Monitoring the assimilation and forecast system performance

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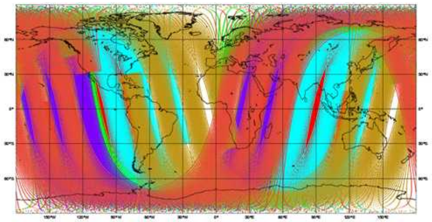
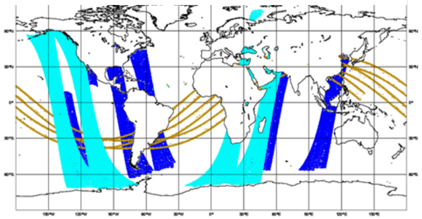
ECMWF-4DVar Observations assimilated ~10^7

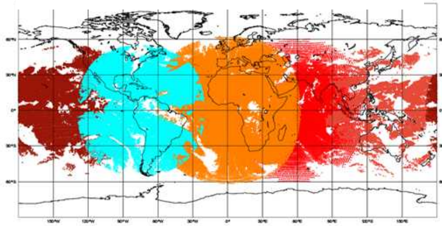
LEO Sounders



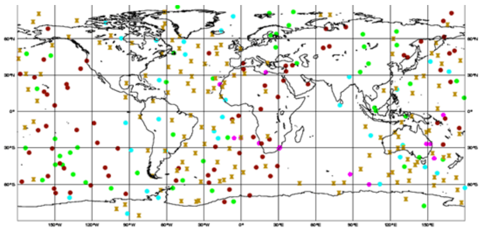
LEO Imagers



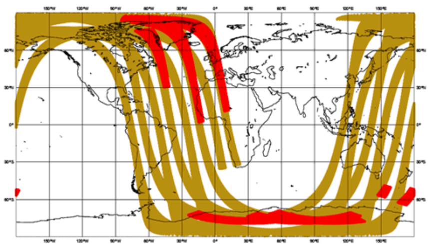
GEO imagers



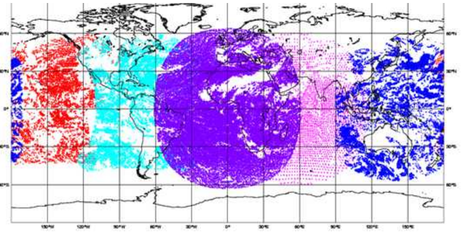
GPS Radio Occultation



Scatterometers



Satellite Winds (AMVs)



6-hourly data coverage

Type of Data	Description
OZONE (O3)	Satellite ozone retrieval
GOES-Radiance	Geostationary satellite infrared sounder radiances
METEOSAT-Rad	Geostationary satellite infrared sounder radiances
AMSU-B	Satellite microwave sounder radiances related to H
MSG	Geostationary satellite infrared radiances related to H and T
MTSAT	Geostationary satellite infrared radiances related to H and T
AMSRE	Satellite microwave imager radiances related to clouds and precipitation
MHS	Microwave sounder radiances related to H
SSMI	Satellite microwave imager radiances related to H and surface wind speed
AIRS	Satellite infrared sounder radiances related to H and T
AMSU-A	Satellite microwave sounder radiances related to T
IASI	Satellite infrared sounder radiances related to H and T
HIRS	Satellite infrared radiances
ERS-QuikSCAT	Satellite microwave scatterometer
AMVs	Atmospheric Motion Vectors derived from satellite cloud imagery
GPS-RO	Satellite GPS radio occultation
PILOT	Sondes and American, European and Japanese Wind profiler (u,v)
TEMP	Radiosondes from land and ship measuring p_s, T, RH , u and v
AIREP	Aircraft measurements of T, u and v
DRIBU	Drifting buoy measuring p_s, T, RH, u and v
SYNOP	Surface Observations from land and ship stations: measuring p_s, RH , u and v

Monitoring the assimilation and forecast system performance

$$\mathbf{x}_a = \mathbf{K}\mathbf{y} + (\mathbf{I}_q - \mathbf{H}\mathbf{K})\mathbf{x}_b$$

$$\mathbf{K} = \mathbf{K}(\mathbf{B}, \mathbf{R}, \mathbf{H}) = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

Y Observation
X_b Background
B Model Accuracy
R Observation Accuracy
H Model

$$\mathbf{x}_f = M\mathbf{x}_a$$

$$\mathbf{e} = \mathbf{x}_f - \mathbf{x}_a^v$$

$$J(\mathbf{e})$$

$$(\mathbf{H}\mathbf{x}_a - \mathbf{y})^T \frac{\partial J_e}{\partial \mathbf{y}} + (\mathbf{x}_a - \mathbf{x}_b)^T \frac{\partial J_e}{\partial \mathbf{x}_b} = 0$$

$$\frac{\partial J_e}{\partial \mathbf{y}} \qquad \frac{\partial J_e}{\partial \mathbf{R}} \qquad \frac{\partial J_e}{\partial \mathbf{B}}$$

Outline

- **Model sensitivity to data assimilation input parameters**
  - Forecast error sensitivity to observation $\frac{\partial J_e}{\partial \mathbf{y}}$
  - Forecast error sensitivity to observation error variance $\frac{\partial J_e}{\partial \mathbf{R}}$
  - Forecast error sensitivity to background error covariance matrix $\frac{\partial J_e}{\partial \mathbf{B}}$
- **ECMWF system performance**
  - All data and in particular GPS-RO
- **Complementary diagnostic tool**
  - Observation Influence in the analysis
  - Multi-Range- forecast versus observations
  - OSE
- **Conclusions**

$$\frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} = \mathbf{K}^T \Rightarrow \mathbf{K}^T \mathbf{H}^T$$

$$OI = (HK)_{ii}$$

$$DFS = tr(\mathrm{HK})$$

Monitoring the forecast system performance

$$\mathbf{x}_a = \mathbf{K}\mathbf{y} + (\mathbf{I}_q - \mathbf{H}\mathbf{K})\mathbf{x}_b$$

$$\mathbf{K} = \mathbf{K}(\mathbf{B},\mathbf{R},\mathbf{H}) = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

Y Observation
X_b Background
B Model Accuracy
R Observation Accuracy
H Model

$$\mathbf{x}_f = M\mathbf{x}_a$$

$$\mathbf{e} = \mathbf{x}_f - \mathbf{x}_a^v$$

$$J(\mathbf{e})$$

$$\frac{\partial J_e}{\partial \mathbf{y}} \quad \frac{\partial J_e}{\partial \mathbf{R}} \quad \frac{\partial J_e}{\partial \mathbf{B}}$$

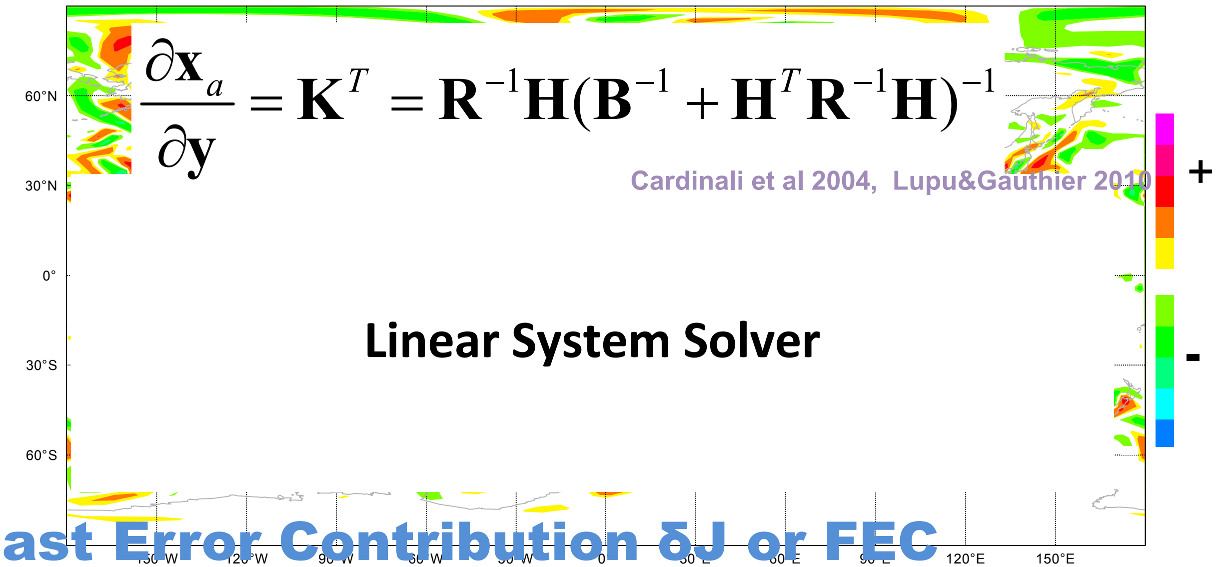
Forecast sensitivity to observation: Equations

J_e is a measure of the forecast error e.g Energy norm

$$\frac{\partial J_e}{\partial \mathbf{x}_a}$$

Forecast error sensitivity to the analysis
Rabier F, *et al*. 1996
2nd order SG

$$\frac{\partial J_e}{\partial \mathbf{y}} = \frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} \frac{\partial J_e}{\partial \mathbf{x}_a}$$



$$\frac{\partial \mathbf{x}_a}{\partial \mathbf{y}} = \mathbf{K}^T = \mathbf{R}^{-1}\mathbf{H}(\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}$$

Cardinali et al 2004, Lupu&Gauthier 2010

$$\frac{\partial J_e}{\partial \mathbf{y}} = \mathbf{R}^{-1}\mathbf{H}\mathbf{A} \frac{\partial J_e}{\partial \mathbf{x}_a}$$

