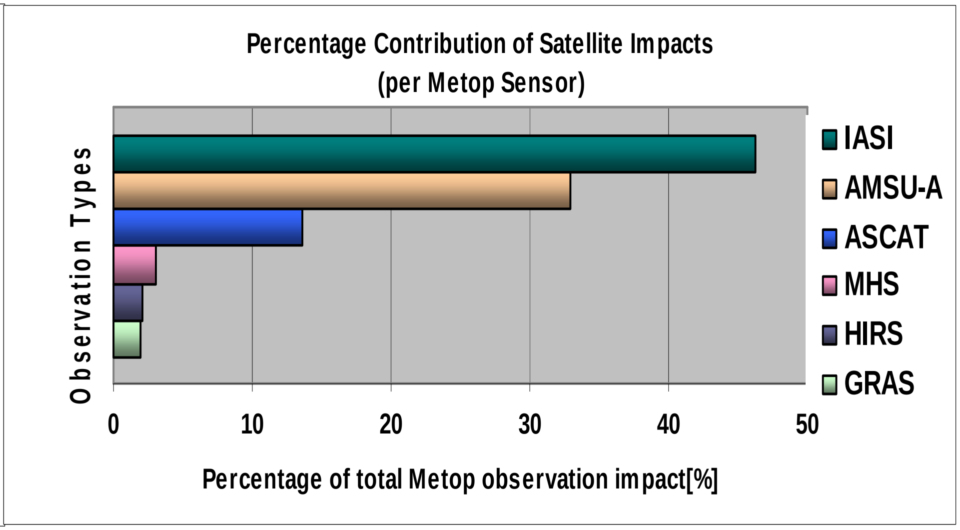


- The FSO of satellite data dominates the surface-based observations; about 64% of the short-range forecast-error reduction is due to satellite observations and the other 36% to conventional observations.

- The observation impact of satellite is mainly led by LEOs, including Metop and NOAA. LEOs contribute about 58% of the total observation impact.

