TECHNICAL MEMORANDUM

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Impact of satellite data

Stephen English, Tony McNally, Niels Bormann, Kirsti Salonen, Marco Matricardi, Andras Horanyi, Michael Rennie, Marta Janisková, Sabatino Di Michele, Alan Geer, Enza Di Tomaso, Carla Cardinali, Patricia de Rosnay, Joaquín Muñoz Sabater, Massimo Bonavita, Clement Albergel, Richard Engelen and Jean-Nöel Thépaut

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European Centre for Medium Range Weather Forecasts
Shinfield Park, Reading, Berkshire RG2 9AX, England

Summary

This report reviews the current value of satellite data assimilation activities at ECMWF and outlines the strategy for future development. The Centre makes extensive use of satellite observations in atmospheric, ocean and land surface analyses, and also for atmospheric composition both in the Integrated Forecasting System and in MACC (Monitoring Atmospheric Composition and Climate). Many satellite data types such as the sounders are very well established and form the backbone of the observing system. It is essential for any state of the art Numerical Weather Prediction system to get the sounder assimilation right, and properly maintain it. Whilst recognising the importance of what we might call conventional satellite data this report will focus on new developments and areas that are increasingly important. ECMWF contribute very significantly to the future development of the global observing system both through assessing the potential impact of new data and by being pioneering in the use of innovative satellite data, including data from research satellites such as those in the A-train and ESA's Earth Explorer missions. As NWP systems improve it is becoming harder to acquire observations good enough to improve further the accuracy of the forecast. It is important to make well informed choices about which new observations investment should be made and then to do the hard work to make sure we can exploit these observations. Through better observations, advances in data assimilation techniques and in the way observations are handled satellite data is continuing to make a major contribution to improve medium range weather forecast skill.

1 Introduction

In the last twelve years the number of satellite instruments assimilated in the operational IFS (Integrated Forecasting System) at ECMWF has increased from 12 to over 50, with a further 25 instruments used passively as can be seen in Figure 1. This trend is expected to continue, with over 90 instruments likely to be used by 2017. Additional instruments are used by the Monitoring Atmospheric Composition and Climate (MACC) system for atmospheric composition. European, American and Asian satellite programs use many different observation techniques to provide these observations. A major challenge for satellite data assimilation is to maintain the expertise to handle such a variety of different types of observation and to be pioneering in the preparation for and exploitation of new observations. Progress is being made on many fronts: to use more instruments, to use more data in cloudy scenes, to use more data over difficult surfaces. This paper examines where the priority should lie between these aspects, focussing on some key developments likely to make a difference in the coming decade, and where most resources should be placed. Some aspects of measuring the forecast impact of satellite observations will be discussed, and also the question of how we measure impact, especially as we now need to measure very small changes in finely tuned systems. This paper will not focus on the important work of maintaining the basic system, but this is and will remain the activity requiring most resources. It is essential to get the basics right, and to continue to use existing satellite data properly to maintain the large scale. It is also essential to build the technical infrastructure in a way that is clear, flexible and easy to update and manage.

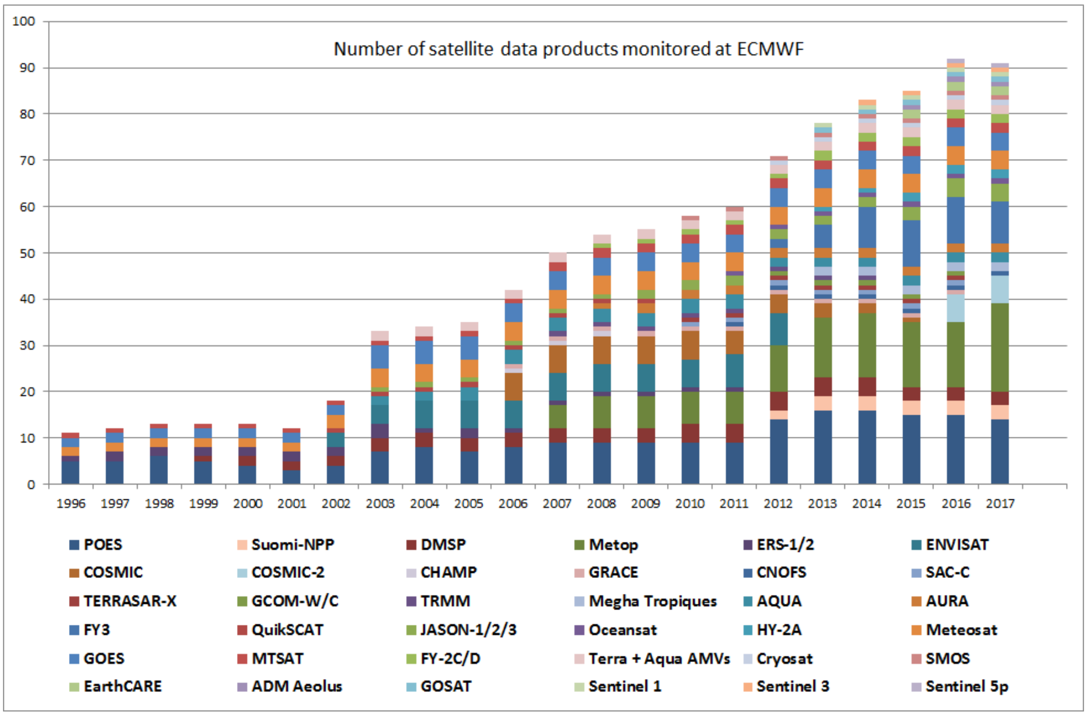

Figure 1 **The number of instruments operationally monitored at ECMWF. In 2013 the number stands at nearly 80, though 25 of these are not actively assimilated.**

In order to develop the science and infrastructure for so many observation types it has been necessary to share developments through partnerships with satellite agencies and other weather services. The clearest example of this is the Satellite Application Facilities (SAFs) of EUMETSAT. These programmes make investments in weather services and research institutes. ECMWF is actively involved in three SAFs: NWP, radio occultation mission and hydrology. In addition various short term collaborative studies led to specific developments in support both of ECMWF IFS and also a wider community of satellite data users. It is only through such international collaboration that ECMWF has been able to maintain such a rich diversity of satellite observations in the operational IFS.

2 Assessing the current value of satellite data to NWP

This section will begin by assessing recent studies measuring the value of satellite data to NWP and will end discussing the problems and possible future directions for validating experiments aimed at measuring small changes in the forecasting system.

ECMWF frequently runs Observation System Experiments (OSEs) where a particular observation type is removed from the IFS in a research experiment and the loss of forecast skill measured. Recent examples include Bormann, Fouilloux and Bell (2012), Di Tomaso and Bormann (2010), and McNally (2013). Every few years, and most recently in 2009-10 by Radnoti *et al* (2010), this is carried out in a systematic way for all observations so their relative contribution can be measured and compared.

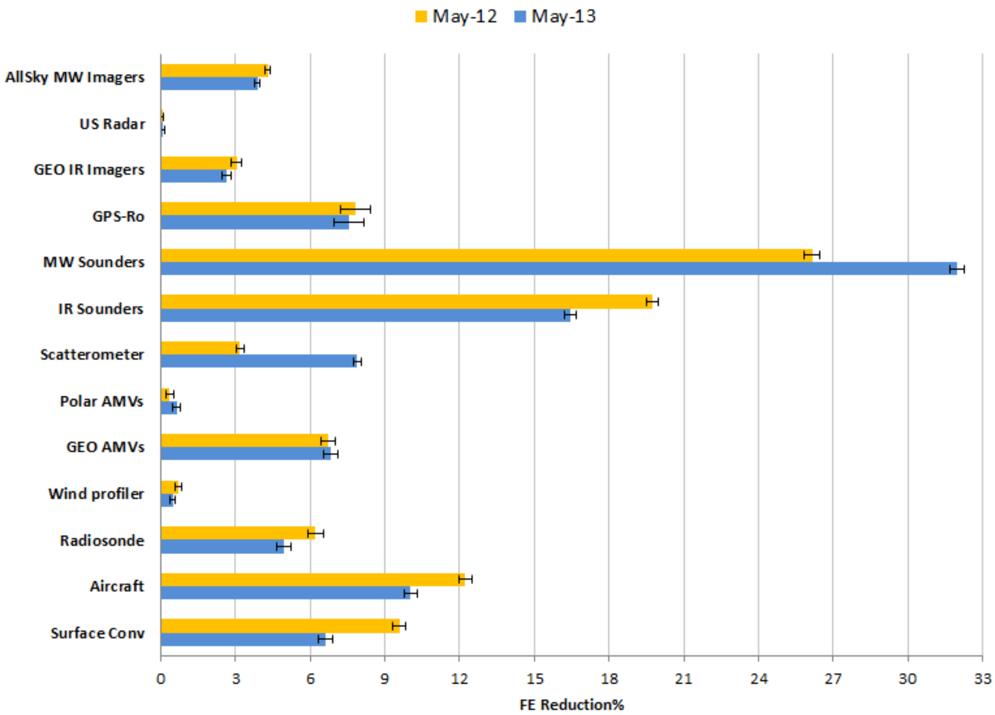

Figure 2 **The percentage contribution of various observation types to the total forecast error reduction, sometimes referred to as FEC (Forecast Error Contribution) or Forecast Error Reduction (FER), in terms of the dry energy norm. The error bars represent the 99% confidence intervals based on a t-statistic.**

In addition to OSEs, attempts have been made to monitor forecast impact on a routine basis using the adjoint of the forecast model in the 4D-var data assimilation system. The adjoint provides forecast sensitivity to initial conditions so that it can be inferred how much an individual observation could contribute to the reduction in forecast error. This has become known as the Forecast Error Contribution (FEC) and can be expressed either as a reduction in the forecast error or as a percentage contribution to the total forecast error reduction. It is related to how closely observations fit the short range forecast, but allows a way of comparing the current impact of observations in a consistent way. FEC and OSEs measure different aspects of forecast impact: OSEs provide occasional but comprehensive analysis of the observation impact on meteorological fields; FEC provides a routine analysis but for a particular target metric (e.g. the global dry energy norm of the 24 hour forecast). The FEC can therefore provide an assessment of changing impact with time, so for example impact in May 2012 can be easily compared with impact in May 2013, as shown in Figure 2. However as the FEC relies on linear assumptions it can only be used for short range forecasts, typically 24 hours. The changes in satellite data impact due to the changing satellite Global Observing System (GOS) can be clearly seen: microwave sounders contribution has increased from 26% to 33% due to the introduction of ATMS and the Metop-B AMSU-A and MHS, scatterometer contribution has increased from 5% to 8% with the introduction of OSCAT and Metop-B ASCAT, and the contribution of infrared sounders has fallen from 20% to 16%. This does not mean the infrared sounders are less valuable, but with other data increasing, their overall contribution has decreased. Effort is being directed to better understand the relationship between FEC and OSE information.

There are some clear and striking themes emerging from recent OSEs at ECMWF. Firstly every time additional microwave sounder data is added to the assimilation, some small additional positive impact is found. This is despite the system already using many microwave sounders. Generally speaking the consistent neutral to slightly positive impact of new observations indicates that the data assimilation system is close to optimal. When the Metop-B AMSU-A was added this was the 7th such sounder in the ECMWF IFS. However the introduction of Metop-B AMSU-A shed some light on why we continue to find additional impact. It was found that if Metop-B AMSU-A is assimilated identically to Metop-A AMSU-A (i.e. without channel 7 which is broken on Metop-A) less impact is found than when channel 7 is used. This shows that the impact of a single channel can be detected, at least for some situations. Channel 7 peaks in the upper troposphere and is the lowest peaking channel to have, for the vast majority of situations, no significant sensitivity to the emission from the earth's surface or from clouds. This channel is no longer available on Metop-A, Aqua and NOAA-19 AMSU-A. Therefore the Metop-B AMSU-A channel 7 data was filling a gap. For the same reason NOAA-16 AMSU-A was also returned to operational use, becoming the 8th microwave sounder being assimilated. Therefore although observations from many microwave sounders are assimilated it should be noted almost every AMSU-A has at least one broken channel. It is nonetheless interesting that we always find additional positive impact when we add another AMSU-A. By contrast it has been found that adding additional hyperspectral infrared sounders does not always give additional impact. The system is using many channels from AIRS and Metop-A IASI, and adding Suomi-NPP CrIS and Metop-B IASI has yet to demonstrate a measureable positive impact. This may mean it is easier to exploit radiances measured in the microwave part of the spectrum than those from the infrared. However it should also be noted that per day we use over 6,000,000 observations from AIRS and IASI and only 3,200,000 from AMSU-A, ATMS and MHS combined. Therefore despite the large number of microwave sounders being used, there are more infrared sounder observations from just two instruments. It is an important area of research to fully understand the behaviour of the infrared sounders in the assimilation and to try to optimise their impact.