Linear System Solver

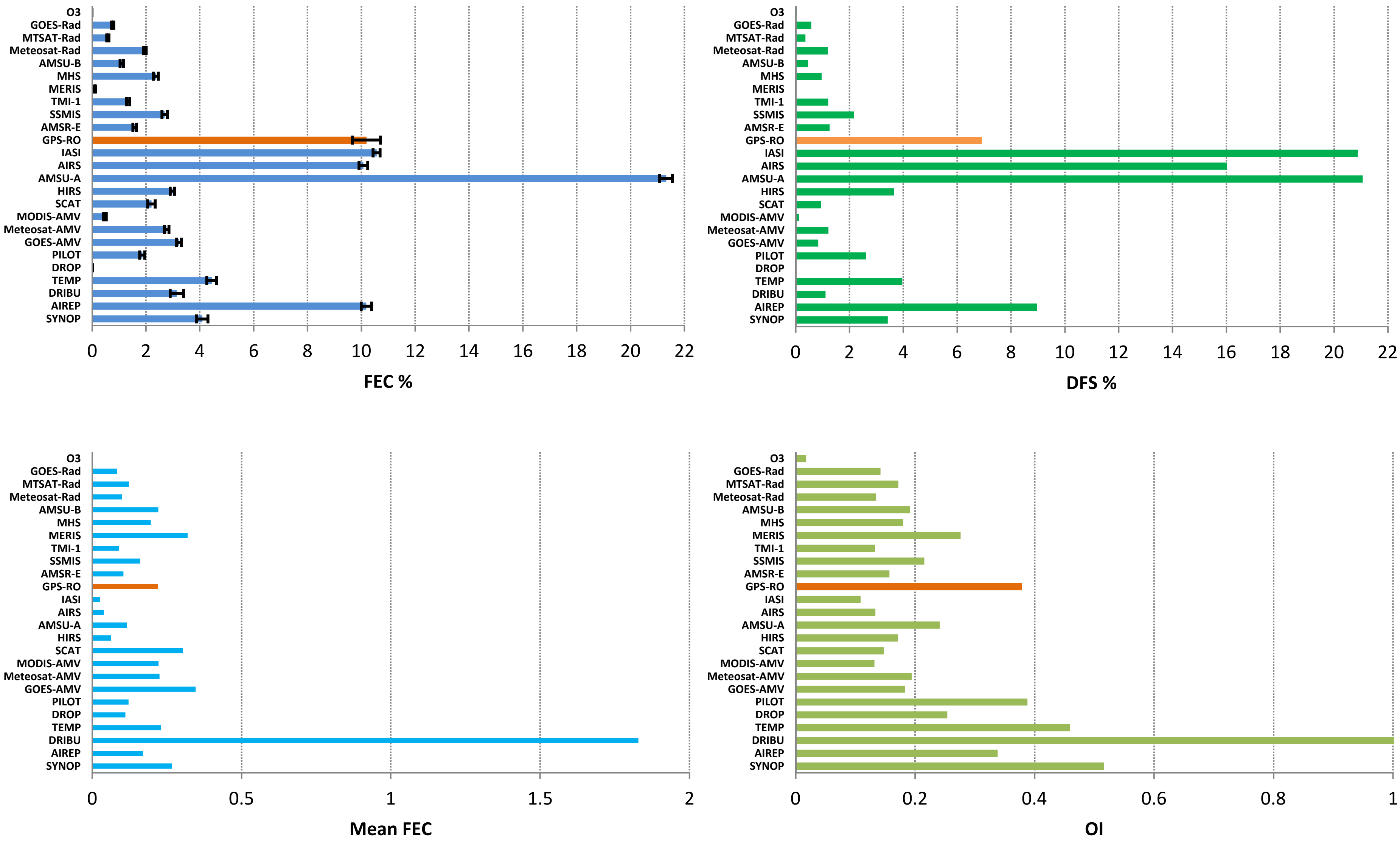
Computing the Forecast Error Contribution δJ or FEC

$$< \frac{\partial J_e}{\partial \mathbf{x}_a}, \delta \mathbf{x}_a > = < \frac{\partial J_e}{\partial \mathbf{x}_a}, \mathbf{x}_a - \mathbf{x}_b > = < \frac{\partial J_e}{\partial \mathbf{x}_a}, \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}_b) > = < \mathbf{K}^T \frac{\partial J_e}{\partial \mathbf{x}_a}, (\mathbf{y} - \mathbf{H}\mathbf{x}_b) > = < \frac{\partial J_e}{\partial \mathbf{y}}, \delta \mathbf{y} >$$

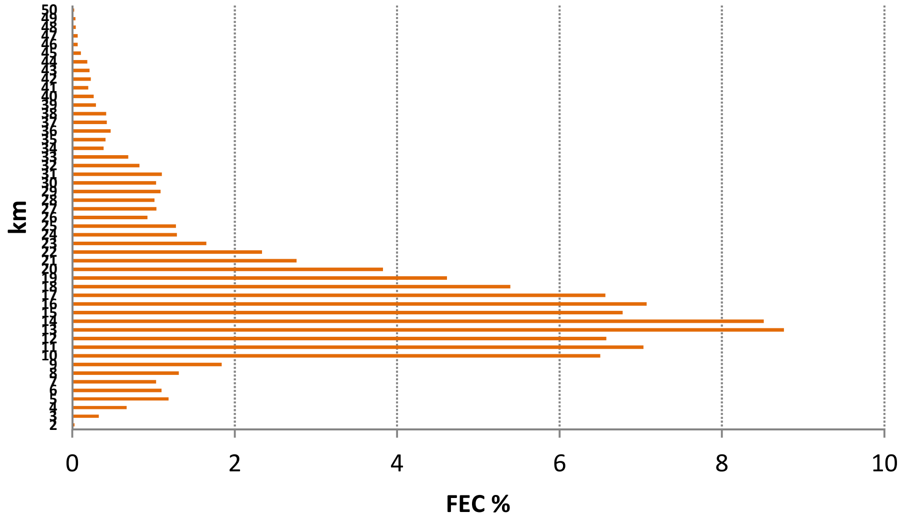
$$\delta J_e = \frac{\partial J_e}{\partial \mathbf{y}} (\mathbf{y} - \mathbf{H}\mathbf{x}_b)$$

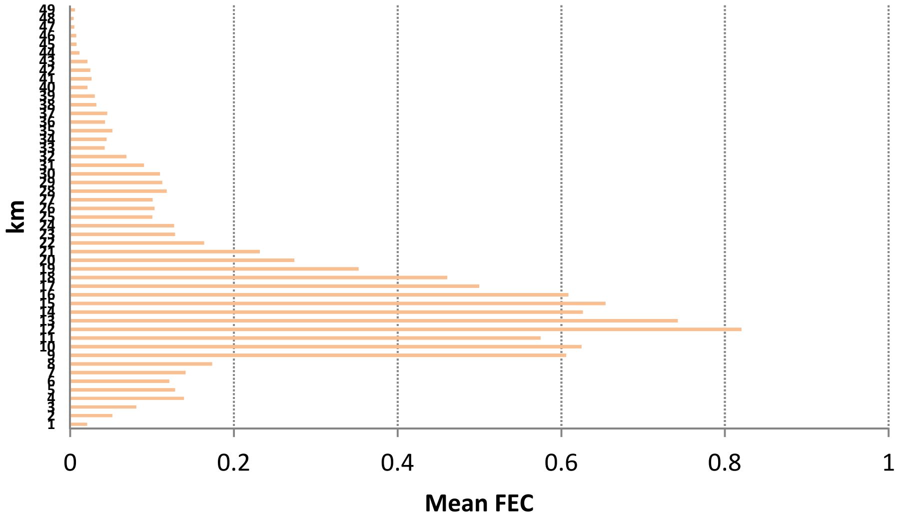
Langland&Baker 2004, Zhu&Gelaro 2008, Cardinali 2009

