The relative contributions of the various space observing systems to the ECMWF forecast system

G. Kelly and J-N. Thépaut

ECMWF
Reading, U.K.

Abstract

The study was sponsored on behalf of EUMETSAT to evaluate the impact of the space component of the Global Observing System (GOS) through Observing System Experiments. In this study the relative contributions of the various space observing systems have been assessed within the context of the ECMWF data assimilation system.

It is inspiring to see that all the space base sensors contribute in a positive way to the overall improvement of the ECMWF forecast system. Sensors like AMSUA, AIRS and HIRS are clearly very important. In addition the humidity analysis requires AMSUB (also MHS), GEO CSRs and SSMI. SCATT clearly impacts on the surface wind in the Southern Hemisphere and finally the impact of AMVs and MODIS winds is clearly demonstrated.

Context

At its meeting at ECMWF on the 3rd of May 2003, the EUCOS Scientific Advisory Team (E-SAT) discussed the need to investigate the interdependencies between the space-based and terrestrial components of the observing system. It was suggested that such an investigation could be based on a set of carefully designed Observing System Experiments (OSEs). Studies should be designed so as to provide guidance on the future development of the terrestrial observing system in view of the increasing capabilities of the satellite observing systems provided by the meteorological space agencies. In recent years, several NWP centres have demonstrated substantial benefit from the assimilation of e.g. ATOVS radiances and scatterometer winds. In 2003 data have become available from the first in a series of second-generation radiometers (AIRS on AQUA) providing significantly enhanced temperature and humidity sounding capabilities - to be followed (in the 5-10 year time frame) by similar instruments on the future operational METOP and NPOESS series of satellites.

It was agreed that, as far as EUCOS is concerned, the primary issues were:

What are the relative contributions of various components of the terrestrial observing system within the current overall composite observing system?

How should the terrestrial systems evolve over the next five to ten years and beyond to complement the projected evolution of the space-based observing systems?

An OSE study project specifically designed to evaluate the role of the terrestrial component of the Global Observing System has been sent to and reviewed by EUCOS
managing (Andersson et al. 2004). The first set of OSEs have been performed following the guidelines indicated in Andersson et al. (2004) and reports are available.

**Assessing the current Space Observing System**

Following a number of discussions between EUMETSAT, ECMWF and EUCOS, it was agreed that specific OSEs dedicated to examining the various contributions of the different components of the Space Observing System were necessary to complement the original proposal and provide a comprehensive assessment of the Space/Terrestrial links. It was also agreed that the robustness of this combined assessment would be strengthened by the adoption of similar strategies for experimentation and validation between the two proposed studies.

This proposal also takes onboard one of the outcomes of the Third WMO Workshop on the Impact of Various Observing Systems on NWP, which suggested that due to a large degree of redundancy of the Global Observing System (GOS), performing impact studies by removing one element of the GOS can show very limited impact and does not necessarily highlight the intrinsic benefit of the element in question. The scenarios in which the contributions of different elements of the GOS are investigated are by adding datasets or combination of datasets to a reference.

**Observing System Experiment Studies**

Previous studies suggest the overwhelming importance of satellite observations as a whole in NWP (Kelly et al. 2004). We have investigated the current relative contributions of the various space observing systems within the context of the ECMWF data assimilation system. In the proposed studies, we will assume that the current full conventional Observing System is maintained, and the main focus here is to evaluate how specific satellite systems (infrared temperature soundings, microwave temperature soundings, imagers, scatterometers, etc…) contribute individually to the robustness of the GOS. Because the evaluation of satellite sensors is best done in the Tropics and Southern Hemisphere a reference system was chosen to be the full conventional system (NO SAT) plus the AMVs. The NO SAT is considered too poor to provide a good analysis outside the Northern Hemisphere.

The observational scenarios tested are:

(i) **BASELINE** all conventional observations used in NWP (radiosonde + aircraft + profiler network + surface land data + buoy observations + ship data)

(ii) **REFERENCE** = **BASELINE** + Atmospheric Motion Vectors (AMVs) from GEO+MODIS

(iii) **REFERENCE** + **HIRS** radiances

(iv) **REFERENCE** + **AMSUA** radiances

(v) **REFERENCE** + **AMSUB** radiances

(vi) **REFERENCE** + **SSMI** radiances

(vii) **REFERENCE** + GEO Clear Sky Radiances (CSR)

(viii) **REFERENCE** + **AIRS** radiances

(ix) **REFERENCE** + **SCATT** winds
Experimental set-up

The data assimilation framework used for all the OSEs presented in this report corresponds to the system operational until June 2005 (cycle 29r1). The main characteristics are listed below:

- T511 L60 forecast model resolution
- 4D-Var assimilation, 12 hour window
- T95/T159 L60 analysis inner loop resolution
- T511 L60 analysis outer loop resolution
- Conventional observations currently assimilated in the system include:
  - Radiosondes, Pilots and wind profilers
  - Synops, Ships, METARS and buoys (moored and drifters)
  - Aircrafts (AMDARS, AIREPS, ACARS) including ascent/descent reports
- Satellite observations assimilated in the system for the atmospheric analysis were at that time for the winter run:
  - Atmospheric Motion Vectors from GEO (Met-5/7, Goes-9/10/12 and LEO (MODIS Terra and Aqua) platforms
  - Clear-sky water vapour radiances from GEO (Met-5/8, Goes-9/10/12)
  - Level 1c IR radiances from NOAA-14/17 (HIRS) and AQUA (AIRS)
  - Level 1c μW radiances from NOAA-15 (AMSU-A), NOAA-16 (AMSU-A and AMSU-B), NOAA-17 (AMSU-B), AQUA (AMSU-A) and DMSP 13/14/15 (SSM/I)
  - Sea surface winds from scatterometers QuikScat and ERS-2
  - Ozone products from NOAA-16 (SBUV) and ENVISAT (SCIAMACHY).

In the summer experiments the analysis was changed to cycle 29R2 to include data from the new satellite NOAA 18:

NOAA-14 HIRS was blacklisted due to becoming noisy and data from NOAA-18 Level 1c IR radiances from AMSUA and MHS were included.

In compliance with the study, two sets of assimilation have been performed:

(a) Winter period, from 20041204 until 20050125

(b) Summer period from 20050715 until 20050915.

The first 10 days are excluded from the verification to ensure a reasonable warm-up phase for each assimilation scenario. No real difference in the impact was found between summer and winter so the mean scores were combined to give a sample of 89 days for each experiment. In total more than 1000 days of data assimilation were run including the warm up period. All experiments are validated using the operational analysis.
Assimilation assessment

The evaluation of this phase of the report is presented in terms of mean anomaly correlation, geographical maps of RMS error differences and mean RMS error differences including statistical significance. The largest impact occurs in the Southern Hemisphere and in the Tropics, here the relative differences between different satellite instruments are more clearly seen.

Validation of the use of a REFERENCE assimilation for evaluation of various space components.

In the Southern Hemisphere the BASELINE system (without satellite data) was considered too poor as a basic reference. The two figures below show the large improvement in both hemispheres by adding the AMV’s. The forecast impact is evaluated in terms of Geopotential 500 hPa Height (anomaly correlation for mean scores and Normalised RMS error for geographical and scatter plots).
Evaluation of control data assimilations

(a) CONTROL minus BASELINE (Impact relative to Radiiances+AMVs)
The plots, shown above, are normalized RMS of Geopotential height differences. In the Southern Hemispheric analyses are very different. The BASELINE is too poor to act as a reference to evaluate satellite sensors.
(b) **CONTROL minus REFERENCE** (Relative impact of Radiances)

![Diagram 1](image1)

**scatter plot**

control minus reference

Root mean square error forecast

N. hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050905 00UTC

500hPa Geopotential 00UTC
confidence: 99 % population: 89

Population: 89

![Diagram 2](image2)
The plots, shown above, are normalized RMS of Geopotential height differences. In the Southern Hemisphere the two analyses remain very different. The REFERENCE system which is now the BASELINE plus AMVs is considerably improved compared with NOSAT baseline. This system (REFERENCE) is used to add radiances from a single satellite sensor type (eg: AIRS (aqua) or AMSUA(several satellites)) to study forecast impact.
(c) **REFERENCE minus BASELINE** (Relative impact of AMVs on NOSAT)

![Graph showing the relative impact of AMVs on NOSAT](image)

**scatter plot**

reference minus baseline

 Root mean square error forecast

N: hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050305 00UTC
500hPa Geopotential 00UTC
confidence: 90% population: 89
Population: 89
The plots, shown above, are normalized RMS of Geopotential height differences. In Northern Hemisphere the impact of the AMVs are small but in the Southern Hemisphere analysis the addition of the AMVs substantially improve the assimilation.

RESULTS

A series of seven different data assimilation (corresponding to different observation scenarios) have been run for a summer and winter period.

All these data assimilation experiments have a sensor type added to the REFERENCE assimilation from the operational data stream. Some sensors (e.g. AMSUA) are on various operational satellites whereas AIRS only flies on AQUA.