Satellite impact by platform



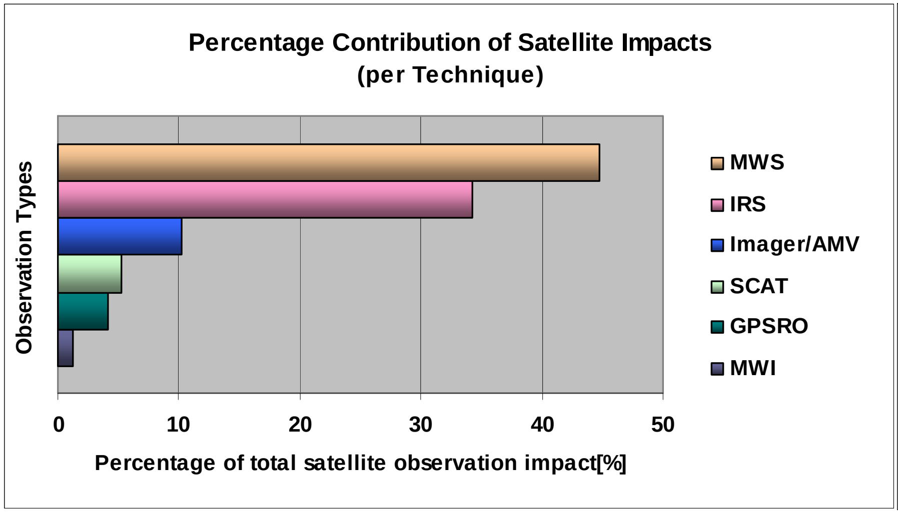


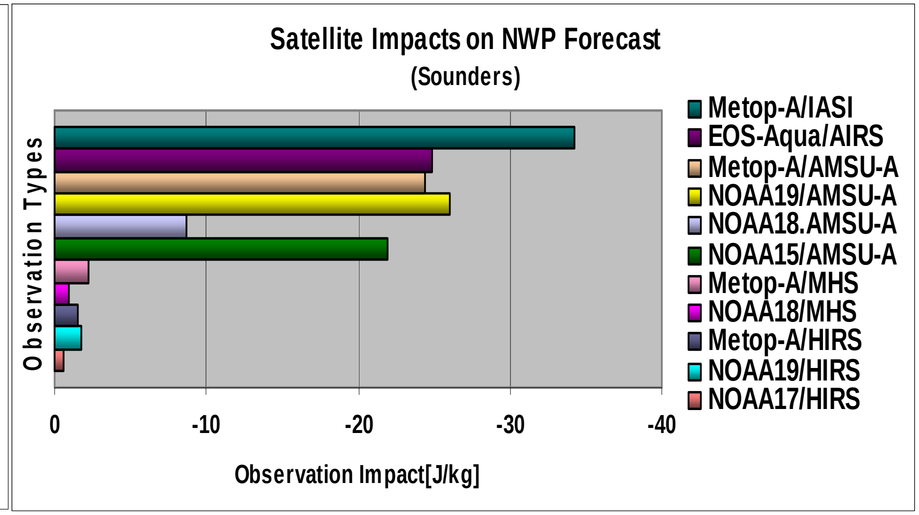
- Metop-A is measured as having the largest impact of any satellite platform (38%), followed by NOAA and Aqua.

- IASI is the most valuable sensor on Metop-A and the dominant role of Metop-A, compared with the NOAA series satellites is mainly due to the additional instruments - IASI, ASCAT and GRAS.

- Meteosat shows the strongest impact among GEO satellites, its impact here being mainly due to a large volume AMV data assimilated.

Satellite Impact by technique

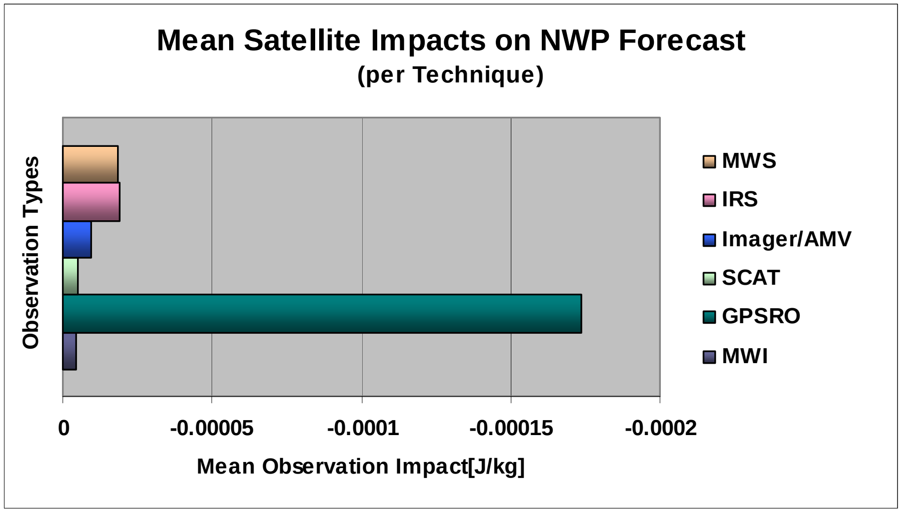




- The microwave and infra-red sounders together are measured as having an impact of about 79% of the observation impact of all satellite; 45% is from microwave soundings and the other 34% from infra-red soundings.

- The impacts of the hyper-spectral IR sounders, Metop-A/IASI and Aqua/AIRS, are similar to those of each microwave sounder.

Satellite impact by technique per sounding



- GPSRO has the largest observation impact per sounding among the satellite techniques in this study.

- The observation impact per soundings changes depending on the data used in a data assimilation system; however, it can be said that GPSRO data seems to be one of the most promising satellite observing techniques.