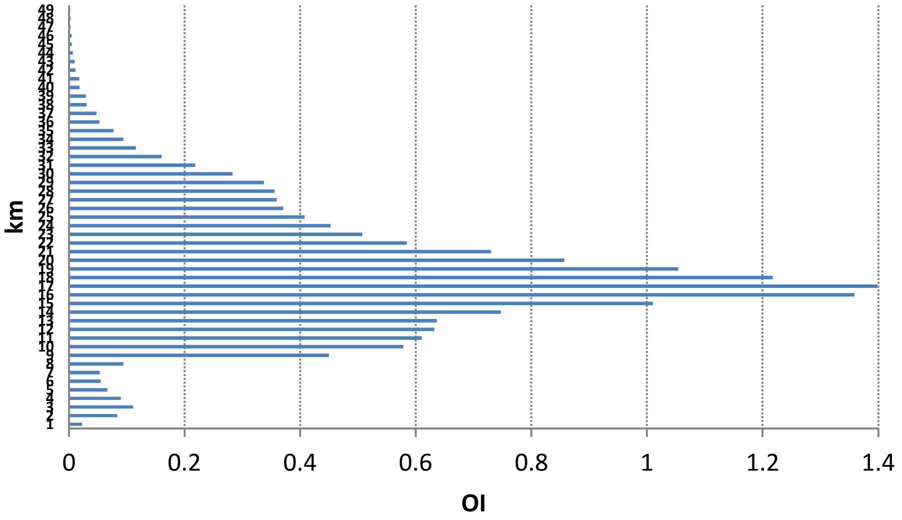
ECMWF System performance June 2011



GPS-RO June 2011





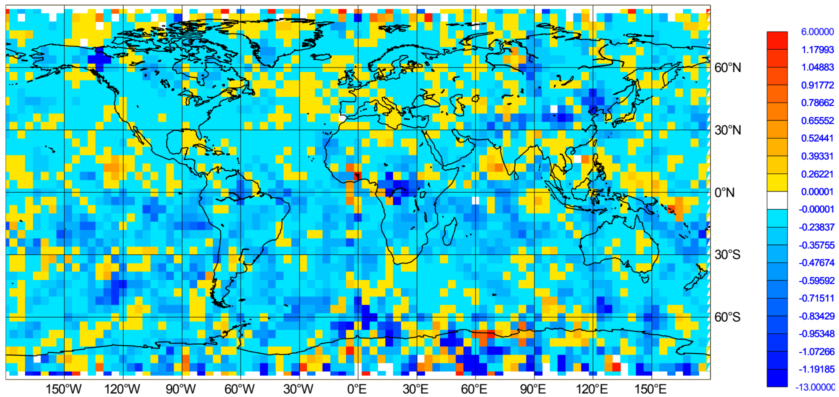


June 2011 GPS-RO

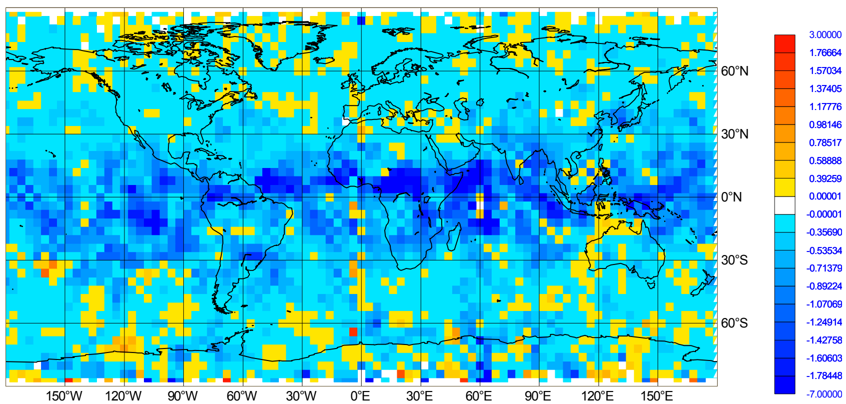
Forecast Error Contribution

Km

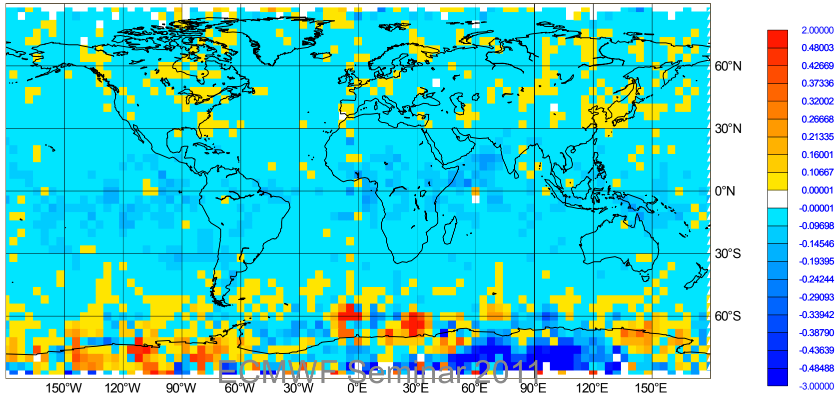
2-12



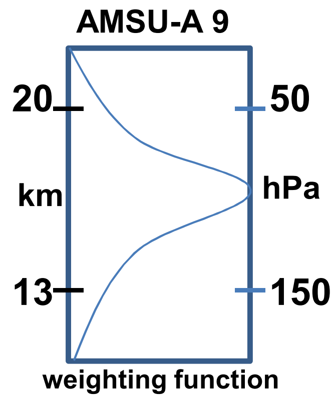
13-20



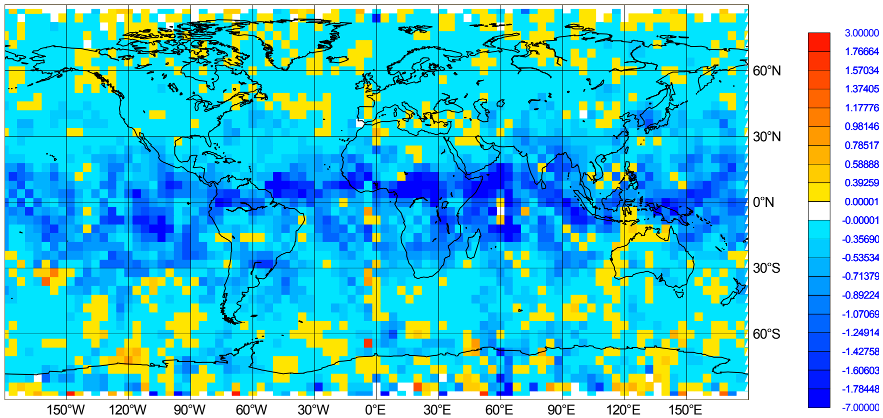
21-50



June 2011

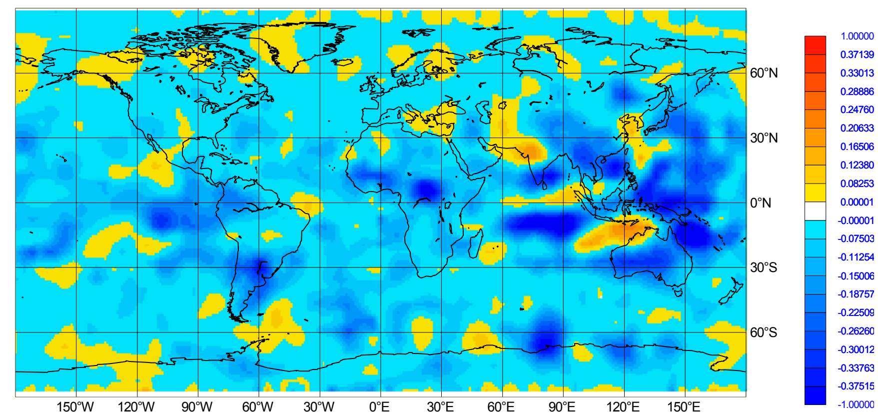


GPS-RO 13-20km Mean=-0.31

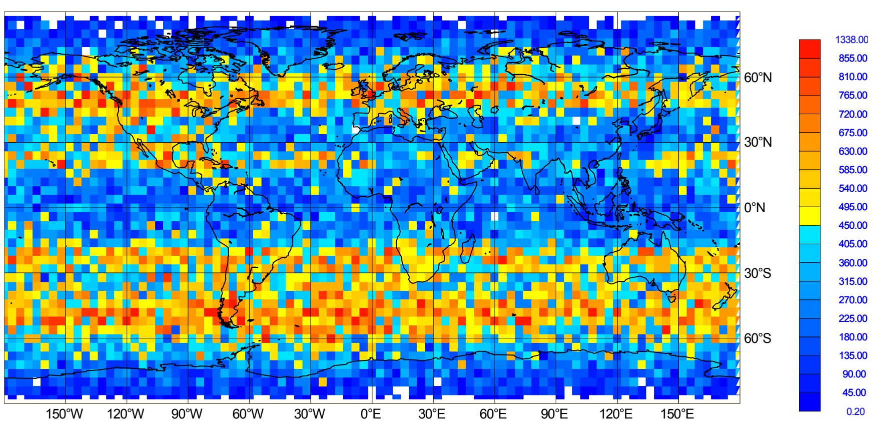


FEC

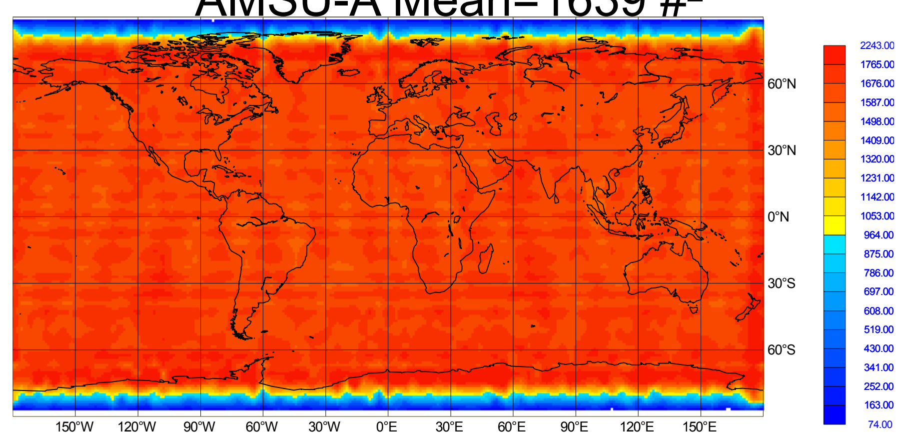
AMSU-A ch=9 Mean=-0.07



GPS-RO Mean=436 $\#^2$

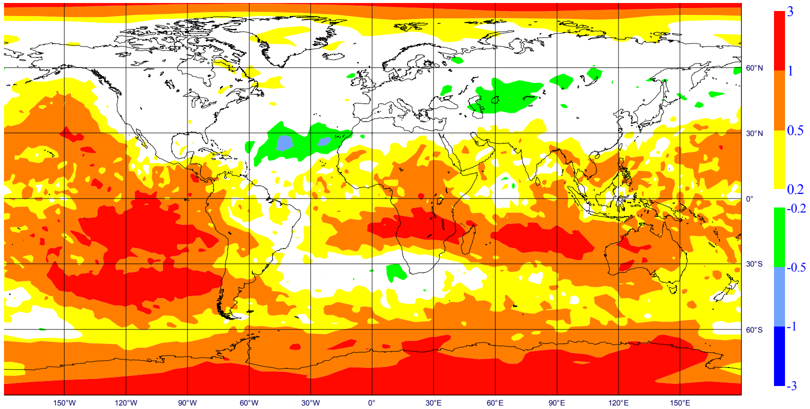


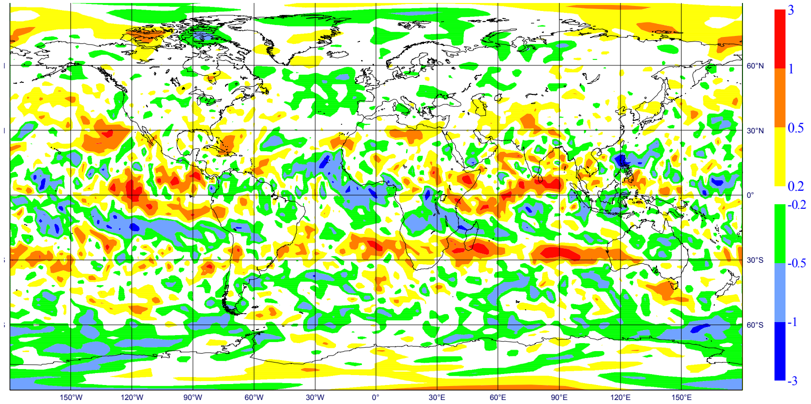
AMSU-A Mean=1639 $\#^2$



OSE With-Without GPS-RO Mean Difference Level 39

T **analysis** **U**



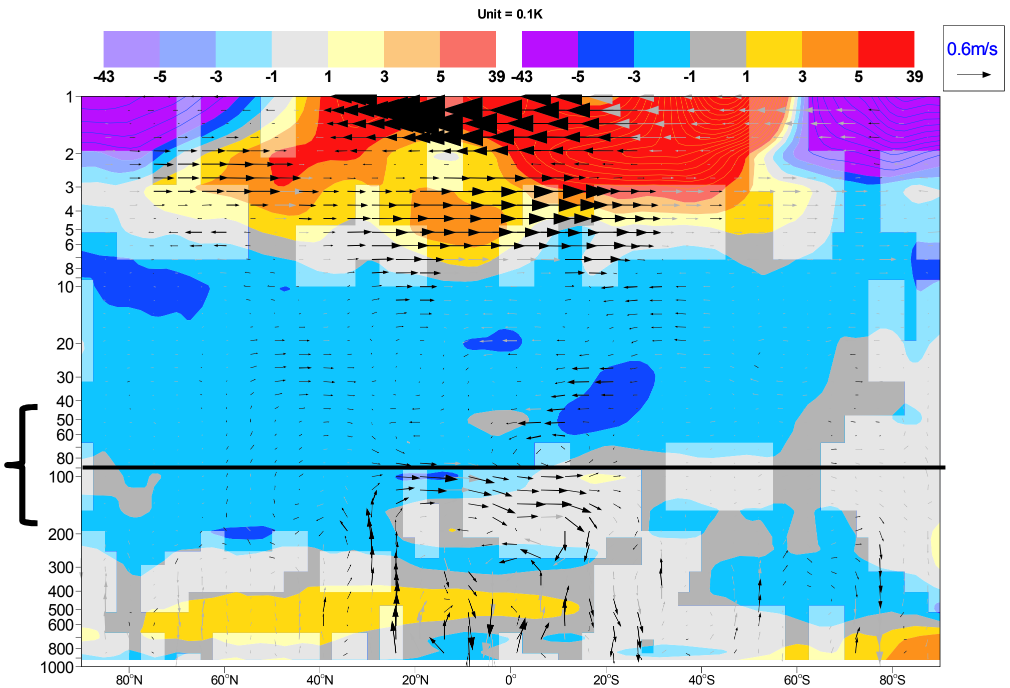


24 hour

Mean FcError

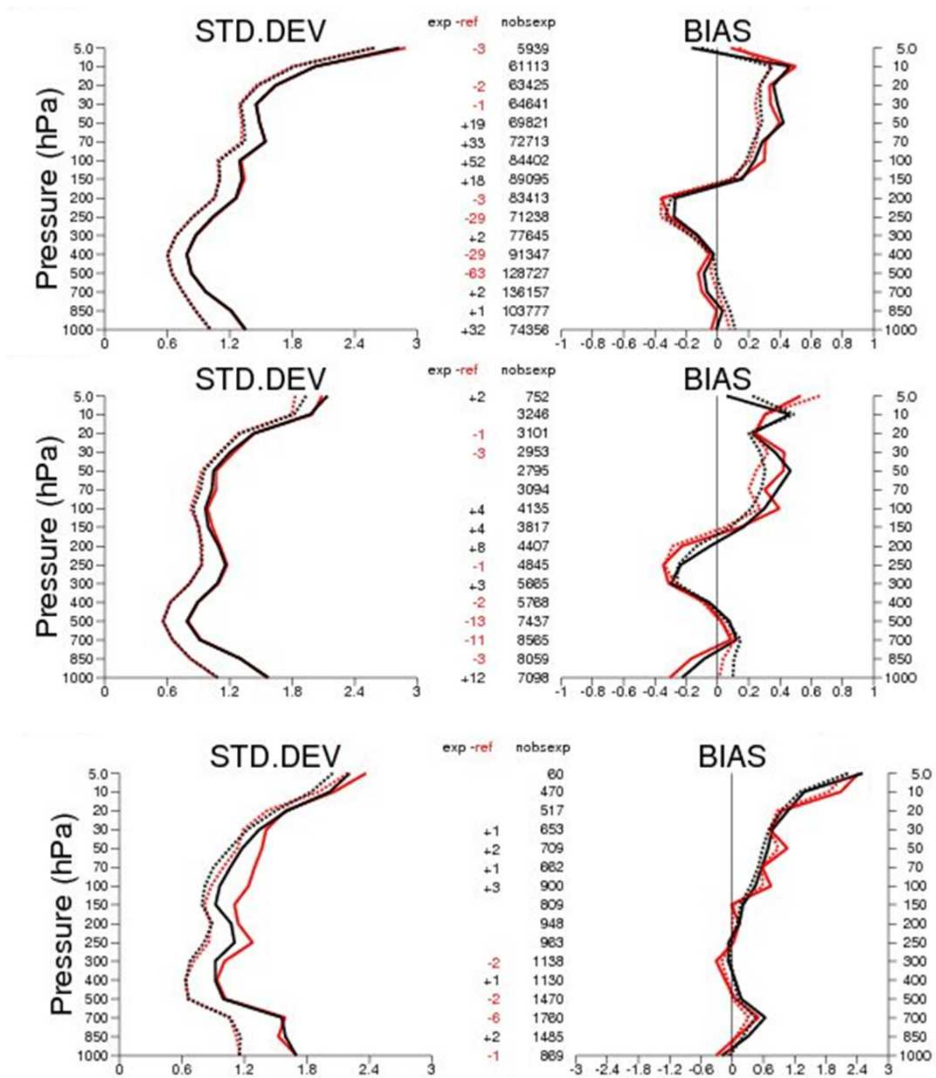
JJA

T & Wind



Radiosonde Temperature Obs-Departure June 2011

OSE: With versus Without GPS-RO



background departure o-b(ref)
background departure o-b
analysis departure o-a(ref)
analysis departure o-a

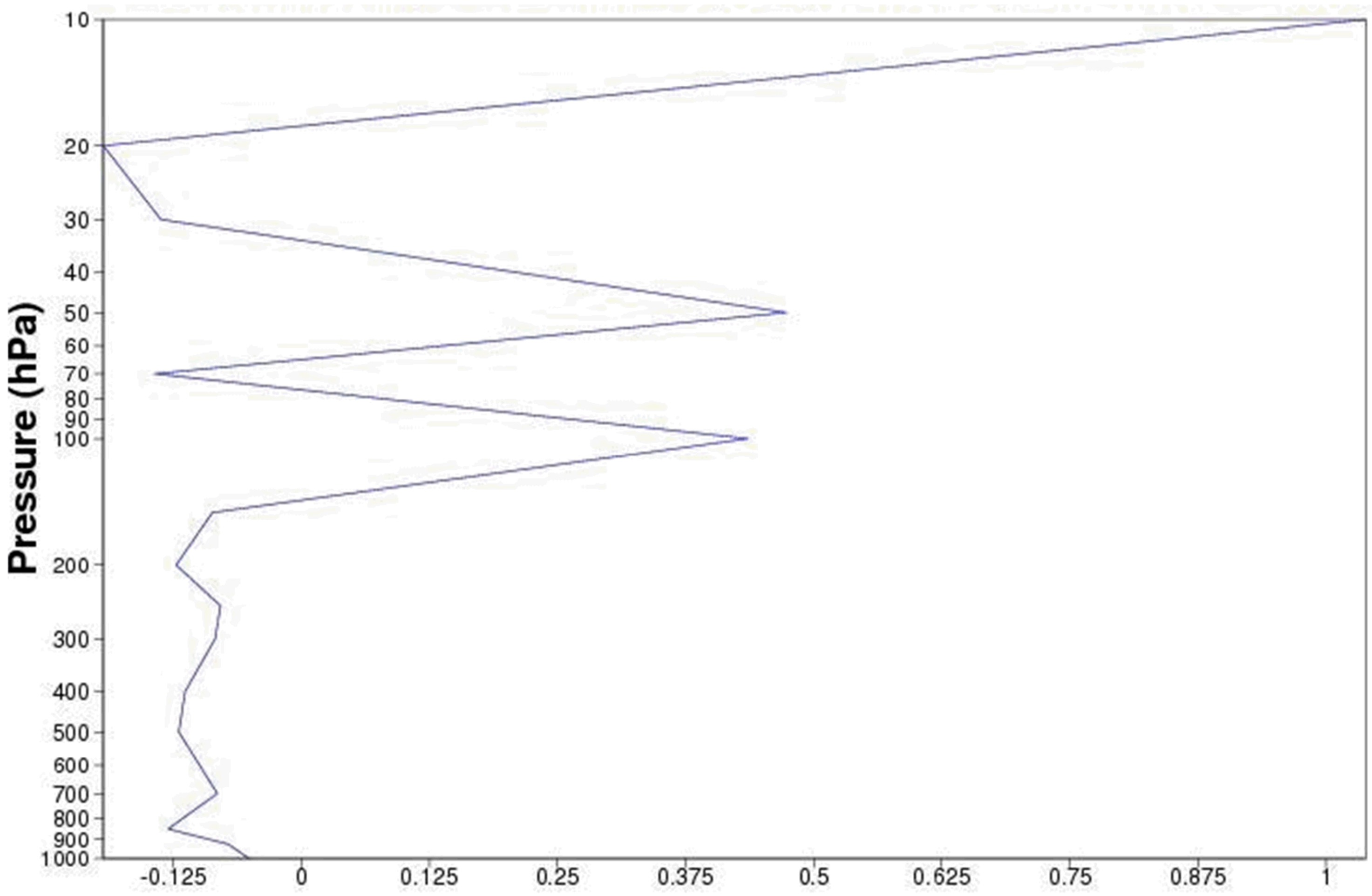
N. Hemisphere

North Pole

South Pole

Average Temperature Profile S.H. June 2011

OSE: With minus Without GPS-RO



Monitoring the assimilation and forecast system performance

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$$\mathbf{K} = \mathbf{K}(\mathbf{B}, \mathbf{R}, \mathbf{H}) = \mathbf{B}\mathbf{H}^T(\mathbf{R} + \mathbf{H}\mathbf{B}\mathbf{H}^T)^{-1}$$