Two additional experiments have been run to evaluate:

(a) The impact of the MODIS winds and this has been done by removing MODIS winds from the ‘REFERENCE’.

(b) A comparsion of AIRS (which includes humidity and temperature channels) with of two microwave instruments AMSUA and AMSUB.

AMSUA is sensitive to temperature and AMSUB humidity. The results of this study does not fit logically with the other experiments and will be included in appendix (a)

The evaluation of forecasts has also been done using three variables and at various levels:
Geopotential 500 hPa Height (anomaly correlation for mean scores and Normalised RMS error for geographical and scatter plots)
Relative Humidity at 850,500 and 200 hPa (mean scores in percent and Normalised RMS error for geographical and scatter plots)

Vector wind at 1000 and 200 hPa (mean scores in percent and Normalised RMS error for geographical and scatter plots)

At a particular level and variable the mean curves show the impact from the eight experiments, however only the sensors that show impact are further validated with geographical and significance scatter plots.

The mean plots are grouped into three selections of sensors in order to avoid too much congestion on a single plot:

AMSUA, HIRS and AIRS

SSMI, AMSUB and GEO CSR

SCATT, GEO AMV and GEO CSR (repeated)

(a) 500 hPa Geopotential Height

The overall impact on geopotential height in the troposphere is similar at all levels, hence, plots are shown at 500 hPa. It is evident from the three sets of plots below that AMSUA, AIRS and HIRS are clearly the sensors with the strongest impact. In addition significant impact comes from the removal of the MODIS winds from the reference system.
Impact of adding AMSUA to the REFERENCE
Impact of adding AIRS to the REFERENCE

![Graph showing the impact of adding AIRS to the REFERENCE configuration.](image1)

**scatter plot**

reference+airs minus reference

Root mean square error forecast

N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0

winter 43 cases summer 46 cases

500hPa Geopotential 00UTC

confidence: 95 population: 89

![Scatter plot showing the root mean square error for reference+airs minus reference.](image2)
scatter plot
reference-airs minus reference
Root mean square error forecast
S.hem Lat -90.0 to -20.0, Lon -180.0 to 180.0
winter 43 cases summer 46 cases
500hPa Geopotential 00UTC
confidence 95% populations 95
Impact of adding HIRS to the REFERENCE
scatter plot
reference+hirs minus reference
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
date: 20041216 00UTC to 20050305 00UTC
500hPa Geopotential 00UTC
certainty: 99 % population: 89
Population: 89
Impact of removing MODIS from the REFERENCE

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**NormDiff in RMS of fc-Error: (REFERENCE) - (GEO_AMV)**
Lev=500, Par=z, fcDate=20041214-20050125 0Z, Step=48 Cases=43
NH=0.01 SH=-0.14 Trop=0 Eur=0 NAmor=-0.01 NAtl=-0.01 NPac=0

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**scatter plot**
reference minus reference-modis amv
Root mean square error forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050905 00UTC
500hPa Geopotential 00UTC
confidence: 90 % population: 89
Humidity

The influence of the humidity observations on the forecast are mostly in the tropics and their influence on the forecast decays more quickly in time than geopotential. As a consequence humidity verification has been focused on the short range forecast (to day four).

The results are also evaluated at three atmospheric levels as different satellite sensors sense different regions of the troposphere.

Relative humidity at 850 hPa

With reference to the mean plots below, SSMI is the most important sensor affecting this level. Even after adding SSMI to the REFERENCE there is still relative large gap to the CONTROL suggesting the there is a small but additive contribution of many other sensors contributing to the moisture analysis.
Mean curves
850hPa Relative humidity
Root mean square error forecast
Tropics Lat -20.0 to 20.0 Lon -180.0 to 180.0
Date: 20041214 00UTC to 20050605 00UTC
Mean calculation method: standard
Population: 80 (averaged)

Forecast Day
Impact of adding SSMI to the REFERENCE

scatter plot
reference+ssmi minus reference
Root mean square error forecast
Tropics Lat -20.0 to 20.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050905 00UTC
850hPa Relative humidity 00UTC
certainty: 90 % population: 89
Population: 89
Relative humidity at 500 hPa

With reference to the mean plots below AMSUB and CSRs (particularly in the SEVIRI region) are the most important sensors affecting this level.
Mean curves
500hPa Relative humidity
Root mean square error forecast
Tropics Lat -20.0 to 20.0 Lon -180.0 to 180.0
Date: 20041214 00UTC to 20050505 00UTC
Mean calculation method: standard
Population: 89 (averaged)