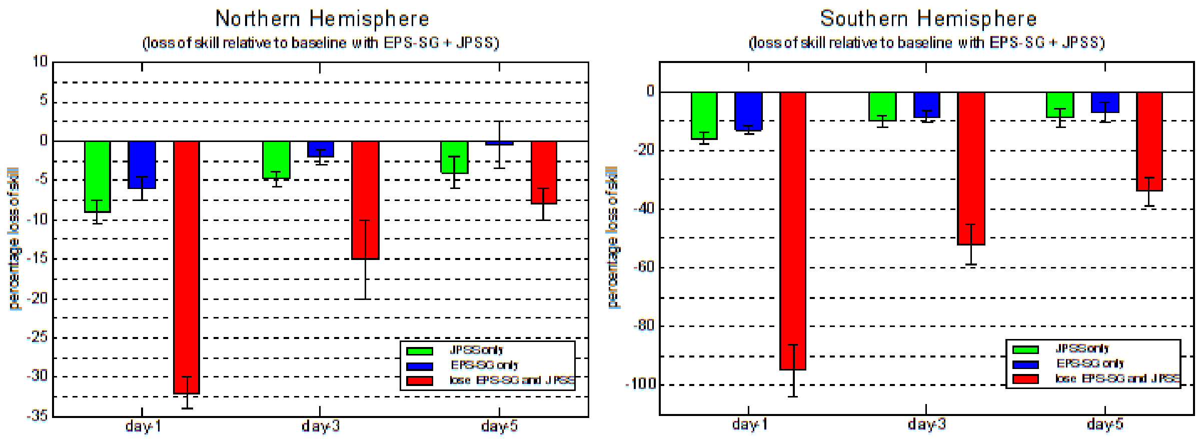

Figure 3 **Impact of removal of a simulated future JPSS and EPS-SG satellite in a two satellite system, using Metop and Aqua/NOAA-18 data as proxy for EPS-SG and JPSS respectively.**

Looking to the future we may not have as many instruments as we now enjoy. This is in part due to the cost but also the new process for managing the end-of-life of meteorological satellites to reduce the amount of space debris. These space objects pose a threat to satellite missions and must be tracked, and satellites such as Metop-A make frequent manoeuvres to avoid collision. It is critical to maintain these most important satellite observations (as shown in Figure 2) and therefore how to optimise the deployment of what are likely to be scarcer observations is a topic of high relevance to all NWP centres. ECMWF is working closely with space agencies to evaluate options for the future design of the global observing system. Recently it was noted that if the US polar orbiters in the afternoon orbital plane do not exceed their expected lifetime there will be a gap in coverage; the nominal life of Suomi-NPP ends before the first JPSS satellite is launched. This gap has received much attention in the United States. ECMWF studied the impact of a future global observing system for satellite sounding with either only EPS-SG or only the US JPSS satellite, or neither. Figure 3 shows that the impact of losing either EPS-SG or JPSS is significant, but not catastrophic. The impact of losing both is indeed very large. This confirms that we do need both JPSS and EPS-SG. The system with neither is very poor so the risk associated with a gap on the US side is very high. This study confirms the need for at least two operational polar sounding missions.

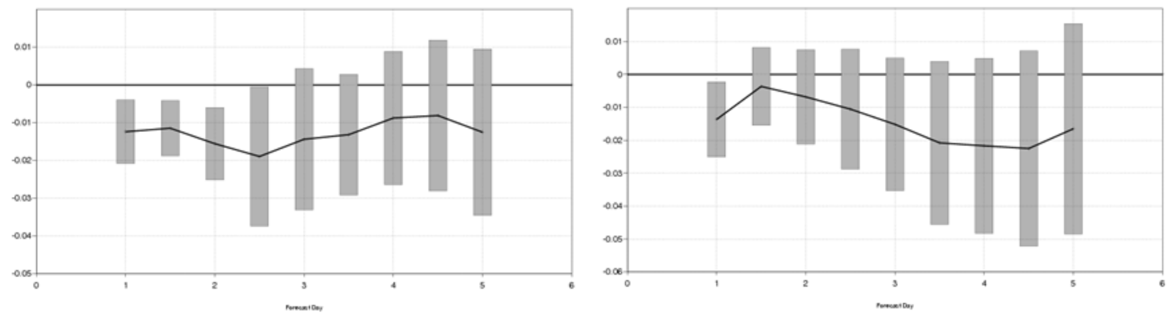

Figure 4 **Improvement in forecast skill as measured by the 500 hPa anomaly correlation using three optimally spaced satellites - NOAA-15, 18 and Metop-A - versus - NOAA-18, 19 and Metop-A - for Northern Hemisphere (left) and Southern Hemisphere (right). Negative values denote the optimally spaced orbits are better.**

In addition to uncertainty over the afternoon orbit there is also considerable uncertainty over the early morning orbit. This has for many years been operated by the DMSP satellites of the United States Department of Defence (DoD) providing data in three well-spaced orbital planes (early morning - around 5am; morning – around 9.30am; afternoon – around 2pm). However the quality of the sounding data from the SSMIS instrument operated by the DoD has never matched the sounders operated by NOAA and EUMETSAT because their design is optimised for microwave imaging, not sounding. Furthermore the DoD do not currently have a programme to continue operating after the last DMSP satellite is launched. The future for the early morning orbit is unclear so ECMWF joined a WMO led initiative to explore the value of the earth morning orbital plane. The first question is does a third satellite still provide useful information? The second question is does it need to be in an orbital plane well separated from the other two? Future Chinese Fengyun-3 (FY3) satellites are currently planned to operate alternatively in the same morning orbit as Metop and the afternoon orbit of JPSS. Therefore the WMO-led initiative was arranged to explore what advantages there would be scheduling future Fengyun satellites to occupy the early morning position. Following a similar experiment in

2009 by Di Tomaso and Bormann (2010), ECMWF used NOAA-15 as a proxy to study the sensitivity to having satellites in three orthogonal planes (early morning, morning and afternoon) compared to one morning and two afternoon satellites. The results were presented to the China Meteorological Administration (CMA). The results confirm that three AMSU-A instruments are better than two, irrespective of the orbital position, but that optimal separation does give a measurable additional impact compared to operating two of the three satellites in the same orbital plane, as is shown in Figure 4. CMA are now considering whether it is possible to reconfigure FY-3 satellites for the early morning orbit, possibly as early as FY-3E, due for launch in 2016.

It may also prove valuable in future to align the metric used for forecast impact assessment more closely with the main sensitivity of the observations. Scatterometer data are known to improve the quality of surface winds over the ocean and have an impact on atmospheric and wave forecasts but in many traditional metrics the value of Scatterometer observations is not clearly shown. New metrics such as wind shear and vorticity may show more clearly whether Scatterometer data is giving significant benefit, especially in severe weather situations. It is important to ensure that an adequate sample of Tropical Cyclones and severe extra-tropical storms is achieved during testing. A project is on-going to optimize ASCAT winds assimilation strategy and evaluate the current impact of Scatterometer winds on the GOS using both traditional and new diagnostics. First results from OSE experiments showed a negative impact of ASCAT winds in the 12 and 24 hour forecasts when compared to the own-analysis. Bouttier and Kelly (2001) and Geer *et al.* (2010) have seen similar results when introducing new observations and have interpreted this as arising from using the experiment's own analysis as a proxy for truth when the analysis changes are significant. Comparison with independent observations such as Altimeter winds confirmed that the analysis was actually improved and the analysis-based verification results were misleading. This confirms that in addition to considering new metrics we also benefit from independent observations for validation.

Another way to assess the value of observations, both current and future, is being developed using the spread of the ECMWF Ensemble of Data Assimilations (EDA). This has been used to estimate the optimal number of radio occultation (RO) observations needed in the future. By simulating up to 128,000 RO observations and then assimilating the simulated data in the EDA the spread of the EDA could be taken as giving some indication of the sensitivity of the analysis to increasing the number of RO observations. It was found that adding more RO data always reduced the spread of the EDA ensemble, but up to around 10,000 observations this reduction was faster than would be expected from noise reduction alone. It was therefore concluded that up to 10,000 RO observations would continue to bring additional benefits. The true figure may be even higher, but the limitations of our current understanding of the technique mean it is harder to make strong statements.

These techniques for assessing the impact of satellite data work well when assessing major changes, such as withdrawing a complete observation type. Normally improvements to the assimilation of satellite data make small changes to the forecasts and are hard to measure quantitatively with statistical significance. Long and expensive experiments are needed. Let us reflect on how much change it is realistic to see from small incremental improvements. NWP forecast skill has been increasing at a rate of one day per decade for the last three decades. If we assume 100 people are employed primarily to improve forecast skill, this being close to the current size of the Research Department at ECMWF, a mean forecast skill gain per person per year of 90 seconds of forecast lead time is needed to maintain the one day per decade rate of improvement. This is equivalent to approximately 0.015% improvement in the anomaly correlation at 500 hPa. This is undetectably small even for forecast experiments of many years in duration. Some changes are large and are detectable, but this simple analysis shows us that to maintain an impressive rate of improvement of 1 day per decade is built upon many small changes, many of which may not show statistical significance in testing given realistic length of trials. We therefore have a problem: how do we decide whether to make a change or not, if its medium range forecast impact appears neutral in trials? It might be imagined that running experiments against a degraded baseline would help, but even if the degraded baseline is improved, there would be no guarantee forecasts would improve in the context of the full observing system. For example, there might already be an instrument in the full observing system that provided much better quality information than the one tested in the baseline; alternatively, biases or poorly-specified observation errors might not cause problems in the degraded baseline but would definitely degrade the full-system. Potential operational changes must be tested in the context of the full observing system. However, medium range forecast scores need not be the only means of verification. It is easier to achieve statistical significance at short forecast range than in the medium range but verification against analysis is not meaningful in the short range. Measurement of short range impact can be more reliable, but needs to be done carefully against well trusted observations. In future where forecast impact verification is inconclusive, as may become increasingly the normal situation, decisions may have to be increasingly based on whether the short range fit to observations is improved. It should also be noted that even if new observations have a neutral impact they improve the robustness of the GOS to loss of other observations, by providing more redundancy in the system. So the goal of trials is primarily to show observations are not having a negative impact, which would show that the data assimilation is sub-optimal.