Y Observation
X_b Background
B Model Accuracy
R Observation Accuracy
H Model

$$\mathbf{x}_f = M\mathbf{x}_a$$

$$\mathbf{e} = \mathbf{x}_f - \mathbf{x}_a^v$$

$$J(\mathbf{e})$$

$$\frac{\partial J_e}{\partial \mathbf{y}} \qquad \frac{\partial J_e}{\partial \mathbf{R}} \qquad \frac{\partial J_e}{\partial \mathbf{B}}$$

Monitoring the assimilation and forecast system performance

$$\mathbf{x}_a = \mathbf{K}\mathbf{y} + (\mathbf{I}_q - \mathbf{H}\mathbf{K})\mathbf{x}_b$$

B Model Accuracy
R Observation Accuracy
H Model

$$\mathbf{K} = \mathbf{K}(\mathbf{B},\mathbf{R},\mathbf{H}) = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

Forecast Error Sensitivity to Observation Error Covariance

$$\mathbf{B}^{-1}(\mathbf{x}_a - \mathbf{x}_b) + \mathbf{H}^T\mathbf{R}^{-1}(\mathbf{H}\mathbf{x}_a - \mathbf{y}) = 0$$

$$\frac{\partial J_e}{\partial \mathbf{R}} = \frac{\partial J_e}{\partial \mathbf{y}}(\mathbf{H}\mathbf{x}_a - \mathbf{y})^T\mathbf{R}^{-1}$$

$$\mathbf{R}_i(s_i{}^0) = s_i{}^0\mathbf{R}_i, i \in I$$

$$\mathbf{s} = (s_1{}^0, s_2{}^0, \ldots., s_I{}^0)$$

$$\overline{\mathbf{s}} = 1 \rightarrow \mathbf{R}$$

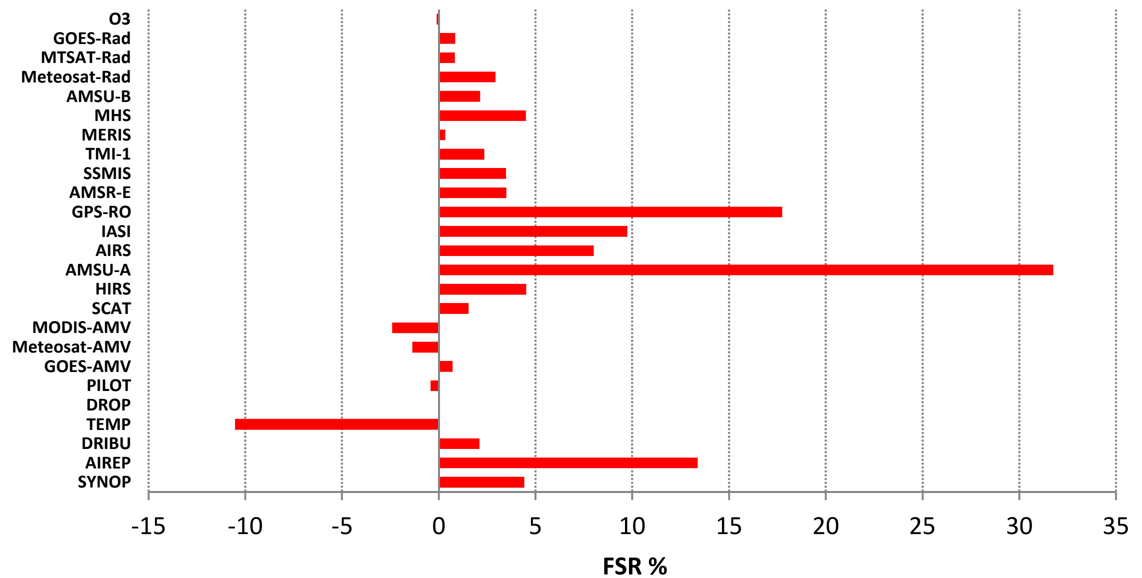
$$\overline{\mathbf{x}}_a = \mathbf{x}_a(\overline{\mathbf{s}})$$

$$\frac{\partial J_e}{\partial s_i{}^0} = (\mathbf{H}_i\overline{\mathbf{x}}_a - \mathbf{y}_i)^T\frac{\partial J_e}{\partial \mathbf{y}}$$