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IASI Land data assimilation with varying surface emissivity

- Develop varying Surface Emissivity over land (by Ed Pavelin)

  Training Data Set: UCSB MODIS surface emissivity database
  Select 12 leading PCs to represent SSE

  $A_i^F = \sum_{j=1}^{nch} F_j(\varepsilon)\varphi_{ji}^F$, $F_j(\varepsilon)$: SSE functional Spectra φ_{ji}^F : Eigen vector

  SSE is included as a background and retrieved with other state variables

  $$J = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - H(x))^T \mathbf{O}^{-1}(y - H(x))$$

- Surface-sensitive IASI channels over land has been assimilated with the varying surface emissivity at the Met Office since 2011 but daytime observation is not assimilated.

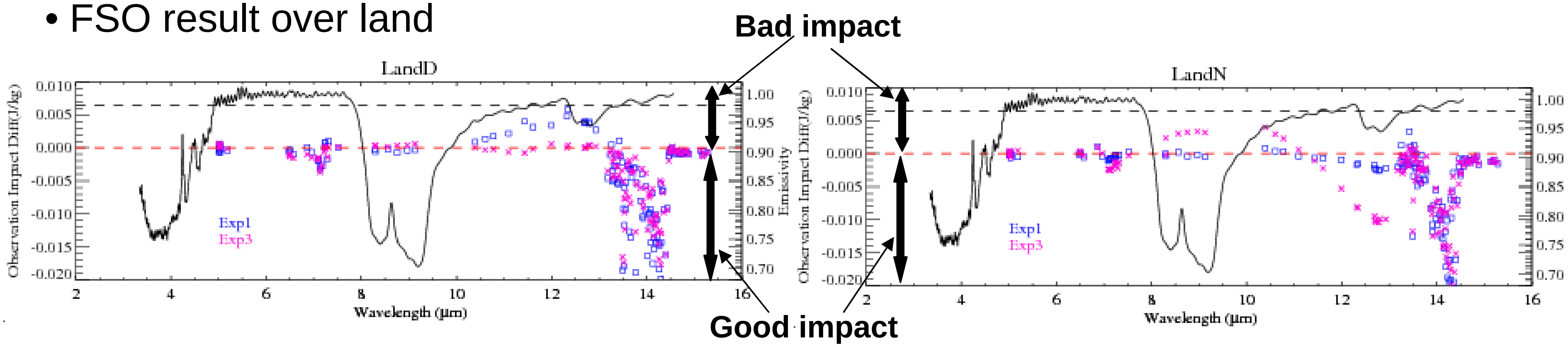
- With the help of FSO method, we try to get the maximum benefit of IASI data by selecting informative channels in the context of the current data assimilation system.

FSO results of varying surface emissivity

- Experiment Period: 2010.6.1.18UTC ~ 2010. 6. 7. 12UTC(6 hourly)
- Experiments :

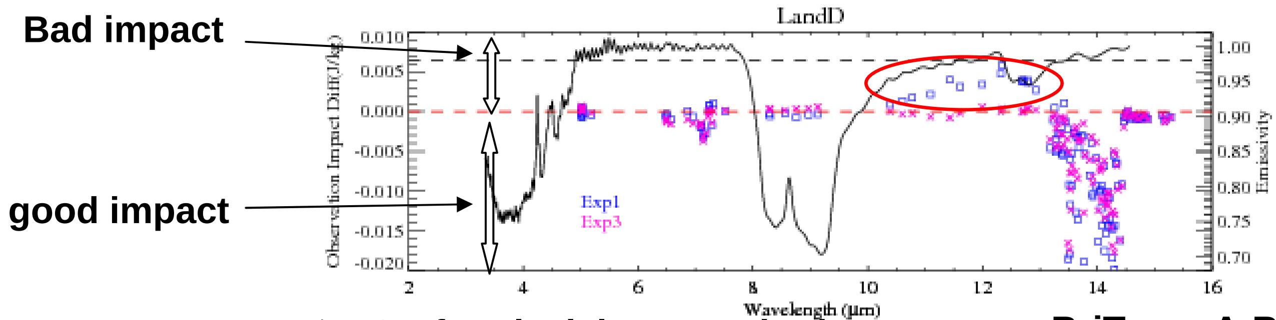
Name	Land Surface Spectral emissivity	Channels
Exp1	**Varying** Surface Emissivity	All channels for day and night time
Exp3	**Fixed** Surface Emissivity(=0.98)	All channels for day and night time