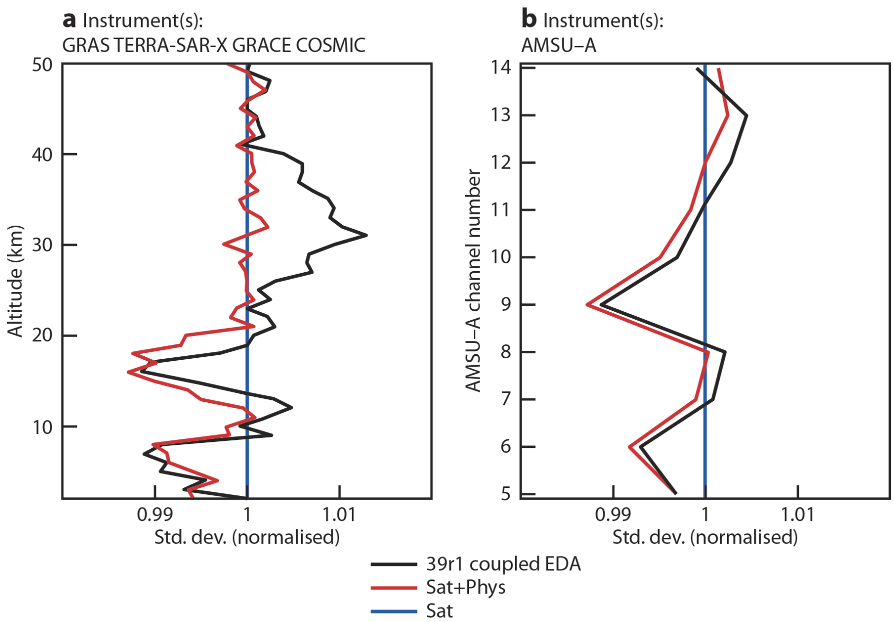

Figure 5 **Normalised standard deviation of background departures of (a) radio occultation observations and (b) AMSU-A observations for the physics and data assimilation changes the main operational scientific upgrade in 2013. AMSU-A is sensitive to temperatures with broad weighting functions. For channels 6, 9 and 12 these are centred around 9 km, 18 km and 30 - 40km.**

Figure 5 shows an example of the verification of individual components of a recent upgrade of the operational system using background fits to satellite observations. If the satellite upgrades are implemented first, then satellite fits can be used as a reference to validate the other changes. This example shows that the model physics upgrades improved background fits to temperature-sensitive GPSRO and AMSU-A observations by around 1% in layers around 8km and 16km in altitude. In contrast the coupled EDA changes caused a small degradation in fits in the mid and upper stratosphere; this was eliminated after a retuning of the background errors. The consistency of the results between GPSRO and AMSU-A, two very different observing systems, lends a lot to the credibility of the background fits to observations as a verification tool. Traditional forecast scores will always be important when running large packages, or measuring the value of a large component of the global observing system. However improved diagnostics to understand changes to the data assimilation system can be used for small changes with less reliance on traditional medium range forecast scores. The difference between observations and background is already used extensively at ECMWF for trial verification. Its continuation and improvement (e.g. inclusion of significance testing) will allow it to become an even more important element of the evaluation of the value of improved initial conditions.

3 Potential for future increased impact of satellite data assimilation

A primary goal of the satellite work at ECMWF is to evaluate which of the many available satellite observations are most likely to improve operational numerical weather prediction and then to fully commit to make use of as many of these observations as quickly and as accurately as possible. Many satellite missions only have a planned lifetime of five years, so it is vital to prioritise correctly and use resources to be able to benefit from the missions for the longest period possible. To illustrate this rather simplistically imagine you have ten satellite instruments, but only two people and each instrument needs two years of effort to implement operationally. If they work together they can implement data from the first instrument after just one year, giving four years of benefit, the second after 2 years, giving 3 years and so on. If they tried to do everything at the same time, taking 5 instruments each, when each instrument reached end-of-life they would only be half way to implementing the data operationally, so no benefit is realised. So the difficult choice to prioritise and even neglect some interesting data must be made. On-going operational support is also a major activity: monitoring the data reception, data quality and responding as and when necessary to data quality issues. This means data with little or no benefit should not be used. So for example the GOES infrared sounder was never evaluated, because the perception was that its impact would be small. ECMWF now only use one HIRS instrument (Metop-A); HIRS was once the most important of all satellite instruments, but now its limited impact does not justify significant effort. The SSMIS temperature sounders could be used, but impact would be small and the maintenance effort considerable, so this too is now monitored with no intention to assimilate the tropospheric and lower stratospheric channels. Therefore one way to maximise the impact of satellite data is to prioritise ruthlessly and correctly and as the forecast system evolves (increased resolution, improved representation of clouds and aerosol, better observation operators) the judgement call we have to make may also need to evolve.

We can also learn about what may be important in the future by looking at the past. Until around 2000 there was a large skill gap between the northern and southern hemisphere forecasts, and then the gap narrowed dramatically. The main reason there was a gap between northern and southern hemisphere skill was the low availability of *in situ* observations in the southern hemisphere. Therefore it is reasonable to attribute the closing of the gap after 2000 to improved satellite observations. However Dee and Uppala (2009) compared operational and ERA-interim verification over the last 30 years and found that improved observations can only explain around a quarter of the improvement, the remainder must be explained by better use of observations (i.e. better data assimilation) and/or a better model, though it should be noted ERA-interim was not using Metop-IASI, Metop-ASCAT or the new instruments on Suomi-NPP so the only major changes in satellite data in this period was the arrival of ATOVS in 1998 and AIRS in 2002. The ERA-interim comparison with operations proves the high value of improved data assimilation especially with poorer observations as we had in 1980. It is reasonable to conclude that substantial improvements in satellite data impact at ECMWF have and will continue to arise from improved data assimilation. It can also be seen that reanalysis provides a remarkable tool for better understanding observation impact, both historically and in real time when the reanalysis provides an unchanging baseline to which the operational forecasts can be compared. Although we have noted that improved observations may have provided only about a quarter of forecast improvement over the last 30 years Radnoti *et al.* (2009) show that satellite data continue to have a very large impact. Loss of the satellite data would still cause catastrophic degradation in the southern hemisphere, and very significant degradation in the northern hemisphere.

It is generally accepted that the most valuable new data is data that fills a gap in the Global Observing System, rather than simply having more of an existing data type, however valuable that data type might be. So where are the gaps? The main gaps are for winds, where vertical profile information is only provided by *in situ* observations, humidity and temperature with very high vertical resolution and certain geographical regions (e.g. Antarctica). The strategy for improving meteorological satellite data assimilation at ECMWF is therefore geared to target these six areas, in priority order:

1. Contribute to data assimilation improvements through very close cooperation with the data assimilation section (section 3.1);
2. Maintain the current operational capability, but continuously reviewing the contribution of each instrument and exploiting new opportunities to replace obsolete systems (3.2);
3. Higher vertical resolution from IR sounders in cloud-free conditions (3.3.1);
4. Preparation for new cloud observations, in particular lidar and radar for vertical profiles of cloud parameters, (3.3.2.1) alongside the all-sky radiance assimilation work (3.4.1);
5. Preparation for new wind observations, in particular vertical wind profiles from ADM Aeolus (3.3.2.2) alongside improving the use of existing wind observations (3.4.2);
6. Improved atmospheric assimilation over land and sea ice, to provide observations in the main geographical data voids, and also including improved land surface data assimilation (3.4.2).

These priorities enable us to judge where we need to develop expertise to meet the challenges that lie ahead in the next ten years. Some, but by no means all, activities in each area are described in section 3. Improved data assimilation is put in first place, and is considered critical to improved impact of satellite data (and observations in general). There are many elements of ECMWF's data assimilation strategy relevant to satellite data impact, and it would be impossible here to discuss them all, but the EDA is discussed in some detail in Section 3.1 as well as some discussion of improved description of observation error in section 3.4. Section 3.2 discusses the priorities for maintenance of current capability through existing datasets development of new data such as the Chinese sounders. Section 3.3 presents the strategy for higher vertical resolution including work towards full spectral resolution assimilation for IR sounders and the activity to develop knowledge, skills and systems for observations providing high vertical wind and cloud information, namely ADM Aeolus and EarthCARE. Finally there are important developments in the use of satellite observations taking place for improved analysis of the ocean, the land surface and atmospheric composition. These last two areas are discussed in section 3.5.

3.1 Improving Jb through better representation of background error

Satellite data needs sophisticated data assimilation techniques to exploit it well and as such has been a major driver for improving the data assimilation algorithm. Many areas, notably variational analysis, improved flow dependent background errors and variational bias correction have been developed primarily to benefit satellite data assimilation. Without appropriate investment in these and similar areas effective satellite data assimilation is impossible.

Background errors are highly spatially and temporally variable, reflecting the instabilities of the atmospheric flow, especially in the proximity of active weather systems, and the accuracy and spatial distribution of the GOS. Hence, a long standing objective of research at ECMWF has been to provide realistic, flow-dependent estimates of background errors to the 4D-Var analysis. This goal had been partially achieved in upgrades of the operational IFS in the period 2011-13 with the use of error estimates from the ECMWF EDA for the balanced part of the 4D-Var errors (Bonavita, Isaksen and Holm, 2012). Adaptive estimates of background errors from the EDA were then extended to the unbalanced part of the 4DVar control vector, with a significant positive impact on analysis and forecast skill (Bonavita, 2013). More recently the use of the EDA in 4DVar has been further extended to compute flow-dependent estimates of background error correlation structures.

A significant advantage of having an online, EDA-based system for the estimation of background errors is that the data assimilation cycle is now able to adapt in real time to changes in observation availability and coverage. McNally *et al.,* 2013 presented an example of this for Superstorm Sandy. Without recalculating background errors from the EDA the forecast accuracy of Sandy was very poor when all the available polar orbiter observations were withheld. This was, to some degree, mitigated by the use of background errors computed from an EDA to allow for the impact of withholding the satellite data on the accuracy of the background. This was because the resulting increase in EDA background errors results in: a) looser background departure rejection limits, allowing larger numbers of observations from other observing systems to be assimilated; b) larger weight being given in the analysis to these observations. This result is not surprising in itself, since Isaksen *et al.* (2010) state that the Kalman Gain matrix used in the EDA itself should be as close as possible to the one used for the reference system. However it raises the prospect whether we should run *ad-hoc* EDA experiments whenever we test changes to the global observing system and to the satellite component in particular, further increasing the computational cost of research experiments.

A partial answer to this question can be found from the results of a set of EDA experiments with drastically different observational coverage:

a. EDA using conventional observations only (5.5% of total observations);

b. EDA using conventional observations and GPSRO (7.2% of total observations);

c. EDA using conventional observations and ATOVS data (41.6% of total observations);

d. EDA using conventional observations and Hyper-spectral sounders (AIRS+IASI) data (53.8% of total observations);

e. EDA using all observations.

Figure 6 shows that for the spatially homogeneous observing systems configurations (b,c,d), the increase in background errors implied by the increase in EDA spread is between 5 and 10% except in the middle to high stratosphere. Comparing these numbers with the reduction in observation counts for the same experiments (7.2%, 41.6% and 53.8% respectively) shows that, due to the redundancy of the current GOS, the globally averaged background errors display only small sensitivity to changes in the GOS if one of the main observation types (ATOVS, AIRS, IASI and, to a lesser extent,

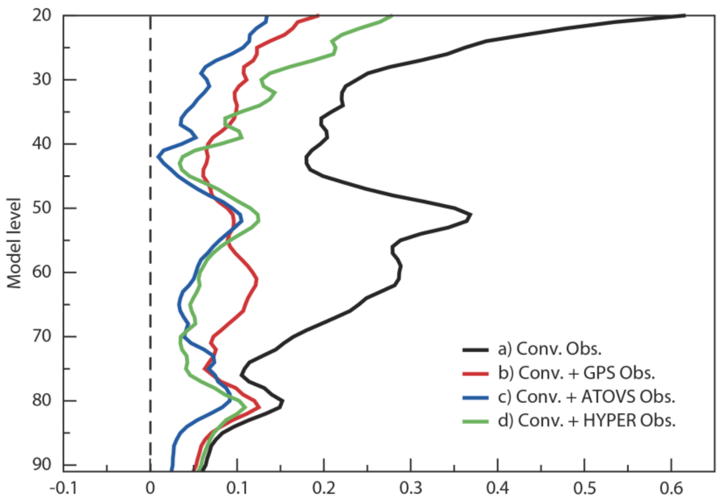

Figure 6 **Vertical profile of the fractional increase of EDA-based temperature background errors for various configuration of the global observing system. Model level 20 corresponds to approx. 10 hPa. Reference is the EDA using all observations.**

GPSRO) are used. This suggests that for small changes in observation use the retuning EDA background errors are not expected to be needed for most research experiments: they will get the correct main signal with operational EDA covariances. On the other hand the capability of the operational assimilation system to optimally adjust background errors to the evolving GOS will increase the accuracy with which current and future observations are assimilated.