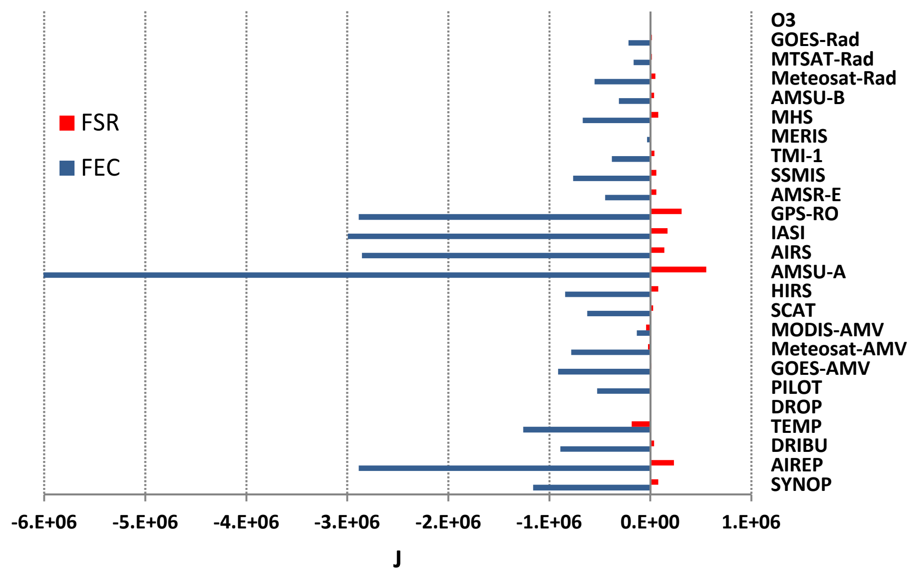
Desroziers&Ivanov 2001, Chapnik *et al* 2006, Desroziers 2009

Daescu 2008, Daescu&Todling 2010, Cardinali&Daescu2011

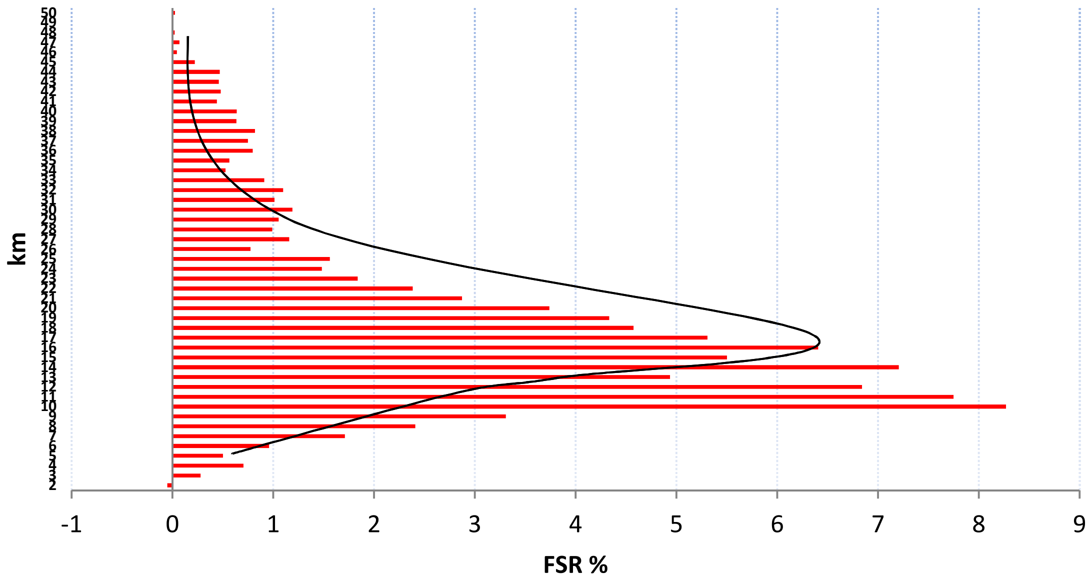
Forecast Sensitivity to R

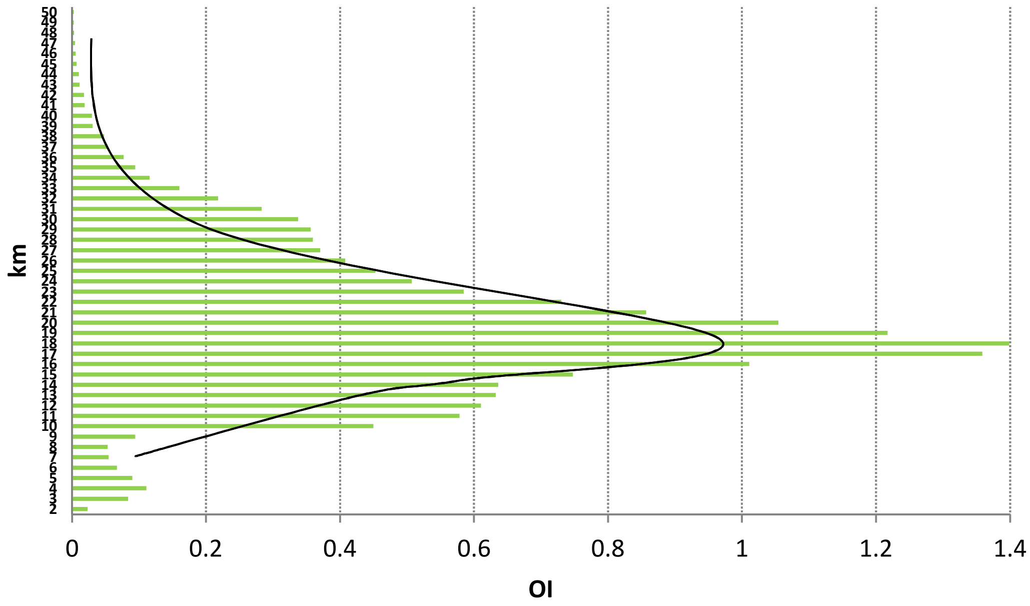


POSITIVE sensitivity values indicate that DEFLATION of the corresponding σ_o will be of benefit