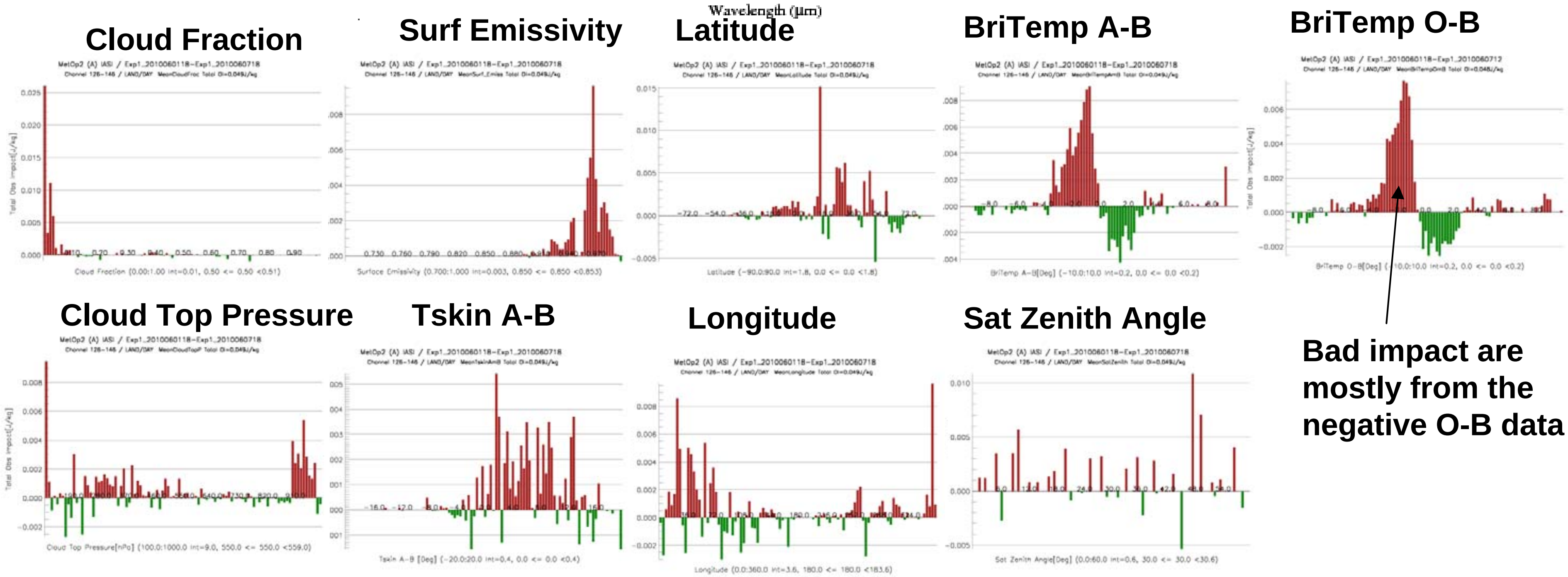
- FSO result over land



- Good impact : 8 -10um where the emissivity at sand sample is much lower than the fixed value
- Bad impact : the high emissivity window region(10-13um) during the daytime
- The daytime IASI channels from 8 to 10 um can be additionally used to improve forecast, but 10-13um at daytime can not be used as a whole.

Can we use daytime 10-13um channels over land?