3.2 Maintaining critical observations

The satellite global observing system is in a permanent state of change with old instruments failing, or being decommissioned and new instruments being made available. Therefore doing nothing is never an option for satellite data assimilation, as in a short space of time no data (or worse still degraded data) would be assimilated. Typically old satellites deteriorate slowly, with instruments becoming degraded and sophisticated monitoring is required to ensure only good data continues to be used without the risk of using bad data. In the future the new protocols for space debris mean that older satellites are likely to be decommissioned even when instruments are still working, so there will be fewer satellites, but this will make it even more critical to get new sources of data into operations quickly. Recent major events include the sudden unexpected failure of ENVISAT in April 2012, the launch between mid-2011 and end of 2012 of many new satellites: Metop-B, Meteosat-10, Suomi-NPP, GCOM-W1, Meghatropiques. In the near future many new launches are expected, notably Aeolus (for winds), EarthCARE (for clouds), SMAP for soil moisture and FY-3C/D (for Metop-quality atmospheric sounding). Looking even further ahead there will be the first geostationary high spectral resolution infrared sounders from both Europe and China and new instruments on the Second Generation European Polar System. ECMWF have followed a strategy of being very proactive with respect to new missions, notably innovative research missions, whilst being selective which new missions to support and which old missions to continue to maintain.

We will consider first the instruments that are a continuation of operational systems. The Metop-B satellite is identical to Metop-A. It might be expected therefore that the implementation of Metop-B instruments would be straightforward if their quality is the same as Metop-A. This was found to be the case for the microwave sounders (AMSU-A and MHS), the radio occultation mission (GRAS) and the scatterometer, (ASCAT). However it has been found that assimilating IASI from two closely spaced satellites has not given the benefits expected. Instrument monitoring shows the quality of the Metop-B IASI instrument is at least as good and for some channels better than the Metop-A IASI. This demonstrates that there are no short cuts, because even if data quality is equal to existing operational data the subtle impacts of issues such as correlated error, small biases or undetected cloud can mean that more data is not always immediately beneficial. The situation for the Suomi-NPP satellite is similar. This satellite carried new instruments that were similar to Metop instruments – the infrared sounder CrIS (similar to IASI) and the microwave sounder ATMS (similar to AMSU-A and MHS combined). As with Metop-B it was relatively straightforward to add the ATMS, and demonstrate small positive impacts. However it has also proven difficult to assimilate the CrIS sounder, despite instrument monitoring that shows very low observation errors. The cause for the lack of positive impact from CrIS may be due to correlated error, perhaps arising from the observation operator rather than the observations themselves. Observation error correlations are not currently accounted for in the data assimilation system. CrIS assimilation remains an on-going area of study. It is important to stress that the CrIS data appears to be of very high quality, what is being exposed is a data assimilation issue in using high quality observations to correct a very accurate background.

Whilst this paper does not discuss in detail how the well-established observations are used it is important to stress that the same mistake must not be made as has been made with conventional (in situ) observations. When the first satellite observations arrived it was recognised that significant effort was needed to exploit them correctly. Dedicated resources were provided to fully understand the observations and to assimilate them as close to optimally as possible. It was considered that conventional observations were easy, not needing the same attention. However differences in how conventional observations are processed between different NWP centres, and even which observations are being received and/or used, has highlighted that attention must be given to conventional observations as well. It is very important that in providing resources to develop new and interesting types of data that we do not cease to give attention to the observations which, as Figure 2 shows clearly, give the largest current impact, namely the microwave and infrared sounders, instruments such as AMSU-A, MHS, ATMS, IASI, CrIS and AIRS.

3.3 Improved vertical resolution in satellite observations

3.3.1 High spectral resolution infrared sounders

The operational use of Infrared Atmospheric Sounding Interferometer (IASI) radiances at ECMWF is currently restricted to a selection of temperature sounding channels in the long-wave region of the spectrum and to a small number of ozone and humidity sounding channels. In principle, to exploit the full information content of IASI, the number of channels used in the assimilation could be increased to cover the full spectrum. NWP users are limited to assimilating a small subset of the full IASI spectrum due to the prohibitive computational cost, but it is also known that the independent information on the atmosphere contained in a single IASI interferogram is significantly smaller than the total number of spectral samples derived from it (Huang *et al*., 1992). Principal Component Analysis (PCA) is a classical statistical method for the efficient encapsulation of information from voluminous data (Joliffe, 2002). As such, it has been proposed as a solution to the above problem.

To investigate the feasibility of using PCA for the assimilation of satellite data, the operational ECMWF 4D-Var has been adapted to allow the direct assimilation of Principal Component (PC) scores derived from high spectral resolution infrared sounders. In the methodology adopted for the direct assimilation of PC scores, the observed IASI spectra are first screened for the presence of clouds and contaminated spectra are discarded. This must be done before assimilation as the PC training has been performed with only completely clear data and none of the eigenvectors correspond to cloud signals. The clear spectra are then projected into PC scores. By only including the highest ranked PC scores (i.e. those with highest information content) we make the assimilation highly efficient. In most other respects the PC assimilation framework is similar to the radiance assimilation framework. However, as with any rotation of the observed space, some aspects will be easy to specify correctly in PC space and others in radiance space.

The observation operator utilized for the simulation of the PC scores, namely PCRTTOV (Matricardi 2010), is a PCA-based version of the RTTOV (e.g. Matricardi *et al*., 2004) fast radiative transfer model. The PCRTTOV fast radiative transfer model performs rapid and accurate simulations of PC scores of IASI radiances using a multiple linear regression scheme. In this scheme, the PC scores are expressed as a linear combination of a selected number of polychromatic radiances simulated by the conventional RTTOV fast model. The regression coefficients are computed using the PC scores obtained from the eigenvectors of the covariance matrix of a large dataset of synthetic noise-free clear sky radiances calculated using an accurate line-by-line model. The PC scores can be computed for any state vector that includes variable profiles of temperature, water vapour, ozone, and surface parameters. The number of predictor variables used in the regression algorithm is a tuneable parameter in the model. By varying this parameter, we can trade off computational efficiency against the accuracy of the simulations (i.e. the accuracy can be increased by increasing the number of predictors used in the regression). The ability of the fast PCRTTOV to reproduce the exact PC scores computed from line-by-line radiances is such that the total error in the simulated PC scores is almost completely dominated by weaknesses in the underlying line-by-line model.

The initial PC assimilation investigations were carried out using short wave band of IASI, because it has high instrument noise and it was perceived there was most to be gained. The results were documented in a series of technical reports (e.g. Matricardi and McNally, 2012). However, IASI short wave channels are not currently used operationally at ECMWF for a number of reasons other than high instrument noise, which include direct solar effects and day-night variations due to non-local thermodynamic equilibrium (LTE) effects. Consequently the focus shifted towards the assimilation of PC scores generated from the long-wave region of the IASI spectrum. A prototype long-wave PC score assimilation scheme (Matricardi and McNally, 2013) has been initially tested in a baseline environment where conventional observations and atmospheric motion vectors (AMV's) are assimilated, but IASI observations are the only satellite sounding data used (either in the form of PCs or radiances). The absence of other satellite data amplifies the influence of IASI and allows changes to the analyses to be more directly attributable. Testing over two separate one month periods (winter and summer) suggests that the quality of the analyses produced by the assimilation of 20 IASI PCs is almost identical to that obtained when an equivalent 165 IASI radiances are assimilated. Indeed in some respects - specifically the fit to radiosonde observations - the analyses based on the assimilation of IASI PCs are marginally improved although this may be related to different tuning. The verification of forecasts launched from these test analyses further confirms that there is no loss of skill from the assimilation of IASI PCs compared to that of radiances. Based on the impressive performance of the PC assimilation prototype, short-term priority has been given to the testing of the IASI PC approach in a full data assimilation system that contains all operational observations (satellite and conventional). Testing in this extremely demanding new baseline environment has allowed us to check that the conclusions reached for the prototype system study were robust. Furthermore, following the investigation into the use of PCs to represent the IASI short-wave and long-wave spectrum, we have taken the logical step of considering the extraction of information from the dedicated IASI water vapour and ozone bands.

To quantify the performance of the revised PC score assimilation system we have designed a set of 4D-var assimilation experiments that consist of a baseline experiment, a radiance assimilation control experiment and a PC score experiment. The baseline experiment (BASE) uses all operational observations (satellite and conventional) with the exception of IASI data. The radiance control experiment (RAD) is identical to BASE, but additionally assimilates the 191 IASI channels used in the operational 4D-Var system. The PC score experiment (PC) is identical to BASE, but additionally assimilates 50 PC scores derived from 305 IASI channels obtained by augmenting the 191 operational channels with additional surface, ozone, and water vapour sounding channels. All experiments have been run using a reduced horizontal resolution version (T511, ~40 km) of the ECMWF IFS cycle 38R2 with 137 vertical levels. To date we have tested the period from 1 June 2012 to 15 September 2012 assimilating IASI data over ocean. A considerable amount of attention has been focussed on the specification of the PC score observation error covariance matrix **O**. The matrix **O** should describe the combined error of the observations (PC scores) and forward operator (PCRTTOV). Departure statistics have been accumulated over long periods to obtain an initial estimate of the elements of **O**, computing the standard deviation of the observed minus background (O-B) departures. Of course these values are not optimal in that they contain a contribution from the uncertainties in the background state and as such can only be regarded as an upper bound to the true error. To separate the contribution of the observation error and the background error in the departure statistics we have used the techniques proposed by Hollingsworth and Lönnberg (1986) and Desroziers *et al.* (2005).

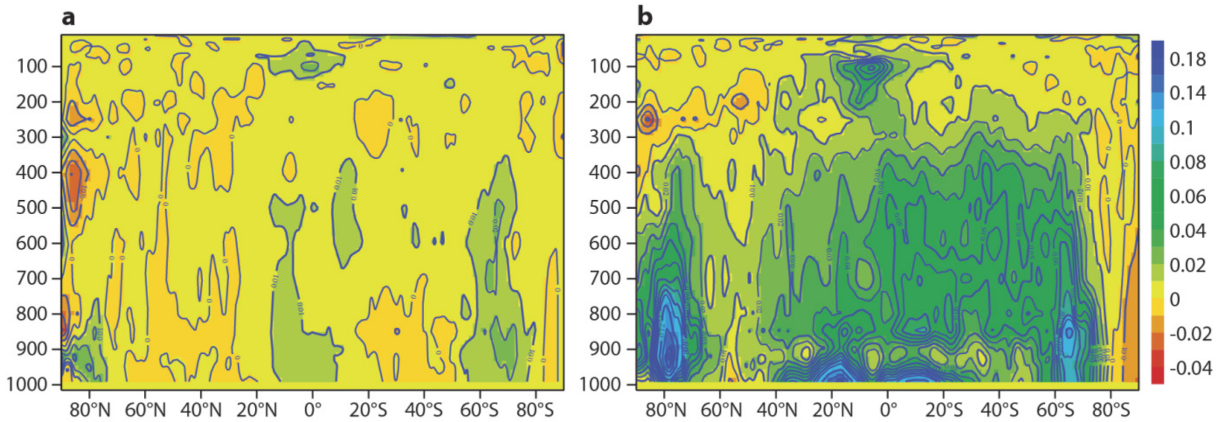

Figure 7 **The difference (experiment-control) of RMS of analysis temperature increments assimilating 191 channel radiances (left) and 50 PC scores (right).**

In a set of preliminary assimilation experiments it was found that both the Desroziers and Hollingsworth/Lönnberg refinements of the diagonal observation error for PC scores produced significantly better results than simply using the untuned standard deviation of observed minus background departures. However, the Hollingsworth/Lönnberg error values gave an additional marginal improvement in analysis fit to radiosondes over the Desroziers estimates so these have been adopted for the main PC assimilation testing. For the observation error covariance matrix **O** of the RAD experiment, we have chosen to use the same diagonal matrix used operationally at ECMWF (see Collard and McNally, 2008). The reason for making this choice was to ensure we have a reliable control based on a sound operationally proven radiance assimilation system (rather than attempting to produce two *matched* systems with no heritage). When assessing the performance of the PC assimilation system it is important to note that the use of PC data is currently restricted to fully clear spectra, in contrast to the radiance assimilation which uses data above cloud as well.