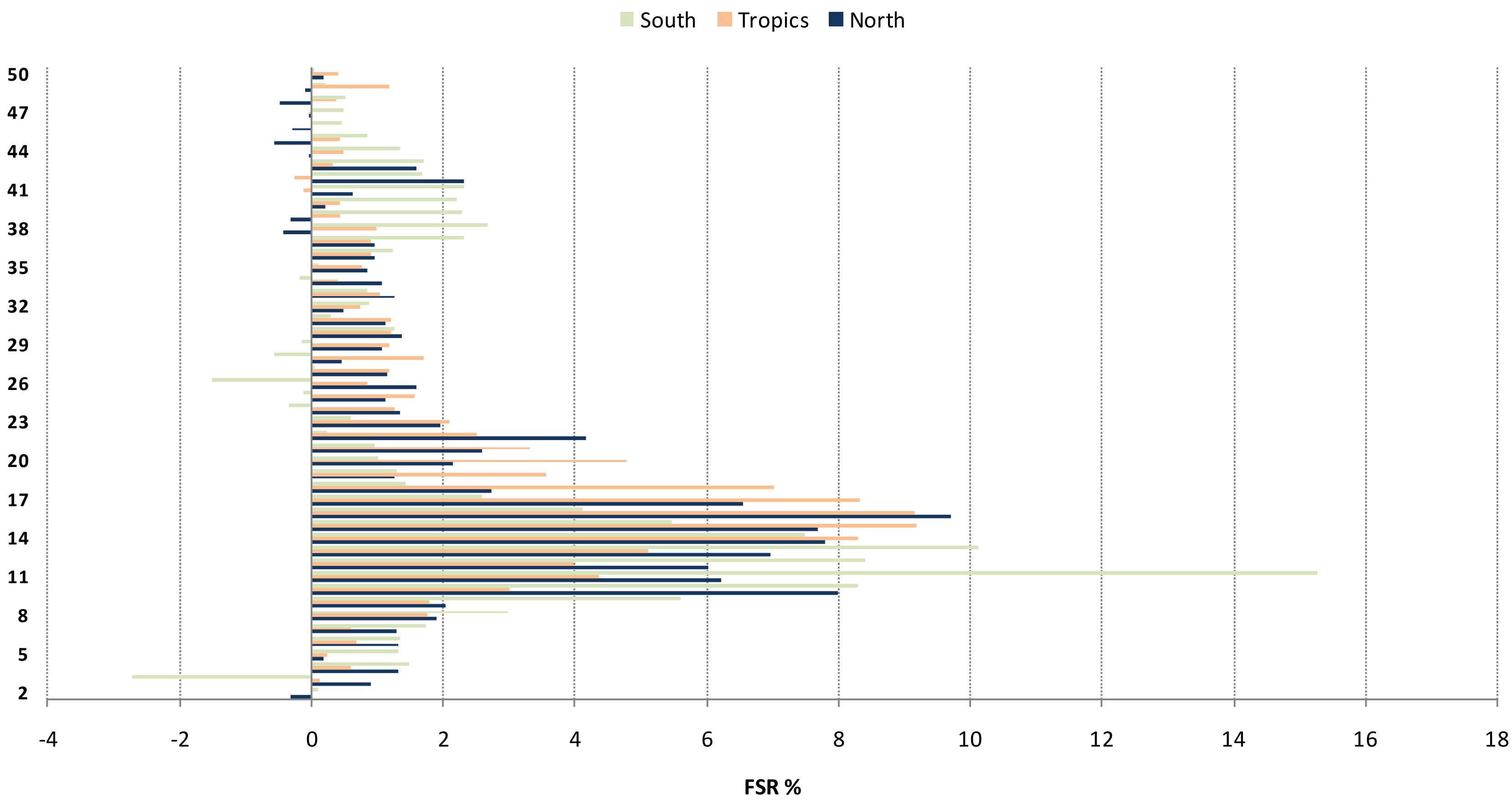


GPS-RO Forecast Sensitivity to σ_o





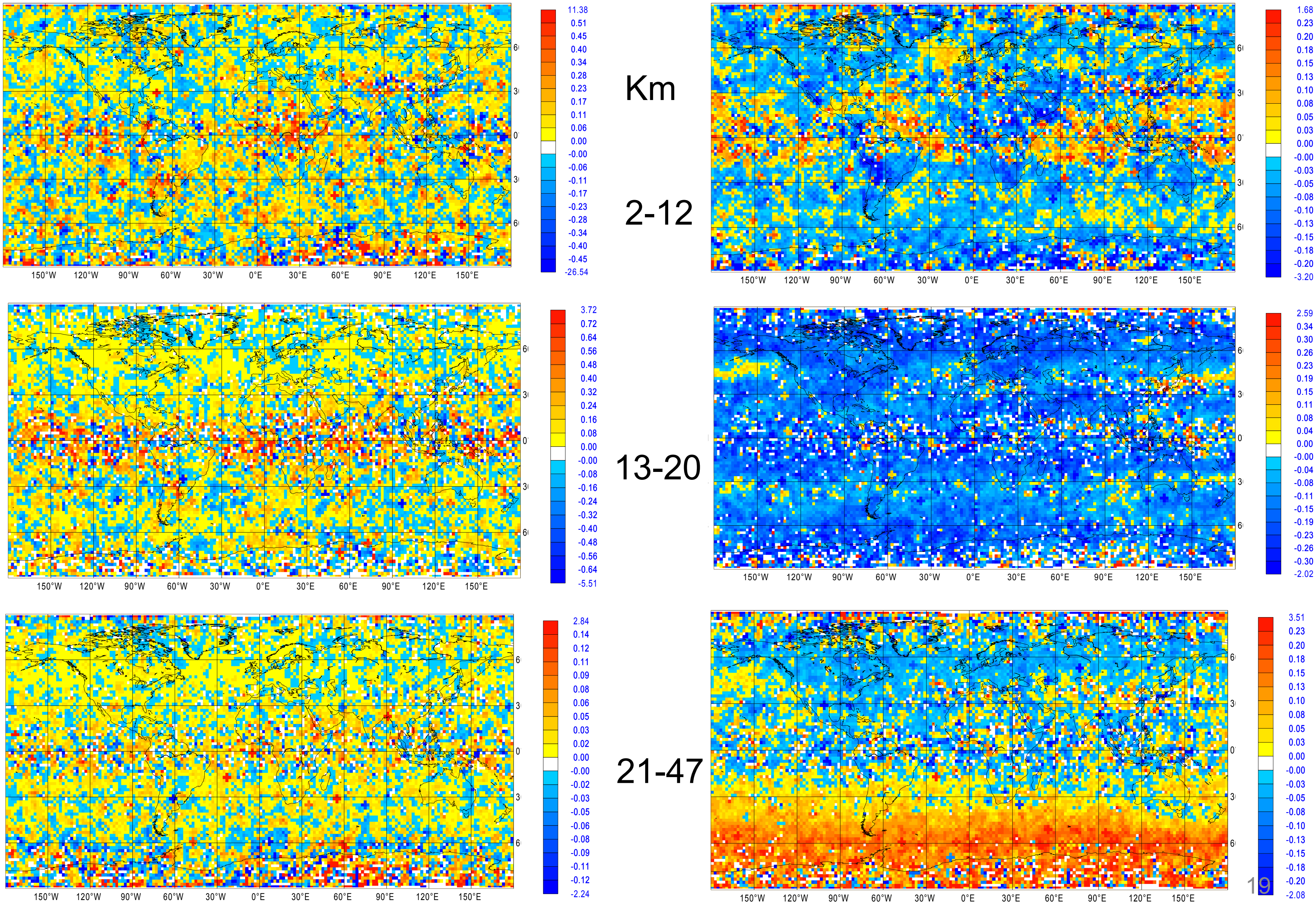
GPS-RO Forecast Sensitivity to σ_o



June 2011 GPS-RO

$$FSR = \frac{\partial J_e}{\partial \mathbf{y}}(\mathbf{H}\mathbf{x}_a - \mathbf{y})$$

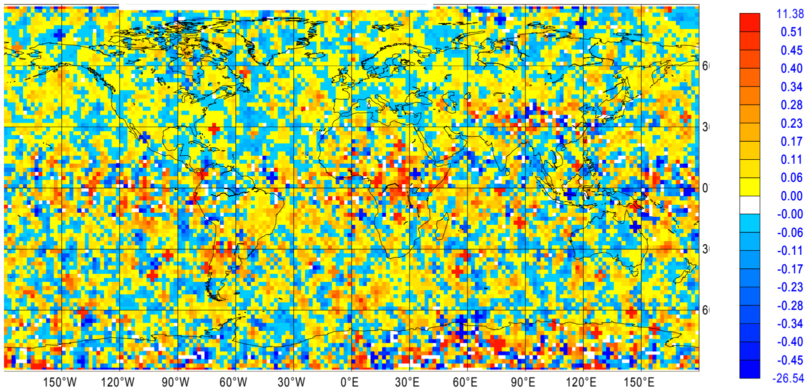
$$(\mathbf{y} - \mathbf{H}\mathbf{x}_a)$$



June 2011 GPS-RO

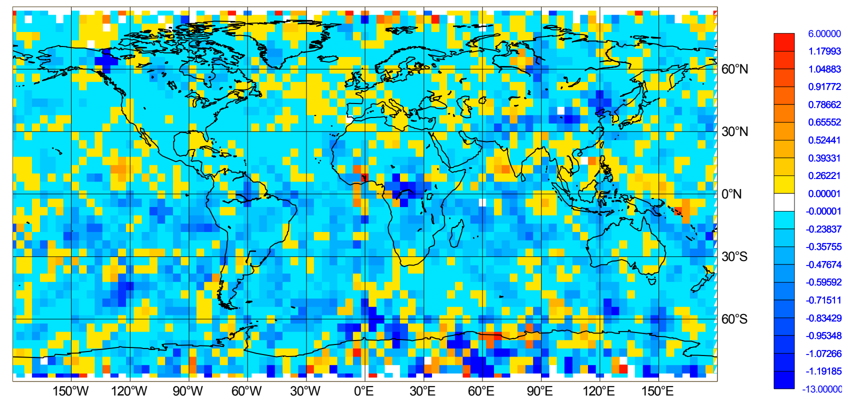
$$FSR = \frac{\partial J_e}{\partial \mathbf{y}}(\mathbf{H}\mathbf{x}_a - \mathbf{y})$$