(i) +scat
(ii) +geo amv csr
(iii) +geo rads
eumet base(i)
control
reference (ii)
Impact of adding AMSUB to the REFERENCE
Impact of adding CSRs to the REFERENCE
Relative humidity at 200 hPa

With reference to the mean plots below AMSUB, CSRs and HIRS are the most important sensors affecting this level.
Mean curves
200hPa Relative humidity
Root mean square error forecast
Tropics Lat -20.0 to 20.0 Lon -180.0 to 180.0
Date: 2004/12/14 00UTC to 2005/06/05 00UTC
Mean calculation method: standard
Population: 89 (averaged)

Forecast Day
Impact of adding AMSUB to the REFERENCE
Impact of adding CSRs to the REFERENCE

scatter plot
reference+csr minus reference
Root mean square error forecast
Tropics Lat -20.0 to 20.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050905 00UTC
200hPa Relative humidity 00UTC
confidence: 90% population: 89
Impact of adding HIRS to the REFERENCE
Vector Wind

The influence of the satellite sensors on the vector wind is strongest in Tropics and Southern Hemisphere.

Analysis of the impact is done for lower and upper levels as different satellite sensors sense different regions of the troposphere.

Surface wind (1000 hPa )

![Surface wind (1000 hPa) graph](image)
**Mean curves**

**1000hPa Vector Wind**

Root mean square error forecast

- Tropics Lat -20.0 to 20.0, Lon -180.0 to 180.0
- Data: 20041214 00UTC to 20050105 00UTC
- Mean calculation method: standard
- Population: 89 (averaged)

Forecast Day

- Reference + scat
- Baseline + geo amv
- Reference + geo rads
- Baseline
- Control
- Reference
Impact of adding HIRS to the REFERENCE

![Map of Normalized Difference in RMS of fc Error](image1)

**NormDiff in RMS of fc-Error:** (REFERENCE+HIRS) - (REFERENCE)

- **Level:** 1000
- **Parameter:** vwind
- **fcDate:** 20041214-20050125 02Z
- **Step:** 24
- **Cases:** 43

- **NH:** 0.01
- **SH:** 0.14
- **Trop:** 0.02
- **Eur:** 0
- **NAmor:** 0
- **NAtl:** 0
- **NPac:** 0.02

![Scatter Plot](image2)

**Scatter Plot**

- **Reference+HIRS minus Reference**
- **Root Mean Square Error Forecast**
- **Southern Hemisphere Lat:** -90.0 to -20.0
- **Lon:** -180.0 to 180.0
- **Date:** 20041214 00UTC to 20050905 00UTC
- **1000hPa Vector Wind 00UTC**
- **Confidence:** 99%
- **Population:** 89

![Graph](image3)

**Graph**

- **Forecast Day**
- **Mean Difference / Mean Score**
- **Forecast Day:** 0 to 8
Impact of adding AMSUA to the REFERENCE

![Impact of adding AMSUA to the REFERENCE](image1)

![Impact of adding AMSUA to the REFERENCE](image2)
Impact of adding SSMI to the REFERENCE
Impact of adding AIRS to the REFERENCE

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scatter plot
reference+airs minus reference
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
date: 2004/12/14 00UTC to 2005/01/05 00UTC
1000hPa Vector Wind 00UTC
confidence: 90% population: 89
Impact of adding SCAT to the REFERENCE

![Graph showing the impact of adding SCAT to the reference.](image)

![Scatter plot showing the root mean square error forecast.](image)
Upper level wind (200hPa)

![Graph showing mean curves for 200hPa Vector Wind in different scenarios over a forecast day.](image)
Mean curves
200hPa Vector Wind
Root mean square error forecast
Tropics Lat -20.0 to 20.0 Lon -180.0 to 180.0
Date: 20041214 00UTC to 20050505 00UTC
Mean calculation method: standard
Population: 89 (averaged)

Forecast Day
Impact of adding HIRS to the REFERENCE

![Image of the impact of adding HIRS to the REFERENCE]

![Image of the scatter plot showing the comparison between reference and HIRS]

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Impact of adding AMSUA to the REFERENCE

![Map showing the impact of adding AMSUA to the REFERENCE](image1)

![Scatter plot showing the root mean square error forecast](image2)
scatter plot
reference + amsua minus reference
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050605 00UTC
200hPa Vector Wind 00UTC
certainty: 90 % population: 89
Impact of adding AIRS to the REFERENCE

![NormDiff in RMS of fc-Error: (REFERENCE+AIRS) - (REFERENCE)](image1)

![scatter plot](image2)

**scatter plot**

reference+airs minus reference

Root mean square error forecast

S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
date: 20041214 00UTC to 20050905 00UTC
200hPa Vector Wind 00UTC
confidence: 99 % population: 89
Impact of adding CSRs to the REFERENCE
Summary of analysis of results

To present the results of eleven sets of data assimilation experiment in a concise way is a somewhat daunting task. There are over 1000 days of assimilation days and the evaluation period consists of 43 days in winter and 46 days in summer.