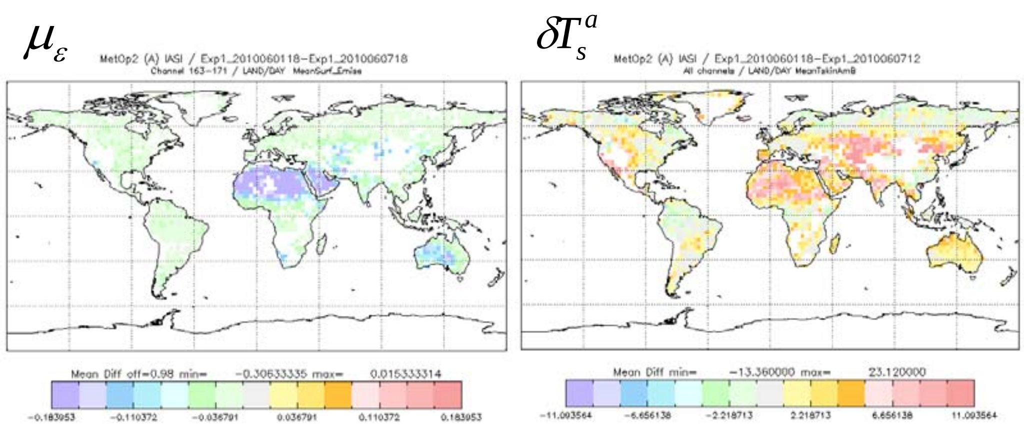
The bad impact are systematically related to the negative O-B data and the positive O-B data can be assimilated to improve NWP forecast

Why negative O-B makes bad impact?

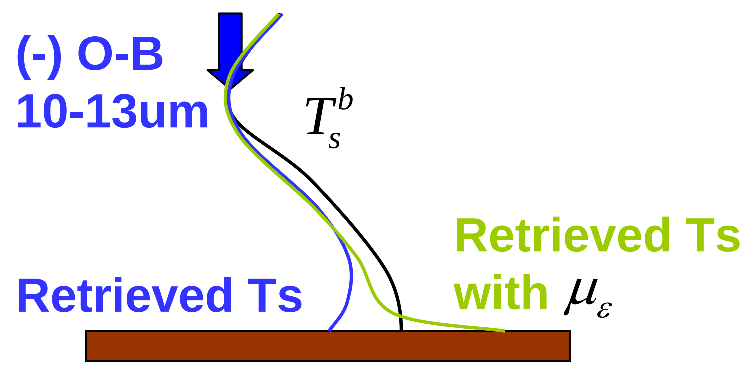
Assume simplified version of skin temperature analysis

$$\overline{\delta T_s^a} = k_1\left(\overline{y_1^o} - (\varepsilon_2 + \mu_\varepsilon)\overline{B_1\left(T_s^b\right)}\right) + k_2\left(\overline{y_2^o} - \varepsilon_2\overline{B_2\left(T_s^b\right)}\right)$$

δT_s^a :analysis increment of skin temperature, T_s^b:background skin temperature, y^o:observation, ε :surface emissivity, μ_ε :surface emissivity change between Exp1 and 3, *k* :kalman gain, *B* :plank function, $\overline{}$: time average, subscript *1* and *2* : 8-10um and 10-13um channels respectively.



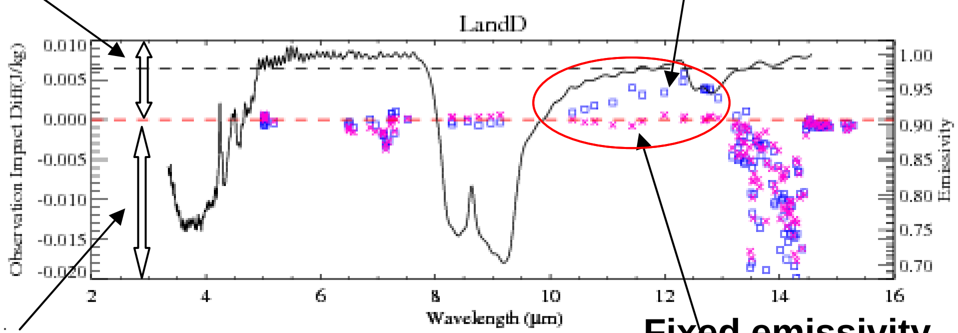
Reduced emissivity in 8-10um induces warmer analysis skin temp than background