Zonally temperature analysis increments RMS difference (defined as the change to the initial conditions at the beginning of the 4D-Var analysis window) indicate that below 200 hPa the assimilation of 50 PC observations produce larger corrections to the background errors than the assimilation of 191 IASI radiances. This effect is universal and as seen in Figure 7 is larger at the Tropics near the surface and at Northern high latitudes in the lower troposphere. Although the data coverage is not identical and the observations are assigned different weights, one could tentatively attribute the origin of these differences to the information conveyed by the additional IASI channels included in the PC experiment. In Figure 8 the change in the background fit to radiosonde temperature observations over the BASE system is shown for radiance and PC IASI assimilation in the Southern Hemisphere and Tropics; a slightly better fit is produced in the troposphere by the assimilation of PC scores. In the Northern Hemisphere, PC score results are more comparable with those obtained from the radiance assimilation (not shown). Forecasts have been run from analyses generated by the BASE, RAD and PC assimilation systems and verified using the ECMWF operational analyses. Forecast scores over the three month test period have been computed as the change in the root-mean-square error compared to the BASE and the difference normalized by the forecast error of the BASE experiment. Differences between the forecasts produced by the PC and RAD system are generally not statistically significant suggesting that the PC score assimilation performs at least as well as the radiance system. The PC assimilation in cloud-free scenes seems to produce a level of performance that is very close to that produced by the operational radiance assimilation system which is based on the use of fully overcast scenes and on channels unaffected by clouds. This result is all the more important in light of the fact that the 50 PC score system based on 305 radiances uses ~20% less computer resources (during the 4D-var minimization) compared to the system that assimilates 191 radiances. This figure represents a significant saving inside the time critical processing path for NWP centres, but could potentially be improved even further. The cost of assimilating a given observation is strongly influenced by the numerous calls to the observation operator and its adjoint.

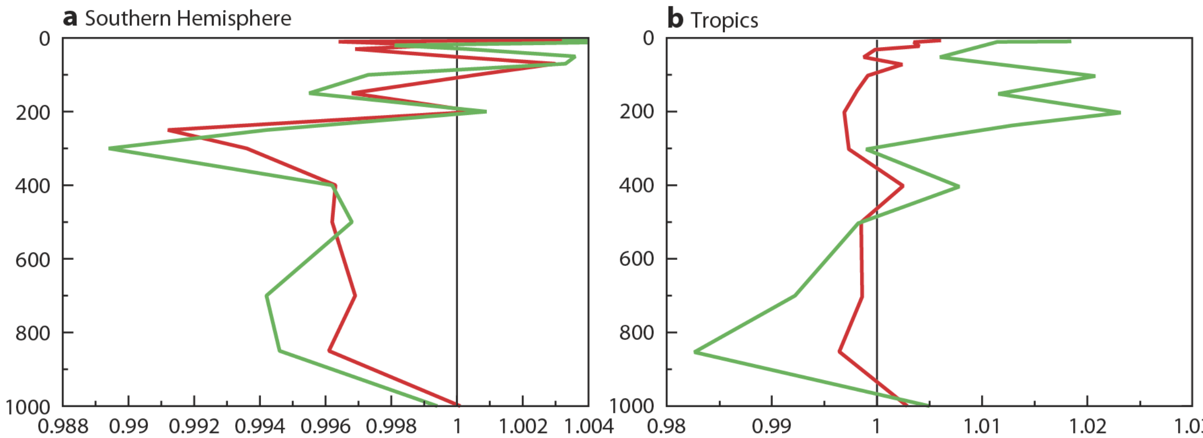

Figure 8 **The normalised change in in background fit to radiosonde temperatures with respect to a no-IASI baseline for Southern Hemisphere (left plot) and Tropics (right plot). Numbers less than 1 indicate beneficial impacts from the IASI observations; so 0.99 indicates a 1% improvement. The red curve denotes the experiment with 191 radiances, the green line the experiment with 50 PC scores.**

The number of predictors used inside PCRTTOV has been chosen for maximum accuracy, but lowest efficiency. Re-setting of this tuneable parameter could further reduce cost. Offline tests have shown that the number of predictors could be reduced by 30% without significantly affecting the accuracy of the PC score simulation. The next step is to investigate how well the PCs assimilation methodology extends to partly cloudy of fully overcast scenes, posing challenges that may take some time to solve. The method used to select radiances whose sensitivity is almost exclusively above the cloud top will not work for PCs, as a single PC can be sensitive to multiple layers in the atmosphere. Therefore it will not be possible to screen cloud-affected PCs in the same way.

To summarise the viability of PC assimilation has been demonstrated for cloud-free scenes. Progress in this area is very timely - at the time of writing there were four such instruments in space (IASI on METOP-A and B, AIRS on AQUA and CrIS on NPP). Work is now urgently needed to take this prototype system forward to a stage where it can be considered as an option for the safe and efficient operational exploitation of these crucial instruments.

3.3.2 Lidars and radars

CloudSat, CALIPSO and EarthCARE

Numerical weather prediction (NWP) models have improved considerably over the past few years in the forecast of clouds due in part to improved initial conditions and progress in parameterisations. The representation of clouds in models has improved to the extent that we can consider the assimilation of cloud-related observations. Active observations can give high vertical resolution for moisture and clouds. CloudSat, described by Stephens *et al.* (2002), and CALIPSO, described by Winker *et al.* (2010), were launched into the A-Train constellation in 2006, providing observations of clouds from almost coincident spaceborne lidar and radar. CloudSat carries the Cloud Profiling Radar (CPR), a 94-GHz nadir-looking radar that measures the power backscattered by clouds. The CALIPSO payload includes CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), a nadir-viewing, dual wavelength (1064 nm and 532 nm), dual polarised lidar. Similar observations will be available in the near future from the EarthCARE (Earth Clouds, Aerosols and Radiation Explorer) mission jointly prepared by JAXA and the European Space Agency (ESA, 2004). In common with the initial all sky radiance assimilation developed by Bauer *et al.* (2006) it is simpler to undertake initial investigation for cloud radar and lidar assimilation using a 1D + 4D-Var approach. The 1D-Var provides the best estimate of the temperature and humidity profile at the observation point that is consistent with the linearised model physics, as described by Janisková and Lopez (2013), the observations and the background. The 1D-Var analysed quantities are then assimilated as ‘pseudo-observations’ in 4D-Var, causing changes in cloud, precipitation, and wind fields.

Figure 9 (panel a) shows a track of radar reflectivity between 60N and 60S derived from the CloudSat 94 GHz radar passing over the Pacific on 23 January 2007. The high spatial resolution observations are averaged to the resolution of the forecast model. The observation operator is used to calculate model equivalent observations. This is labelled background (BG) in Figure 9 (panel b) and shows the ability of the model to produce large scale cloud structures similar to the observations. Overall the model clouds appear at the correct locations, even though there are differences in their vertical structure with respect to observations. The radar reflectivity obtained by assimilating CloudSat observation into the 1D-Var is shown in Figure 9 (panel c). As expected, the radar reflectivity calculated from the analysis is closer to the observations for most profiles except for convective clouds (e.g. between 3S and 18 S latitudes), where it remains closer to the background value. The corresponding 1D-Var analysis increments of specific humidity and temperature are also shown in Figure 10. Interestingly, one can note that temperature increments are not negligible compared with the specific humidity ones. This means that pseudo-observations of both temperature and specific humidity profiles from 1D-Var retrievals should be included into the 4D-Var system.

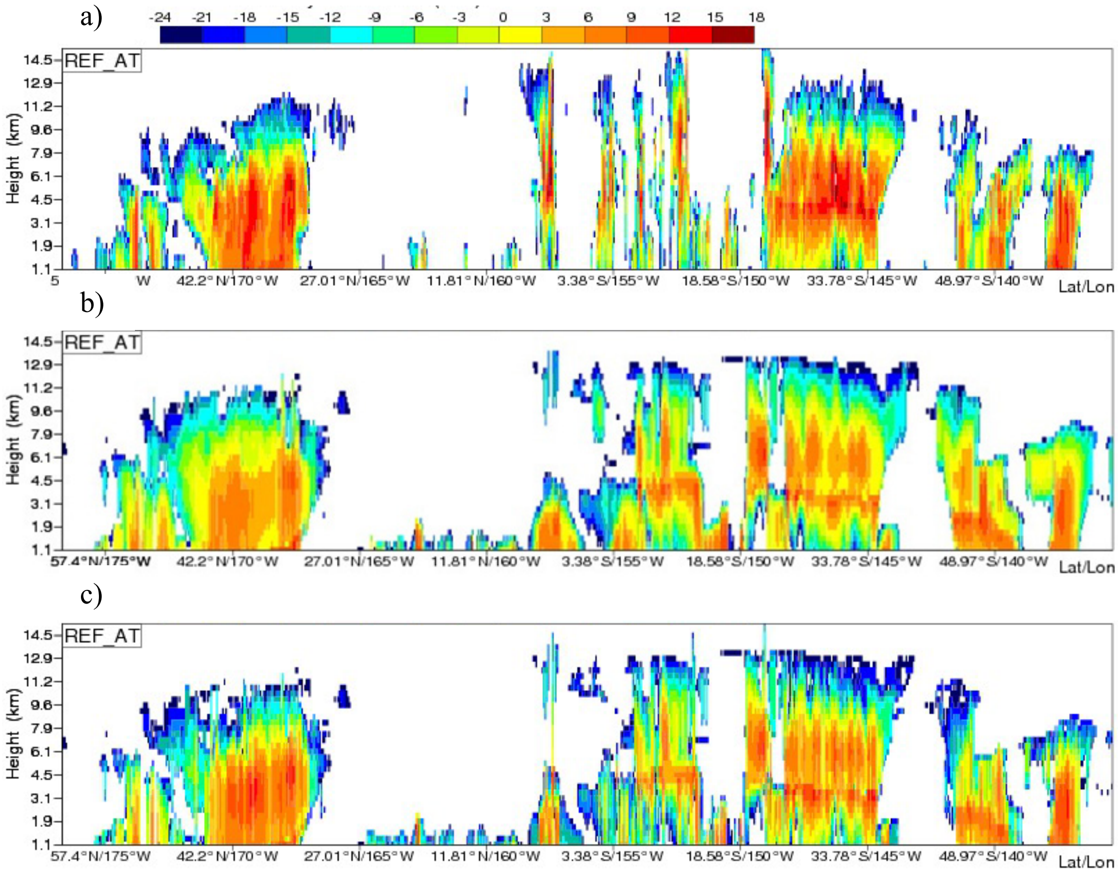

***Figure 9** Radar reflectivity (in dBZ) on 23 January 2007 over the Pacific Ocean: (a) CloudSat observations (averaged), (b) model background (BG), and (c) 1D-Var analysis (AN).*