The variables used for evaluation are geopotential height, relative humidity and wind.

A final summary of results has been condensed to six bar graphs containing all eleven experiments (see below). It is reassuring to see that all the space base sensors contribute in a positive way to the overall improvement of the ECMWF forecast system.

Sensors like AMSUA, AIRS and HIRS are clearly very important. These sensors have a large impact initially on the temperature and humidity but during assimilation process the wind adjusts very quickly. In all the verification of all variables these sensors have the largest effect on the data assimilation.

Additional sensors (AMSUB (including MHS), GEO CSRs, SSMI and SCATT) clearly have their part to play as there is still a gap between AMSUA sensor impact (the largest) and the full system (CONTROL).

The impact on the mid level moisture (500 hPa) of sensors AMSUB and SERVIRI CSRs is clearly positive and is confirmed using the detailed RMS plots for these instruments.

The impact of SSMI and SCATT on the surface wind (1000 hPa) in the Southern Hemisphere is small but clearly shown in the detailed plots.

The sensors that have most impact on the upper level wind (200 hpa) are again AMSUA, AIRS, and HIRS but it is gratifying to see there is some indirect effect on the wind fields from the SEVIRI CSRs.

Finally the impact of AMVs and MODIS winds is clearly demonstrated.

With reference to the comparison one AIRS with one AMSUA/B (see appendix a). AIRS is slightly better on 500 hPa geopotential scores in the Southern Hemisphere but neutral in the Northern Hemisphere. On the other hand the tropospheric humidity impact for AMSUA/B is generally better than AIRS.
Summary of Data Impact

![Graph showing SH RMS error 500 hPa geopotential](image.png)
TR RMS error 200 hPa relative humidity

- control
- amsua
- airs
- hirs
- scat
- ssmi
- amsub
- csr
- geo amv
- reference
- baseline

Day1 Day2 Day3

SH VW RMS error 1000 hPa

- control
- amsua
- airs
- hirs
- scat
- ssmi
- amsub
- csr
- geo amv
- reference
- baseline

day1 day2 day3
SH RMS error 200 hPa vector wind

Day1 Day2 Day3

control
amsua
airs
hirs
scat
ssmi
amsub
csr
geo amv
reference
baseline
Appendix (a)

An extra data assimilation experiment has been run for a summer and winter period. It was aimed at direct comparison of REFERENCE+AIRS with REFERENCE+(AMSUA and AMSUB). This experiment enables a more realistic comparison of microwave and infrared. AMSUA is mostly sensitive to temperature and AMSUB mostly humidity whereas AIRS is sensitive to both humidity and temperature. In this data assimilation experiment only used NOAA 16 AMSU A and AMSUB added to the REFERENCE.

The evaluation of forecasts has also been done using two variables and at various levels

Geopotential 500 hPa Height (anomaly correlation for mean scores and Normalised RMS error for geographical and scatter plots)

Relative Humidity at 500 and 200 hPa (mean scores in percent and Normalised RMS error on a geographical plot)
500 hPa Geopotential impact of adding AMSUA/B and AIRS to the REFERENCE in the Northern Hemisphere
500 hPa Geopotential impact of adding AMSUA/B and AIRS to the REFERENCE in the Northern Hemisphere
500 hPa Geopotential impact of adding AMSUA/B and AIRS to the REFERENCE in the Southern Hemisphere
500 hPa Geopotential impact of adding AMSUA/B and AIRS to the REFERENCE
Humidity impact of adding AMSUA/B and AIRS to the REFERENCE
500 hPa Humidity impact of adding AMSUA/B and AIRS to the REFERENCE
200 hPa humidity impact of adding AMSUA/B and AIRS to the REFERENCE
Conclusions

(comparsion of AIRS and AMSUA+AMSUB-see figures below)

- The impact on geopotential height is a slightly more for AIRS in the Southern Hemisphere compared to the AMSUA/B but results are neutral in the Northern Hemisphere.
- The impact on humidity is greater for the AMSUA + AMSUB than for AIRS in particular in the Tropics.
REFERENCES


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