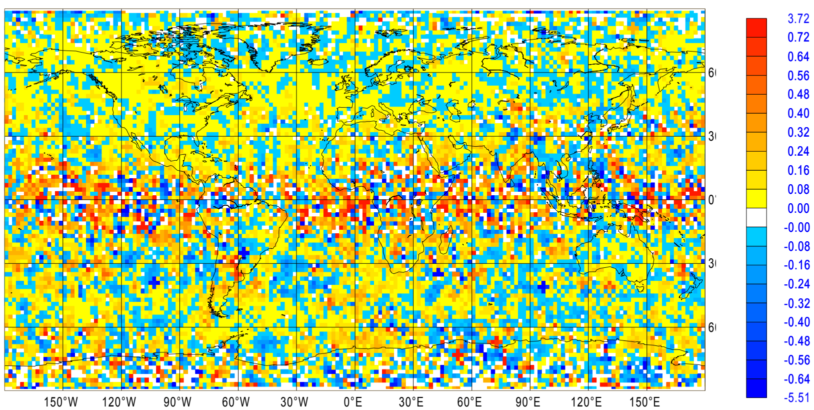
FEC



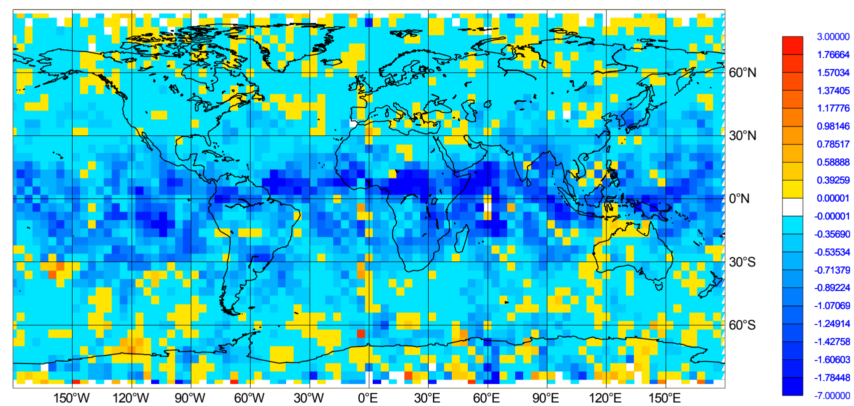
Km

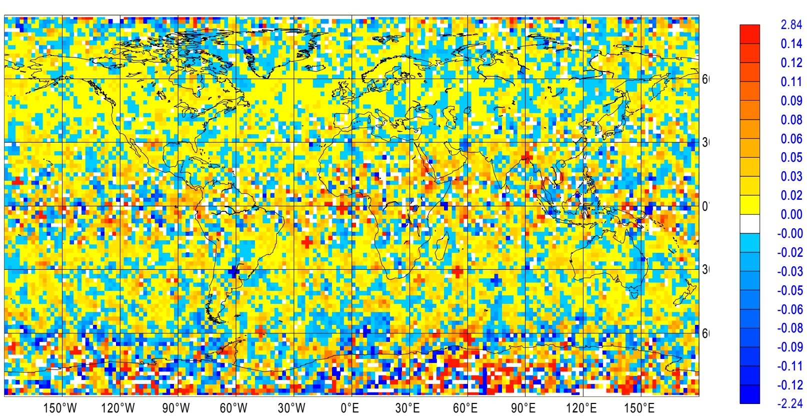
2-12



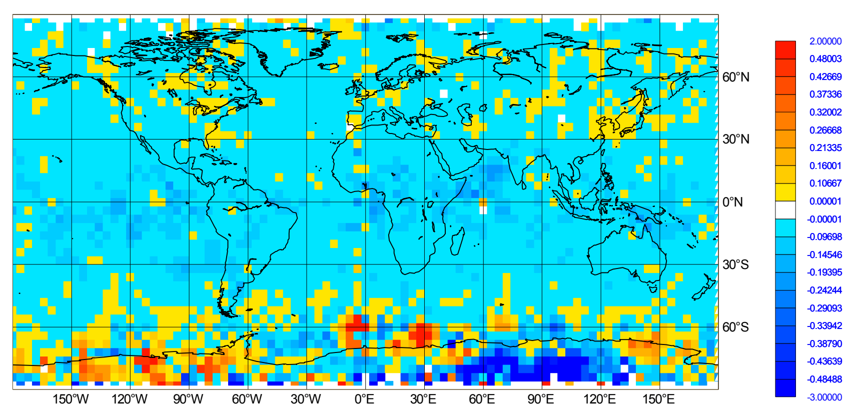


13-20

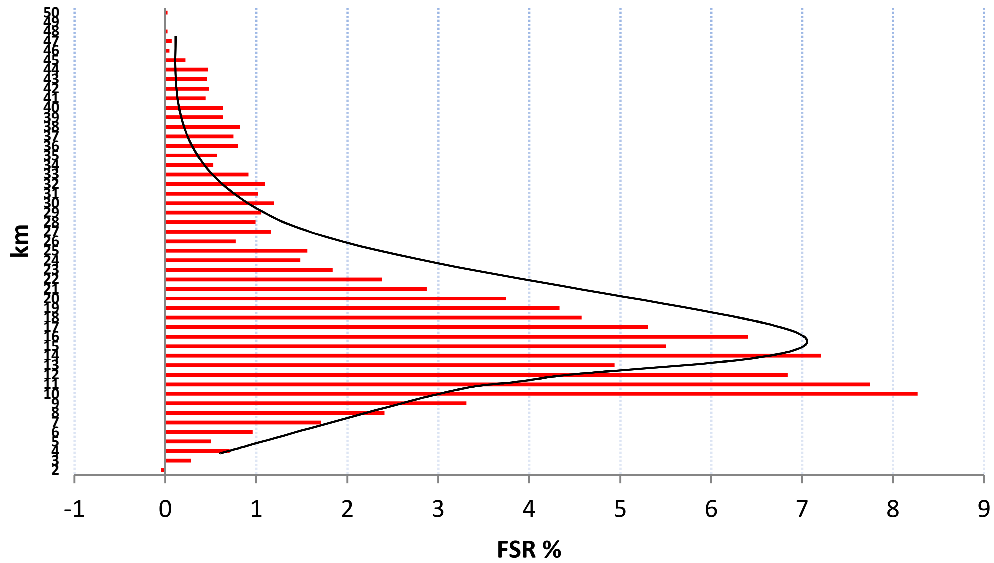


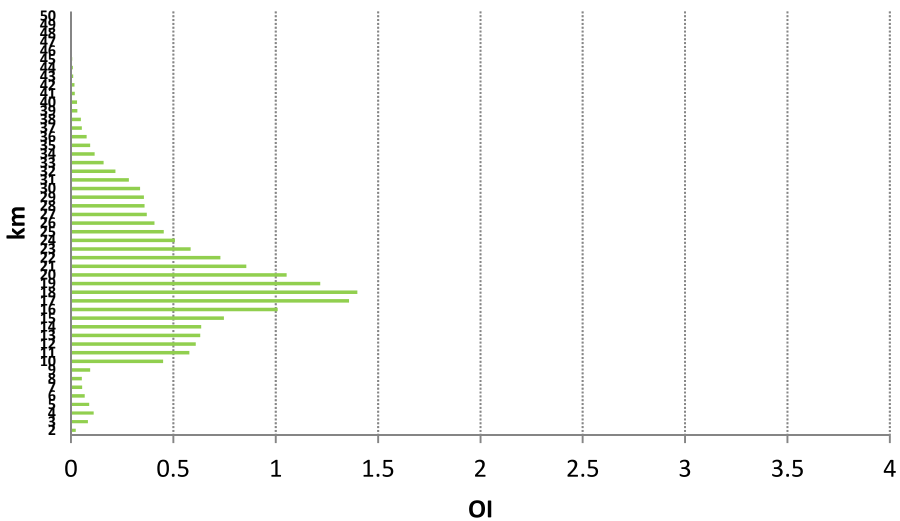


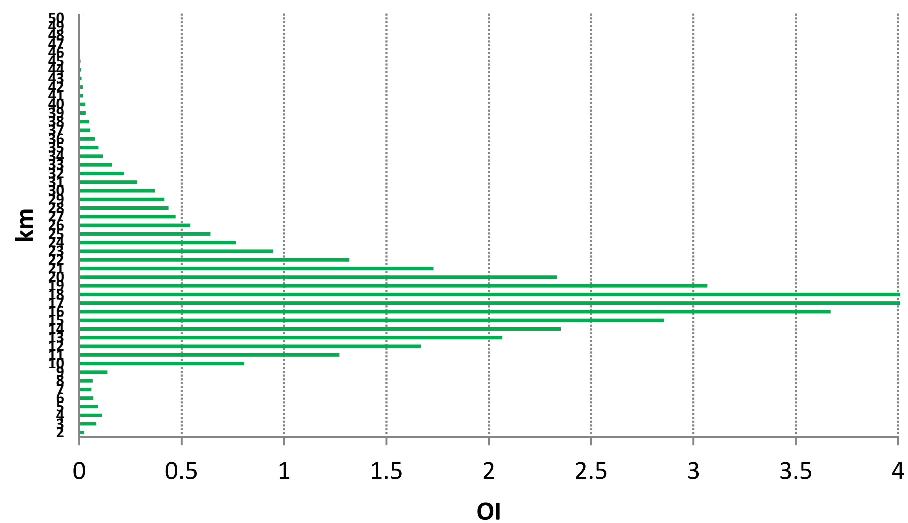
21-50



GPS-RO Forecast Sensitivity to σ_o



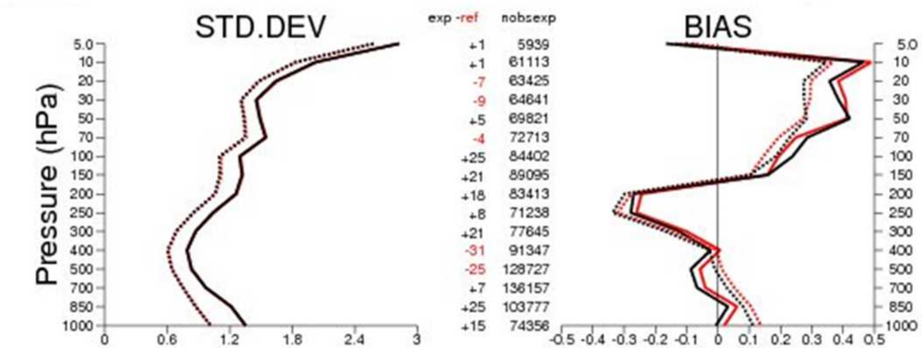




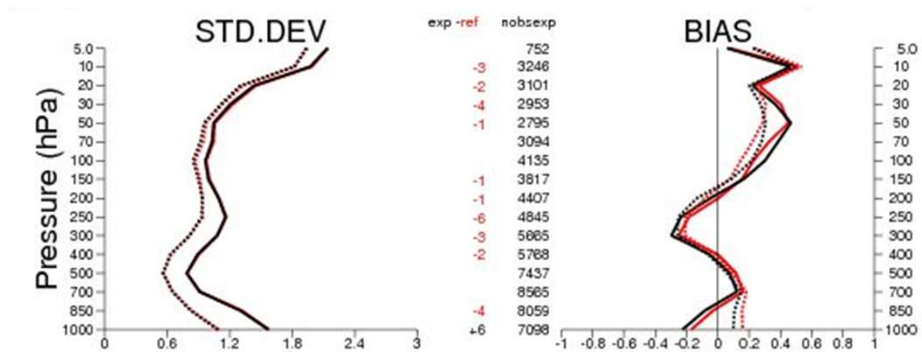
Radiosonde Temperature Mean Obs-Departure June 2011

OSE: CNTR versus Half_σₒ

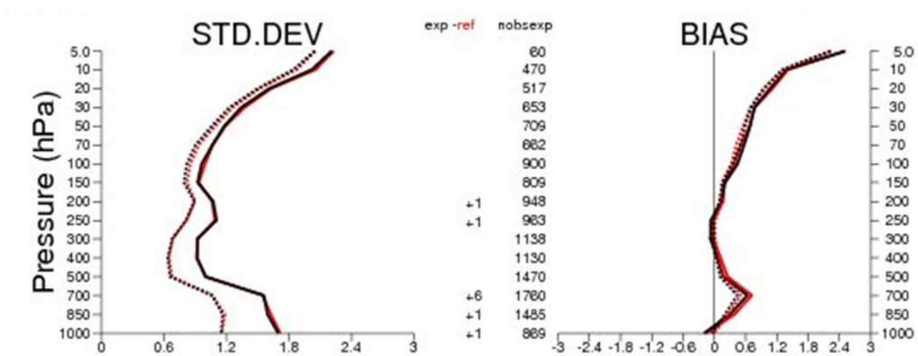
background departure o-b(ref)
background departure o-b
analysis departure o-a(ref)
analysis departure o-a



N. Hemisphere



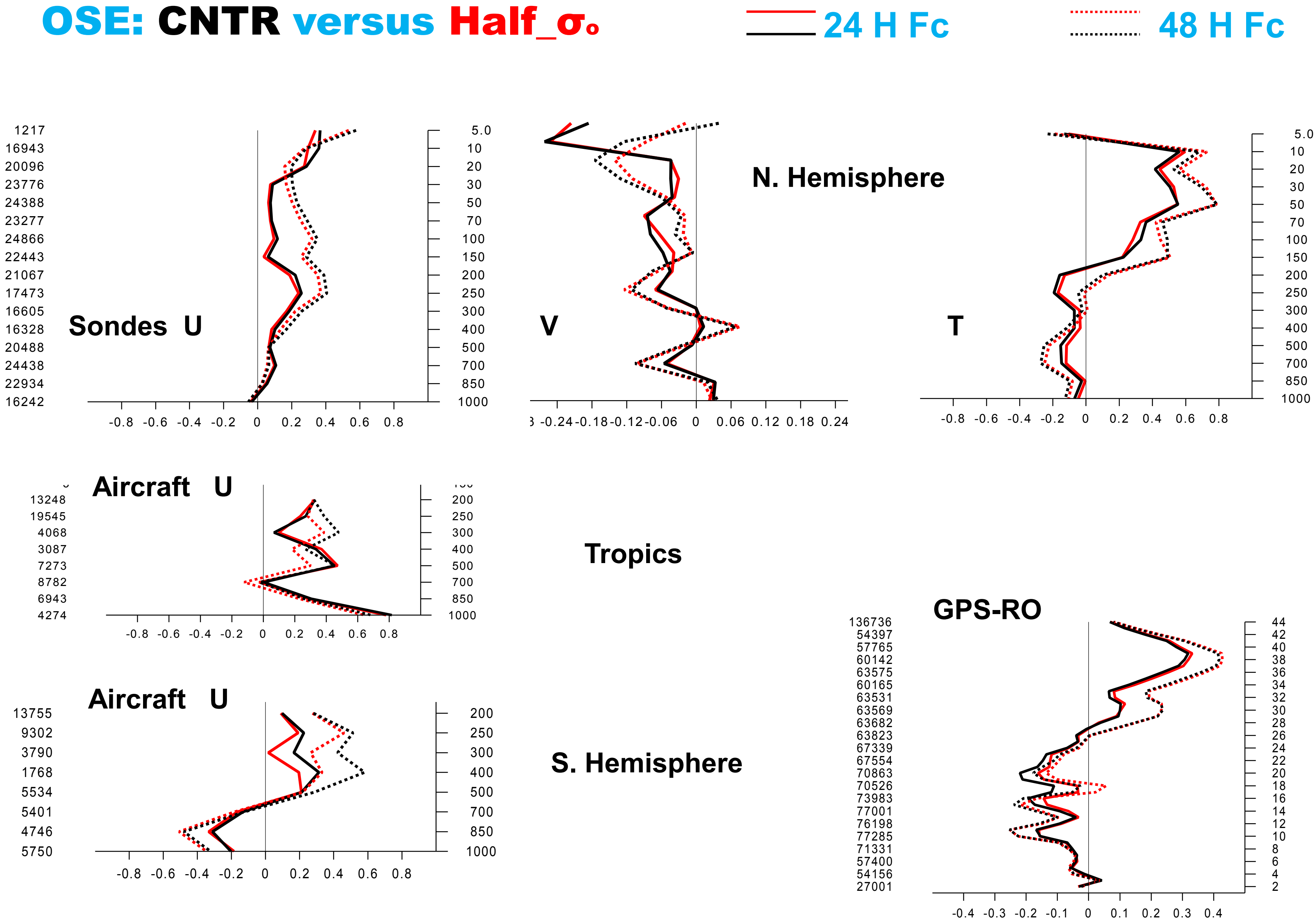
North Pole



South Pole

Mean Difference: 24 and 48 hour Forecast - Observations

OSE: CNTR versus Half_σₒ



Monitoring the forecast system performance

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$$\mathbf{K} = \mathbf{K}(\mathbf{B}, \mathbf{R}, \mathbf{H}) \qquad \mathbf{K} = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