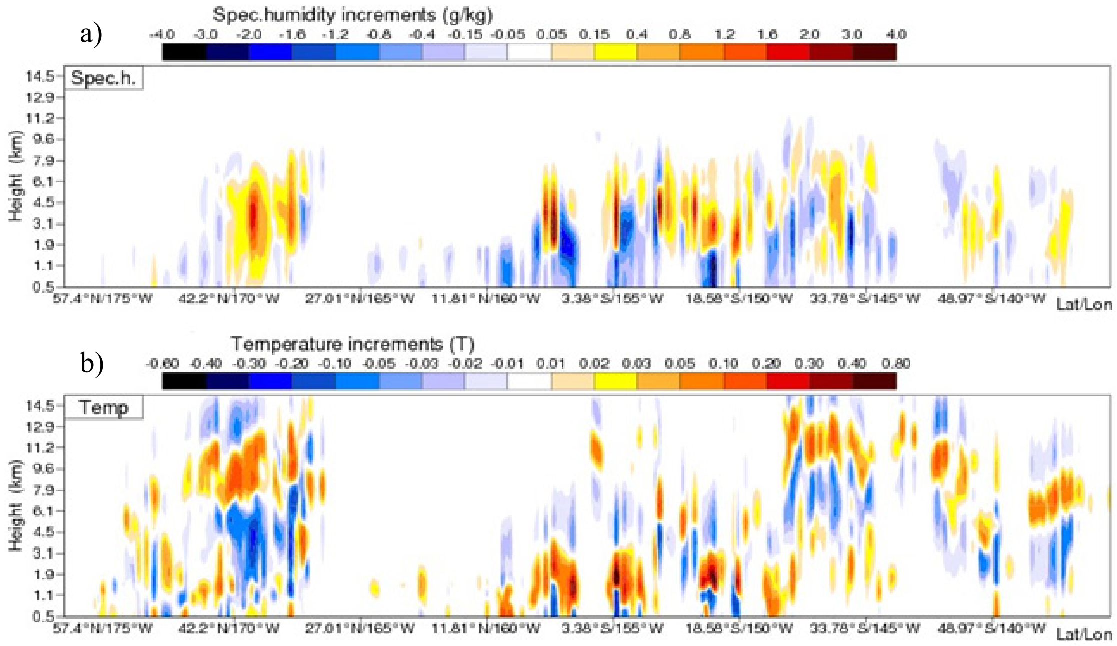

***Figure 10** Analysis increments for specific humidity (panel a) and temperature (panel b) from 1D-Var assimilation of CloudSat reflectivity shown in Figure 8.*

The 1D-Var system has been recently extended with the inclusion of a lidar forward operator (Di Michele et al. 2012) in order to allow the assimilation of cloud observations from CALIPSO. Given that the two satellites are flying a few minutes apart along the same orbit, the datasets are almost coincident, and lidar assimilation has been tested for the same case as CloudSat. The comparison (not shown) with the coincident CloudSat observations highlights the complementarity with respect to radar measurements. Lidar is able to reveal thinner clouds and also details of the upper portion of the clouds. As for the radar, the forecast model is able to locate clouds quite accurately, resulting in a simulated lidar signal that qualitatively matches the observations. However the fine structures of observations are not well reproduced, despite the averaging to model resolution, in part because the model does not fully capture features at the resolution of the Gaussian grid and the model does not have a representation of sub-grid horizontal inhomogeneity. Contrary to the radar case the analysis fit to observations is only marginally better than that from the background. This is partly related to the small observation field of view, and resulting large values of the representativeness error. As this is part of the observation error, as seen by the data assimilation system, this reduces the weight given to the observations in the analysis. Despite this 1D-Var assimilation is able to appreciably modify the BG temperature profiles. Compared to the radar impact the lidar increments occur at higher altitudes and are therefore complementary. At altitudes where both radar and lidar observations are available the increments are consistent.

Janisková et al. (2012) have demonstrated the positive impact that the 4D-Var assimilation of temperature and humidity pseudo-observations derived from CloudSat has on the analysis and forecast of temperature, humidity and winds. An extension of their study is currently on-going where lidar observations or combined radar/lidar observations are used in the 1D-Var for definition of the pseudo-observations.

The progress has been very encouraging. When the work on satellite radar and lidar began, it would have been fair to describe it as an interesting side project. It has now become a key element of the longer term strategic plan. Whilst an operational data source remains many years away, meaning that this effort will progress through partnership with space agencies, it nonetheless now forms a key part of the ECMWF's strategy for improved initial conditions and should form a core part of the satellite GOS in years to come.

ADM Aeolus

Information content studies such as the forecast sensitivity to observations, described by Cardinali (2009), show that for the current GOS there is a very strong need for more wind observations, compared to temperature and humidity. The ADM Aeolus mission is planned to be launched within a few years and will provide single component horizontal line-of-sight (HLOS) wind profiles all over the Earth (in around 100 km horizontal coverage). ECMWF is developing the level-2 processor as well as assessing the potential impact of Aeolus, in collaboration with ESA. Figure 11 shows a strong global sensitivity to wind observations in the upper troposphere and lower stratosphere in general and at jet level (~200 hPa) in particular. This is especially true for the tropical regions.

An important question for wind lidar measurements is whether modern data assimilation systems can use HLOS (single component) winds effectively. This can be studied by extracting the zonal wind component of radiosondes, aircraft and profiler measurements to give information content comparable with a HLOS wind. By assimilating these winds and comparing with full vector wind assimilation the value of HLOS winds can be estimated. Figure 12 shows the improvement in the forecast error assessed using a total energy norm achieved by assimilating the HLOS wind data. This is especially apparent in data sparse regions. However, data dense regions are also positively affected. It should be noted that the results are only accurate in the context of the reference degraded observing system, and also that Aeolus will have a different geographical coverage. We can also see how much of the full vector wind impact can be achieved by only assimilating the HLOS component. Figure 13 shows that this figure is almost always more than 50% and typically close to 75%. All this makes the point very clear that HLOS winds can be effectively assimilated in the 4D-Var system. An area of uncertainty for Aeolus relates to the laser power that can be used. The study has shown that a 25% increase of random observation errors, as might result from a decrease of the laser energy for the mission, degrades the impact by only a small amount.

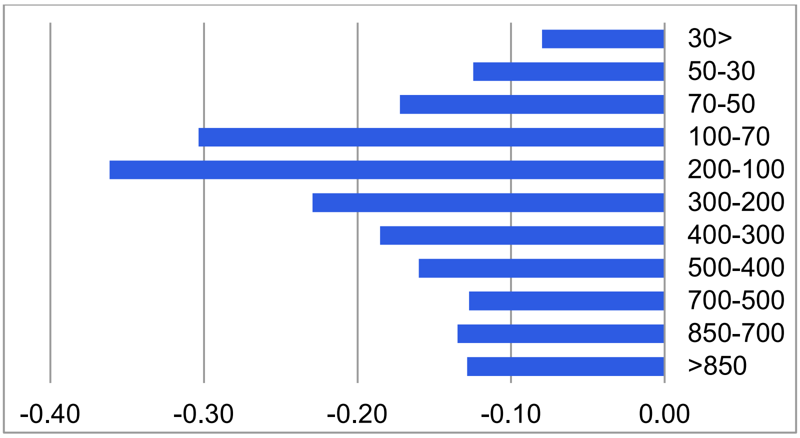

***Figure 11** The total forecast error reduction (J/kg) per observation for wind observations at different atmospheric layers.*

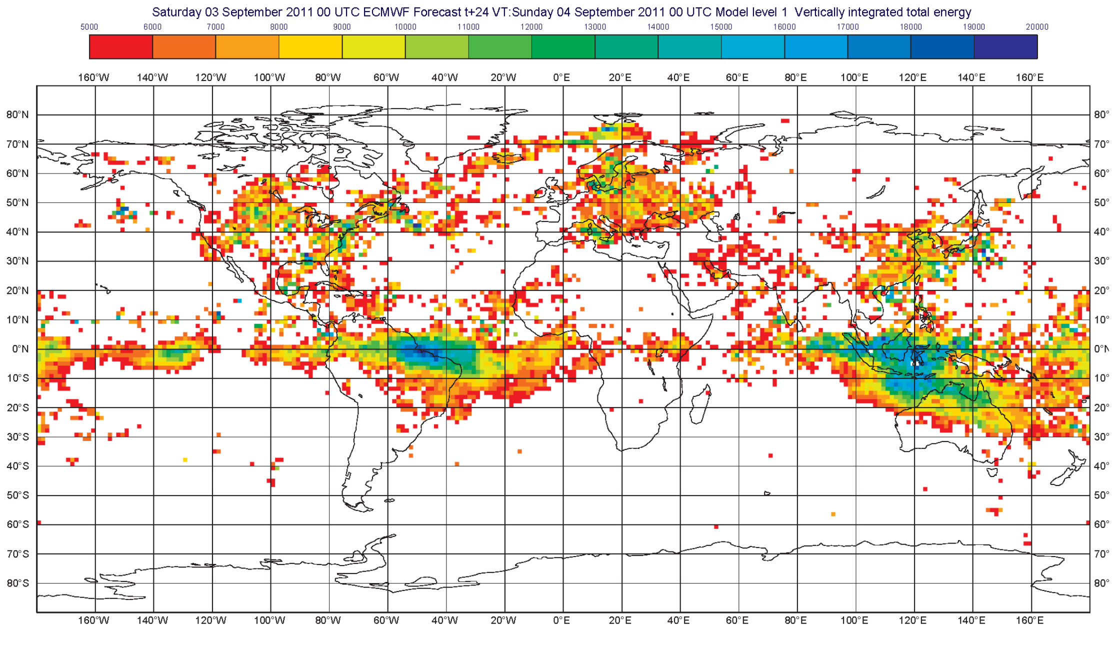

***Figure 12** The reduction of total forecast error based on the dry energy norm when HLOS (zonal wind) data were assimilated.*

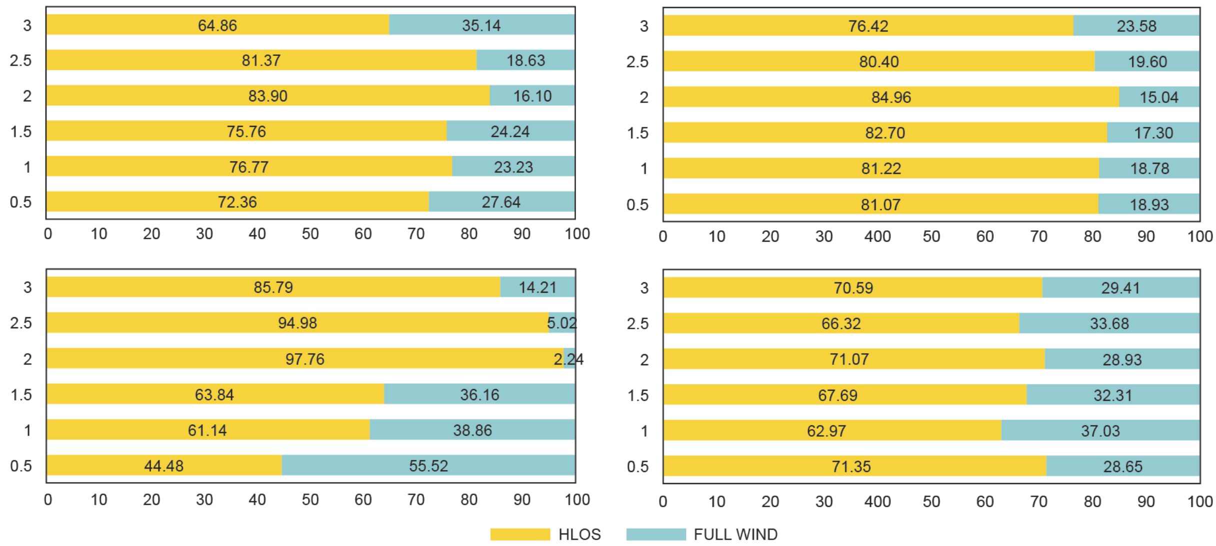

Figure 13 *The percentage impact of HLOS wind information (yellow) compared to the full vector wind for forecasts from 0.5 day to 3 days. The left panels show results for the Northern Hemisphere extra-tropics and right ones for the tropics. Upper panels show 250 hPa and lower panels 850 hPa values.*

The ADM Aeolus mission will operate in continuous pulsed mode at 50 Hz, with laser pulse energy output of 80 mJ at the start of the mission. This will be able to provide valuable observations that should improve the ECMWF analyses and forecasts. On the other hand small observation biases (at or above 0.5 m/s) may be detrimental. Therefore further work is needed to establish the absolute accuracy of Aeolus observations, and the impact of biases in the data assimilation. Aeolus clearly has the potential to provide an important breakthrough in wind observation and alongside EarthCARE, CloudSat, CALIPSO, radio occultation and scatterometers shows the increasing importance of active techniques for atmospheric analysis.