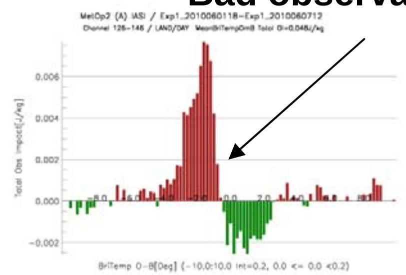


δT_s^a is positive over deserts even with the negative O-B of 10-13um

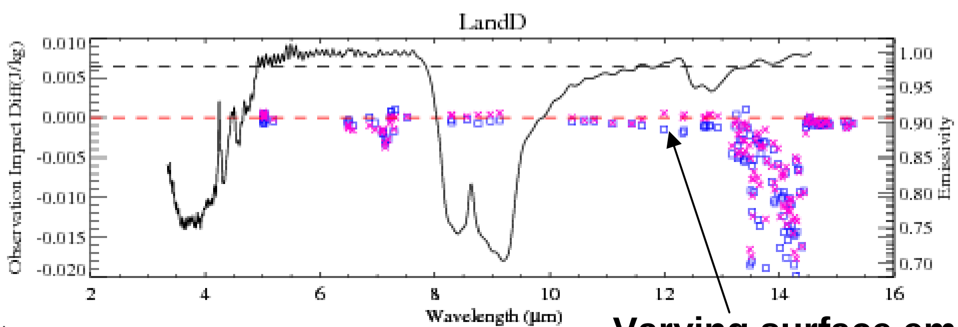
Negative O-B data in 10-13 um doesn't match the analysis results over desert where skin temperature analysis increment is positive and it makes negative FSO.

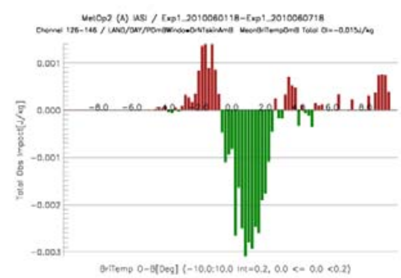
FSO with new channel selection





Remove negative O-B of window channel when the collocated skin temperature analysis increment is positive.





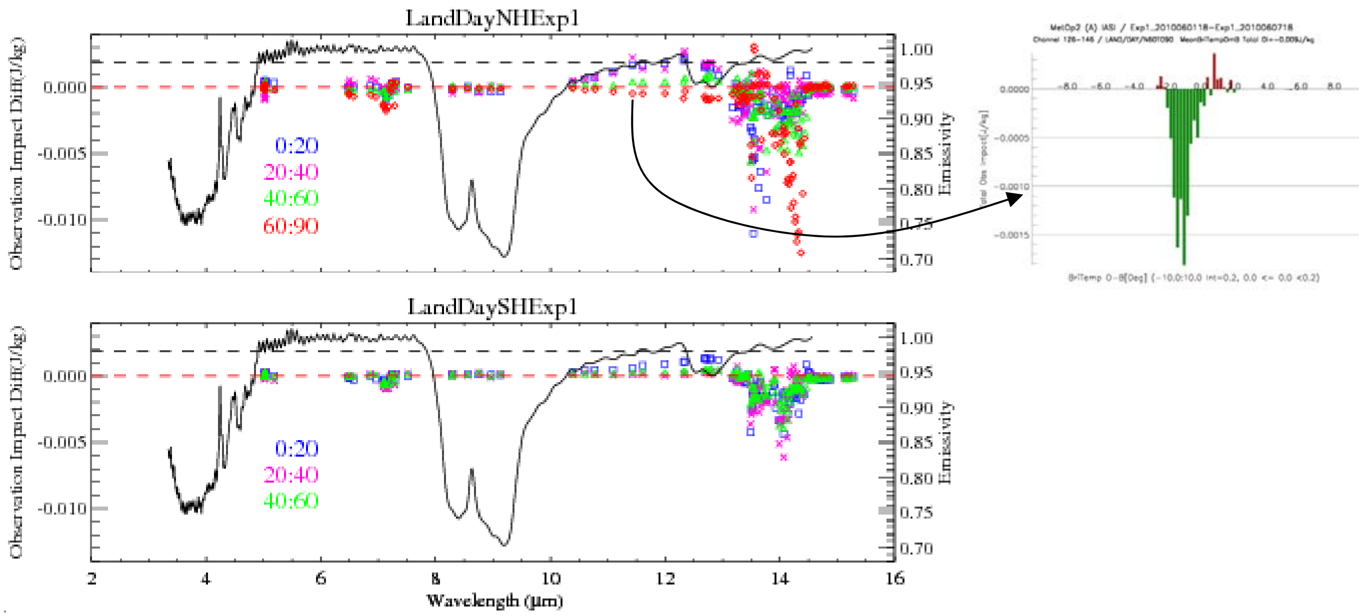
With the help of FSO results, all the surface-sensitive channels can be assimilated to improve the forecast performance by excluding negative O-B window channels during daytime.