B Model Accuracy
R Observation Accuracy
H Model

$$\mathbf{x}_f = M\mathbf{x}_a \qquad \mathbf{e} = \mathbf{x}_f - \mathbf{x}_a^v \qquad J(\mathbf{e})$$

$$\frac{\partial J_e}{\partial \mathbf{y}} \qquad \frac{\partial J_e}{\partial \mathbf{R}} \qquad \frac{\partial J_e}{\partial \mathbf{B}}$$

Monitoring the performance of the assimilation system and the short range forecast

$$\mathbf{x}_a = \mathbf{K}\mathbf{y} + (\mathbf{I}_q - \mathbf{H}\mathbf{K})\mathbf{x}_b$$

B Model Accuracy
R Observation Accuracy
H Model

$$\mathbf{K} = \mathbf{K}(\mathbf{B},\mathbf{R},\mathbf{H}) = (\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$$

Forecast Error Sensitivity to Background Error Covariance

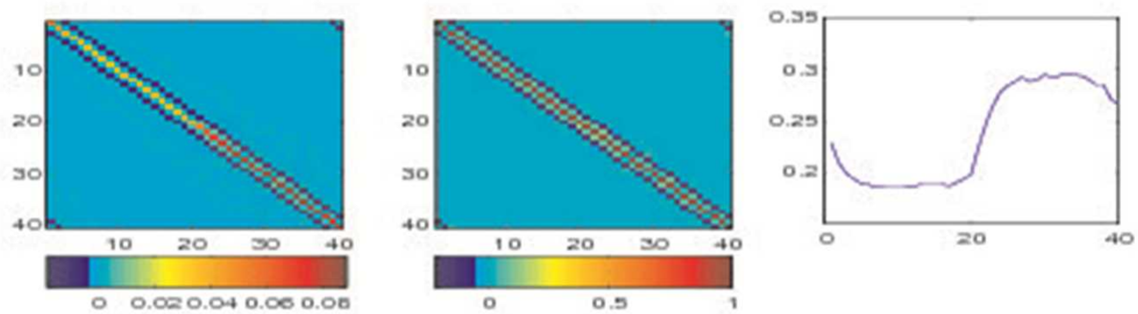
$$\mathbf{B}^{-1}(\mathbf{x}_a - \mathbf{x}_b) + \mathbf{H}^T\mathbf{R}^{-1}(\mathbf{H}\mathbf{x}_a - \mathbf{y}) = 0$$

$$\frac{\partial J_e}{\partial \mathbf{B}} = \frac{\partial J_e}{\partial \mathbf{x}_b}(\mathbf{x}_a - \mathbf{x}_b)^T\mathbf{B}^{-1}$$

FSB: Lorenz-EKF proof-of-concept-concept

Lorenz-40 variable system:
1-20 σ_o=0.5, 21-40 σ_o=1

DAS-1=Idealized EKF update B
5 year, 1-time-step=6h



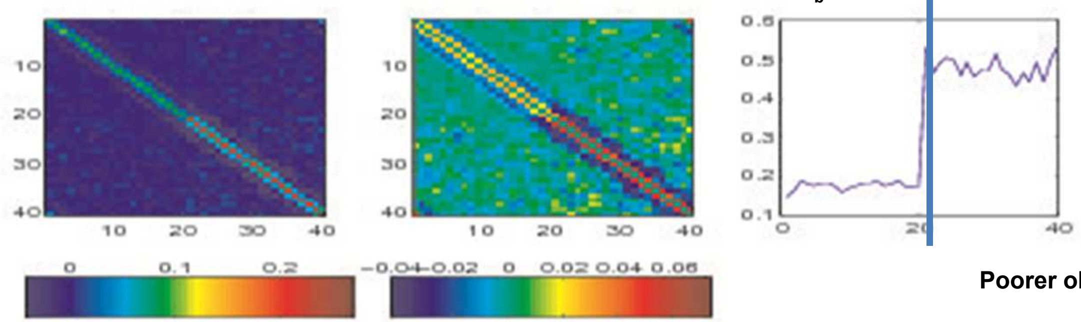
Time-average B= ΣC Σ **Time-average C** **Σ**

DAS with frozen B=I

$$\frac{\partial J_e}{\partial \mathbf{B}}$$

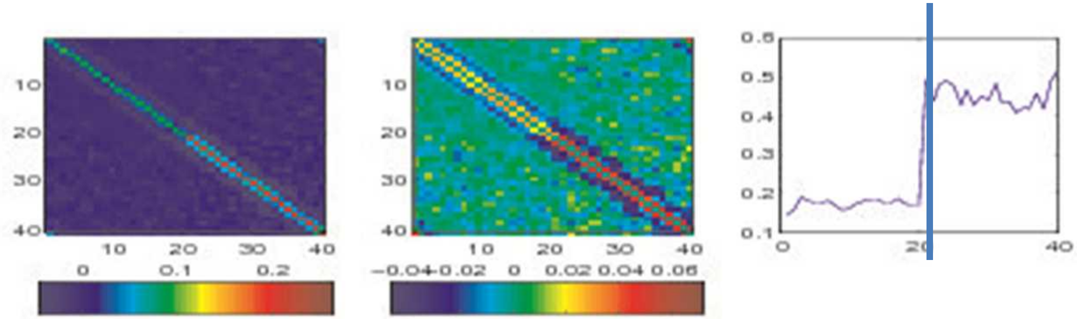
Truth as verification

POSITIVE sensitivity values indicate that DEFLATION σ_b will be of benefit



Poorer obs quality

Analysis as verification



Conclusions

- Over the last decade the assessment of each observation contribution to analysis and forecast has been among the most challenging diagnostics in data assimilation and NWP

- Recently, Daescu (2008) derived a sensitivity equation of an unconstrained variational data assimilation system with respect to the main input parameters: observation, background and their error covariance matrices

- Observation influence and forecast sensitivities have also been developed in a non-adjoint context. Junjie Liu *et al* 2008 and Junjie Liu *et al* 2009 translated the concepts to EnKF system and also showed that the solution is very accurate

- The power of the sensitivity tools is to diagnose the forecast behaviour from a global to regional scale and all throughout the atmosphere. Complementary tools should be used to assess the causes of improvement or degradation

- On average all observations reduce the 24 hour forecast error: GPS-RO reduces the forecast error by 10% together with IASI, AIRS and Aircraft

- Sensitivity to the observation error variance shows that there is a potential benefit if the variances are deflated for almost all the assimilated observations. Model bias reduction is observed when GPS-RO error variances are halved

- Sensitivity to the covariance matrices, B and R can provide guidance toward the real covariance matrices

The Fifth WMO Workshop on the Impact of Various Observing Systems on NWP
Sedona, AZ, United States
22 to 25 May 2012

The workshop will be organised in the following sessions:

- **Session 1: Global forecast impact studies**
- **Session 2: Regional forecast impact studies**
- **Session 3: Specific scientific areas (including network design)**
- **Session 4: Workshop discussions and conclusions.**

To receive an invitation to participate, please submit abstract and title to the organising committee via email to Karen.Clarke@ecmwf.int, by 15 November 2011

1st announcement can be found in the concourse

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Geometrical illustration of the sensitivity guidance in 3D space s=(1,1,1)

positive derivative means the functional aspect will decrease if we decrease the parameter value

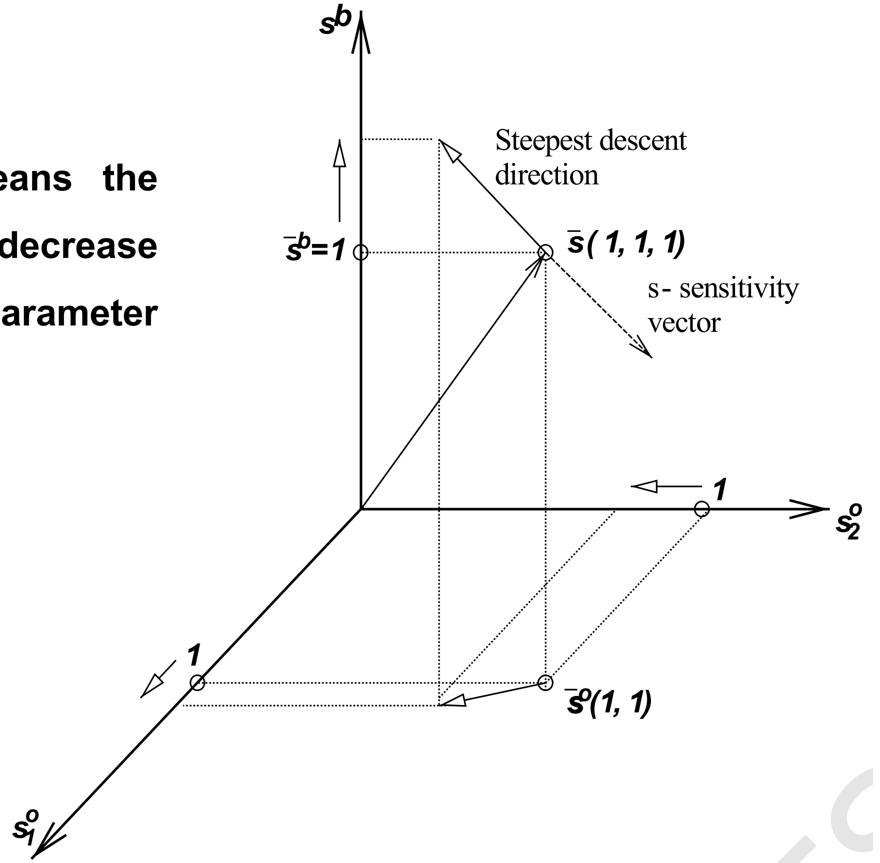

Figure 6. Illustration of the guidance provided by the forecast-error sensitivity to the DAS error covariance weight parameters. The sensitivity vector allows the identification of descent directions in the parameter space that may be used to achieve forecast-error reduction. Increasing the parameter values corresponds to the error covariance inflation in the DAS.