3.4 Improved use of existing observations

All-sky radiance assimilation

In the last decade attempts have been made to increase data coverage from satellites in cloudy and precipitating areas. To make full use of such data is very challenging and some have questioned if, with the limited resources allocated, significant progress can really be made. However the value of providing data in these regions is already being demonstrated. As observation operators, model physics and data assimilation techniques continue to improve, treating clouds as information rather than a problem is likely to become more accepted. It is possible to imagine a future time when the idea of avoiding clouds will be considered obsolete. ECMWF already assimilates microwave imager radiances no matter whether the scene is clear, cloudy or precipitating; this is known as all-sky assimilation. The forecast model inside 4D-Var is able to adapt the water vapour, cloud and precipitation alongside the dynamical fields (i.e. mass and wind) to better fit these observations in the analysis. Currently observations from TMI and SSMIS are assimilated over ocean surfaces. Imager channels at 19, 24, 37 and 91 GHz are assimilated along with, from cycle 39r1, the SSMIS 183 GHz water vapour sounding channels (Geer 2013).

All-sky assimilation produces clear beneficial impacts on short- and medium-range forecasts of wind and geopotential throughout the troposphere. Figures 14 and 15 show the normalised change in wind-vector RMS errors when TMI and SSMIS are added to an otherwise complete observing system. Forecast impacts are around 1% and are statistically significant out to day 4 in the southern hemisphere (Figure 14). The impacts are largest between 20 and 60 degrees latitude in both hemispheres, with statistical significance at the surface and in the mid and upper troposphere (Figure 15). Background fits to other observations are also improved (not shown): there are 0.5% to 1.5% improvements in fits to conventional and satellite wind observations and 1% to 4% improvements in fits to satellite moisture channels. The observation fits benefit from all-sky observations even in the tropics where the verification against analysis looks neutral or poor in the early forecast range (Figure 14). The observation fits support the validity of the forecast scores. To put the 1% improvement in forecast scores in context it is larger than the impact of removing one of the eight AMSU-A like instruments. AMSU-A is the observation type with largest forecast impact. So despite having an information content mainly relating to water vapour, cloud and precipitation, the all-sky microwave imager observations are providing useful and measureable benefits to dynamical forecasts.

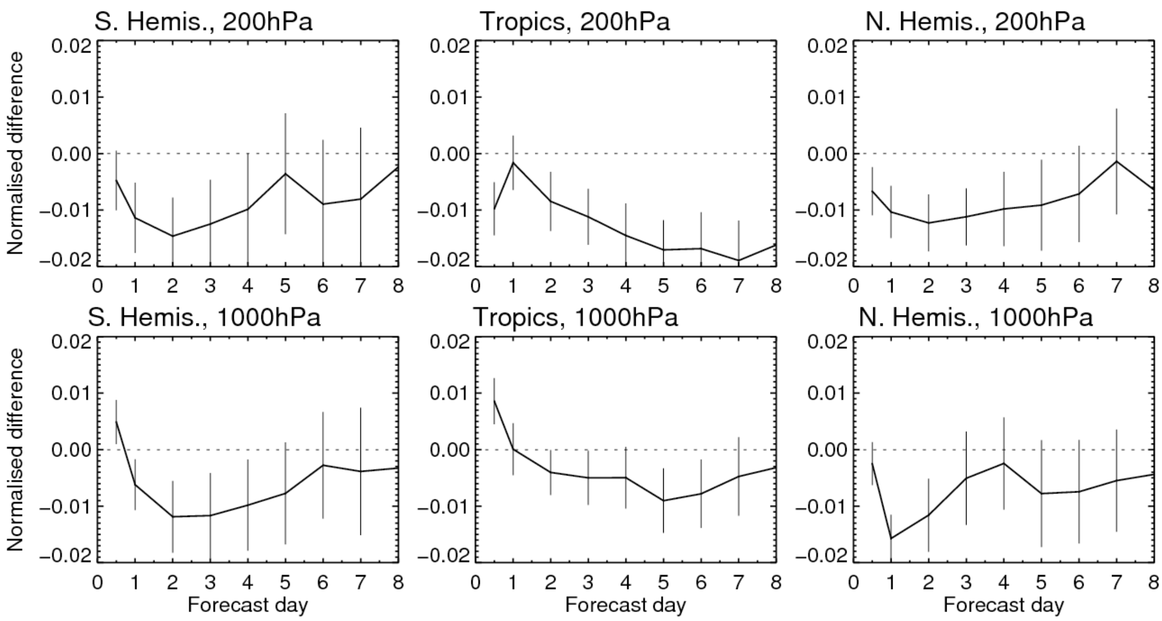

Figure 14 *Normalised change in wind vector forecast error (RMS) when all-sky TMI and SSMIS observations are added to the full observing system. Negative values indicate a reduction in forecast error and show that TMI and SSMIS have a beneficial impact on forecasts; error bars give the 95% confidence limits. Scores are based on a four-month OSE at T511 resolution, June to September 2012. Verification is against own-analysis. Scores at day 1 and earlier should be treated with caution as they can be strongly affected by the choice of verifying analysis.*

Direct assimilation of all-sky radiances was introduced into operations in 2009 (Bauer et al., 2010; Geer et al. 2010). Subsequent improvements to the all-sky approach included (a) superobbing to help match the forecast model's spatial scales for cloud and precipitation and (b) a model for observation error that gives larger observation errors in cloudy and precipitating situations than in clear-skies (Geer and Bauer 2010, 2011). However, though background minus observation fits showed benefits, microwave imagers did not improve dynamical forecast scores very much in some of these configurations (e.g. Geer and Bauer 2010). The significant mid- and upper-troposphere impact in Figures 14 and 15 comes mainly from improvements to the quality of the observation operator in precipitating conditions and the addition of the SSMIS 183 GHz water vapour sounding channels (Geer and Baordo, 2013; Geer, 2013). The benefit to forecasts is likely due to the 4D-Var tracing effect acting through water vapour, cloud and precipitation.

The SSMIS 183 GHz channels could have been assimilated with the same clear-sky approach as MHS, which also has 183 GHz channels. The clear-sky approach uses an observation operator that only simulates clear-sky radiative transfer; cloud-affected observations removed through quality control. However, the clear-sky approach does not have as great a benefit on forecast scores. The all-sky approach roughly doubles the number of available SSMIS 183 GHz observations compared to the clear-sky approach in the southern extra tropics and it also avoids systematic errors coming from undetected cloud (Geer, 2013). The scattering radiative transfer used in the all-sky observation operator is more computationally expensive than clear-sky radiative transfer but in this case the additional expense is justified. These results suggest that there may be benefit in moving MHS assimilation into the all-sky framework along with new 183 GHz water vapour instruments such as SAPHIR.

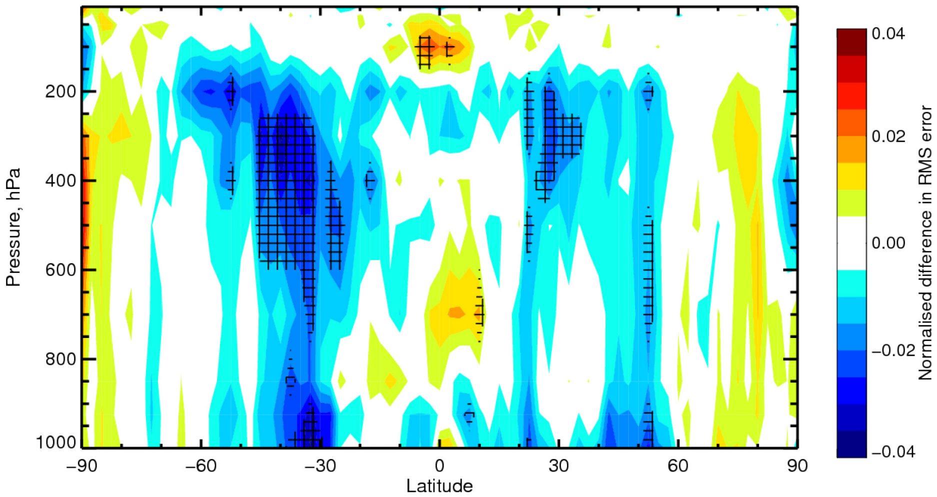

Figure 15 *Normalised change in wind vector forecast error (RMS) at day 2 when all-sky TMI and SSMIS observations are added to the full observing system. Blue colours indicate reduced forecast error arising from the all-sky observations. Cross-hatching indicates statistical significance of 95%.*

Given that AMSU-A is such an important instrument for improving dynamical forecast scores (see e.g. Figure 2, where AMSU-A is the main contributor to the very significant impact of MW sounders) it was also tested in the framework of the all-sky assimilation by Geer et al. (2012). The aims were to increase the number of observations in channels 5 and 6, which are mid and upper-tropospheric temperature channels, where around 20% of observations are lost to cloud-detection. A secondary aim was to reduce systematic errors from cloud contamination. However, it was not possible to improve on the results of the clear-sky AMSU-A assimilation. There is only minor scope for improved assimilation: cloud contamination is a small error source and the 20% of scenes which are removed by cloud detection are those where the forecast model and the all-sky observation operator are least accurate, i.e. areas affected by precipitation and deep convection. A particular problem in the tropics was that the all-sky approach increased rather than decreased the total error (i.e. the standard deviation of background departures) in channel 5. Total errors were increased because of the double-penalty effect: it is better not to simulate clouds and precipitation at all than to simulate them in the wrong place. We want to correct background temperature errors of order 0.1K but the typical background departure standard deviation in cloud and precipitation areas in AMSU-A channel 5 is around 1K to 2K. This number represents background errors in cloud and precipitation, inaccuracies in radiative transfer, and the high representivity error arising from cloud and precipitation on small scales. It is difficult to infer temperature signals of order 0.1K in the presence of 2K cloud errors.

The experiments with AMSU-A were only preliminary and the results might have been improved by the recent developments in scattering radiative transfer (Geer and Baordo, 2013) or a better solution to correlated observation error (e.g. Bormann, 2011). However, it is still fair to say that it is only the channels with principally water vapour, cloud and precipitation sensitivity that have benefitted from the all-sky approach as yet. With these channels, it is not just the direct water vapour and cloud information content that is important, but rather the 4D-Var tracing effect that benefits dynamical forecasts. In contrast, the forecast benefit from temperature sounding channels comes through the direct sensitivity to temperature. Hence the most likely configuration of the microwave assimilation over the next few years will have the imagers and water vapour sounders going through the all-sky route (e.g. TMI, SSMIS, MHS, AMSR2, SAPHIR, GMI) and the temperature sounders maintaining a clear-sky approach (e.g. AMSU-A, ATMS).

Progress towards cloud and precipitation assimilation in the infrared has been slower. The microwave, particularly the lower frequencies, is broadly and smoothly sensitive to deep-layer amounts of water vapour and cloud. The infrared sees only the tops of clouds and is strongly affected by the fraction of the field of view that contains cloud. So far, operational centres have gone down the route of ignoring the model's cloud forecast and instead making a prior or online (sink variable) retrieval of cloud fraction and cloud top height from the observations (e.g. Pavelin et. al., 2008). Even so, these techniques only use those observations or channels where cloud errors are not too important. At ECMWF, this has allowed the assimilation of 100% overcast scenes with a sink variable for cloud top height (McNally, 2009) but the number of valid overcast scenes is small and the forecast impact is limited.