Summary

- **FSO method is applied to evaluate satellite impacts in the Met Office**
  - Satellite data dominates the surface-based observations(64%) and mainly led by LEOs(58%).
  - Metop-A is measured as having the largest impact of satellite platform (38%), followed by NOAA and Aqua
  - The sounders are the most important technique in satellite observation (79% of the all satellite impact); the impacts of the hyper-spectral IR sounders are comparable to microwave sounders
  - The GPSRO technique shows the largest impact per sounding
- **The FSO method gives a guidance to increase subsets of IASI data to improve NWP forecast**
  - The additional use of daytime 8-10 um IASI channels over land can improve the NWP forecast at the Met Office.
  - 10-13um IASI channels can be assimilated after removing negative O-Bs at the deserts (positive analysis increment of skin temperature)

Further Works

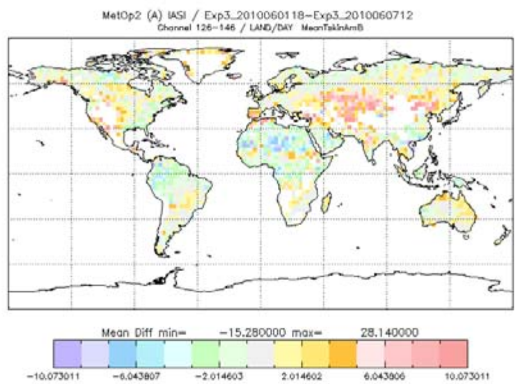
- **Finding a way to implement the IASI channel selection**
  - Verifying the improvement with the non-linear NWP forecasts
  - Considering the sample dependency of the results
    - Seasonal variation of skin temperature, emissivity...
  - In order to avoid complexities caused by the channel selection by O-B values, a simple geographical data selection will be tested in parallel

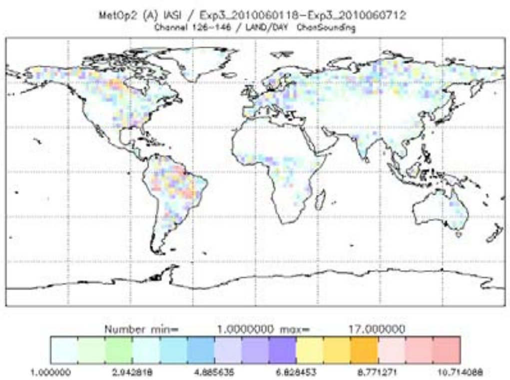


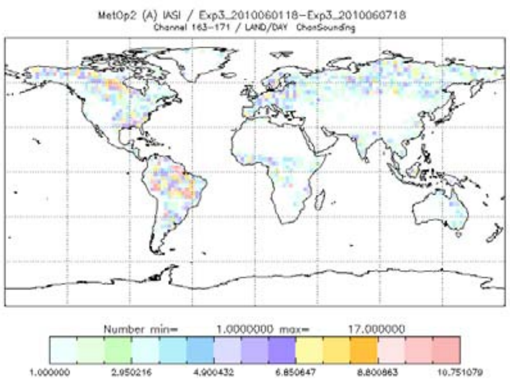
- **Applying similar procedures to extract useful subsets of IASI over sea ice and high land**

Thank you

Exp3 Results







Surface-Sensitive channels are removed over the deserts and analysis increment of skin temperature is negative.