Figure 16 sketches typical relationships between observed brightness temperature and total moisture for a selection of microwave and infrared channels. This is a hypothetical situation in which the total moisture content is increased from zero to the point where cloud forms. As total moisture increases further, the cloud fraction increases to 1 and eventually precipitation occurs. Further increases in total moisture bring deep-convection. At low microwave frequencies (e.g. 37 GHz over ocean) there is a smooth increase in brightness temperature due to emission from radiatively warm water vapour, cloud and rain. In the 183 GHz water vapour sounding channels increases in water vapour and cloud decrease brightness temperatures by pushing the weighting function higher. Scattering from frozen hydrometeors in deep convection decreases the brightness temperatures further. In these channels, where all-sky assimilation has been successful, the response to total moisture is relatively smooth and not too non-linear. Infrared channels in the 6.3 μm water vapour band have broadly similar behaviour to their counterparts at 183 GHz. Even in clear skies the variability of 6.3 μm brightness temperatures with water vapour is large and of a similar magnitude to the cloud signal. Hence the infrared water-vapour sounding channels might be able to provide similar benefits in an all-sky assimilation framework to those in the microwave. In any case, this is the easiest area to start testing all-sky infrared assimilation. In contrast, an infrared window channel (e.g. 10 µm) has its main sensitivity to the cloud top height and pressure.

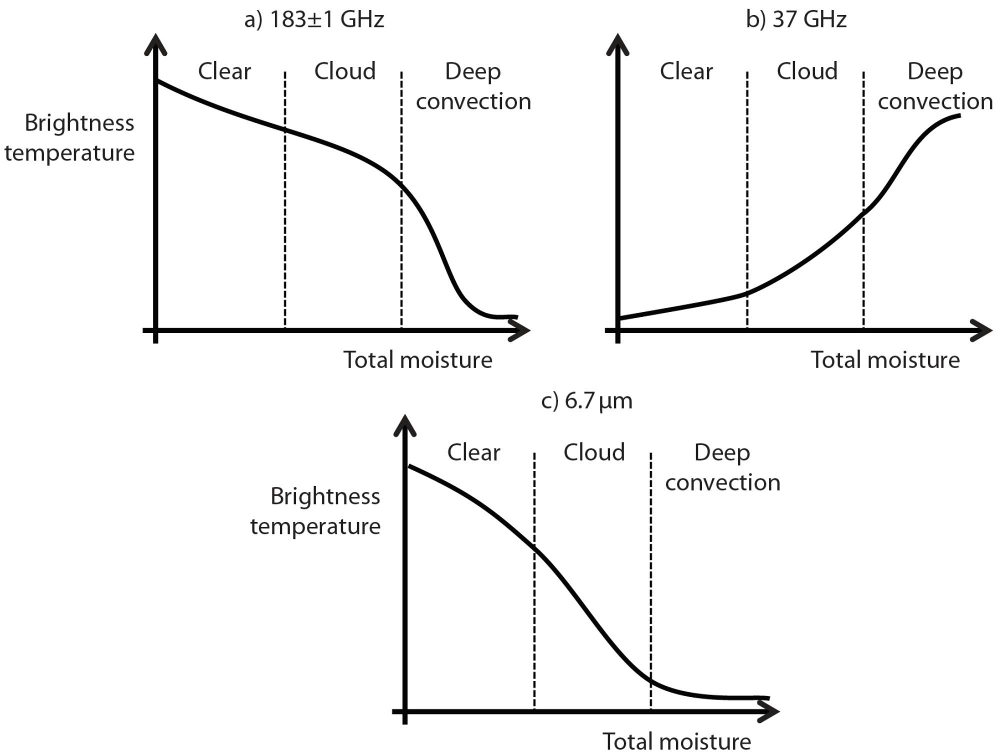

Figure 16 *Illustrative relationships between brightness temperature and total moisture for (a) a 37 GHz microwave imager channel over ocean; (b) a 183 GHz water vapour sounding channel; (c) a 6.3 µm water vapour sounding channel.*

A framework for all-sky infrared radiance assimilation exists at ECMWF but scientific testing has so far been limited because of technical problems such as excessive memory use and failures of the adjoint test (e.g. Okamoto et al., 2012). These problems have now been resolved though the memory usage problem requires a drastic scientific compromise which is to reduce the number of cloudy sub-columns used in the radiative transfer model (Matricardi et al., 2005) from around 50 to 1. However, this is not accurate for use in window channels or other channels sensitive to the lower troposphere where multiple cloud layers need to be simulated. A key future development will be to introduce a two- or three-column overlap assumption similar in concept to those employed in the all-sky microwave, where most of the benefits of multiple independent columns can be reproduced at a fraction of the computational cost (e.g. O'Dell et al., 2007, Geer et al., 2009). However, the initial single-cloudy column approach already works well enough in mid- and upper-tropospheric infrared water vapour sounding channels.

Cloudy infrared water vapour assimilation has been attracting attention elsewhere, particularly in the study of Otkin (2012), though that study relied on an OSSE so the results need to be treated with caution. Proof-of-concept all-sky assimilation runs have been made at ECMWF in the context of the full observing system (minus the HIRS instrument), with the addition of HIRS channels 11 and 12 in a basic all-sky approach (e.g. no superobbing, constant observation error with cloud amount). Channel 12 is a 6.3 µm channel sensitive to mid- and upper-tropospheric water vapour as well as cloud; channel 11 is also a water vapour channel but peaking at lower levels. The assimilation results are encouraging for upper tropospheric humidity, as shown in Figure 17, and no significant negative impact was found from adding HIRS in both clear and cloudy situations.

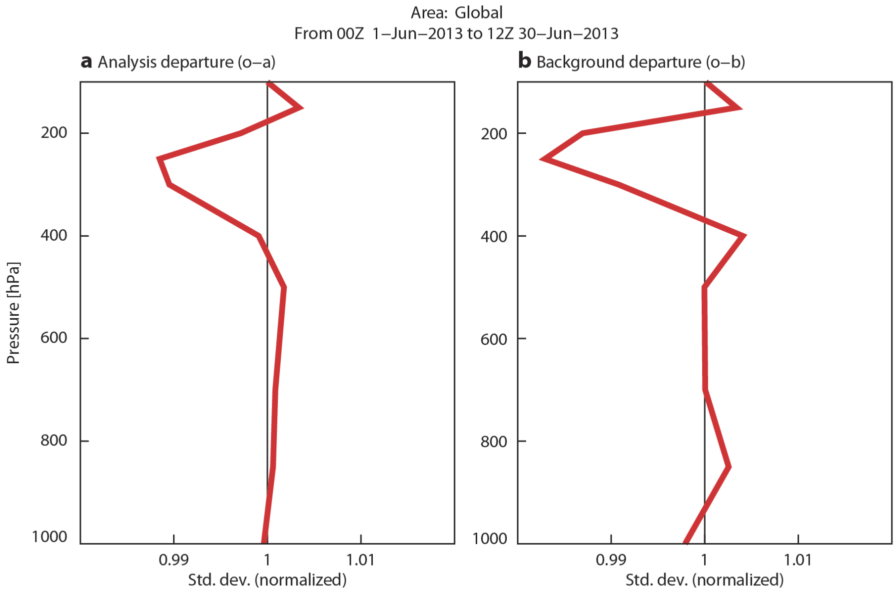

Figure 17 The normalised change in standard deviation of (a) analysis and (b) background differences from radiosonde humidity observations when assimilating cloud affected HIRS channels 11 and 12 in the all-sky system. Values less than one indicate beneficial impacts from the all-sky HIRS assimilation. Note that no HIRS data was used in the control experiment.

To summarise, all-sky assimilation of microwave sensors such as TMI and SSMIS is now an important part of the forecast system with benefits to medium-range scores of around 1%. Though that may sound small, it is significant in the context of the full observing system where for example the denial of one AMSU-A costs only 0.5% in forecast scores. The benefits likely come through 4D-Var tracing of water vapour, cloud and precipitation features, where even in the presence of relatively large forecast and observation operator errors there is still information content to be gained. Over the next few years we hope to apply all-sky assimilation to most other microwave instruments with primary water vapour or cloud sensitivity, such as MHS and SAPHIR. If testing goes well the all-sky approach will even be extended to infrared water-vapour sounding channels such as on HIRS and IASI. In contrast, temperature assimilation in the presence of cloud and precipitation is a much harder problem, and perhaps fundamentally ill-posed with the current quality of short-range cloud and precipitation forecasts. It is still very hard to infer direct temperature signals of order 0.1 K in even in the AMSU-A channels most favourable to all-sky assimilation, since situations where cloud and precipitation are present are subject to errors worth 2-3K in brightness temperature space. In the infrared and in many other microwave channels, the cloud errors can be much larger. For the next few years, we expect to see contrasting approaches to the assimilation of satellite data. For water vapour and cloud channels, the all-sky approach uses super-observations with broad horizontal resolutions, e.g. 80km, and it manages to work despite the current limitations of cloud and precipitation predictability. For temperature channels, the clear-sky approach will likely remain the best choice, with its need for small fields of view to find the holes in the cloud (as small as 1km in the infrared) and very stringent requirements for accuracy in the instruments and the observation operators, e.g. 0.1K. This divergence is likely to be resolved as accuracy of short-term cloud and precipitation forecasts is further improved.

3.4.1 Observation error models

Variational assimilation assumes unbiased observation and therefore there are two aspects to handling observation error. One is to remove systematic error through a process known as bias correction and the other to then represent as accurately as possible the size of the random component of error. The bias correction approach at ECMWF has changed little in recent years, using the variational approach developed by Dee and Uppala (2009). The accurate specification of observation errors is however now receiving more attention than in the past. Bormann and Bauer (2009) found a substantial increase in the impact of microwave sounding observations through a new specification of observation error based on diagnosed error from the Dezrozier *et al.* (2005) method. This has led to a review of observation errors for many observation types and ECMWF is now examining the overall consistency of observation specification for all observation types. Furthermore more attention is now being given to the question of correlated observation error and scene dependence of the observation error variance, both of which have normally been ignored in the past. Changes to observation error need to be made in a consistent way with the quality control, and taking into account the changes being made to the background error term, to retain a balanced data assimilation system that is as close to optimal as possible.

Recent studies have indicated that many satellite radiances exhibit considerable error correlations, for instance between observations from different channels (Bormann and Bauer 2010, Bormann et al 2010, Garand et al. 2007). This is particularly the case for water vapour and lower tropospheric temperature channels from infrared sounders, for which several different observation error diagnostics consistently suggest sizeable error correlations. Most of these are thought to arise from errors of representativeness, the radiative transfer calculations, or residual cloud contamination, rather than the observations themselves. Currently, such error correlations are neglected in the assimilation, and inflated diagonal errors are assigned. Efforts are under-way to instead take these error correlations into account in the assimilation. Experiments show that doing this alters the filtering properties of the assimilation algorithm in a situation-dependent way. While error inflation can counter-act the average effect of neglecting error correlations, no single choice of error inflation will be able to achieve this situation-dependent effect.

Initial assimilation trials have been performed that investigate the role of error inflation and the use of inter-channel error correlations for AIRS and IASI, based on matrices diagnosed using the Hollingsworth/Lönnberg technique (Bormann and Collard 2012). Two series of experiments have been conducted: one in which the error correlations have been taken into account in the assimilation system, and the error standard deviations were scaled by a series of scaling factors which were applied to all channels. In the second series of experiments, error correlations were neglected and only the error standard deviations were used from the observation error diagnostics, again scaled by a series of scaling factors. The two series were compared against an experiment in which AIRS and IASI were denied from an otherwise complete observing system.

Accounting for the error correlations in the assimilation plays a significant role in the assimilation, as is shown in Figure 18 for an evaluation of background-departures for a range of other assimilated observations. Using unscaled diagnosed observation errors without error correlations results in a degradation of the analysis relative to not using AIRS and IASI at all, as over fitting these observations loses some of the high accuracy of the background. When assuming diagonal observation errors, relatively large scaling factors of 2.5-3 are required to partially compensate for this effect. Instead, when taking the error correlations into account, using the diagnosed observation error covariances without scaling achieves a positive impact from the assimilation of AIRS and IASI data. Further improvements can be achieved through moderate scaling of the observation error, with optimal scaling factors of around 1.5. The effect is strongest for humidity, reflecting the strong correlations observed in these channels. Further work is required to determine how best to deal with the inter-channel error correlations, but it is clear that accounting for inter-channel error correlations allows the use of observation errors that are more in-line with characteristics of observation departures. This aspect is also very relevant as the assumed observation errors are used in the EDA to apply observation perturbations, and this aspect deserves further careful study.

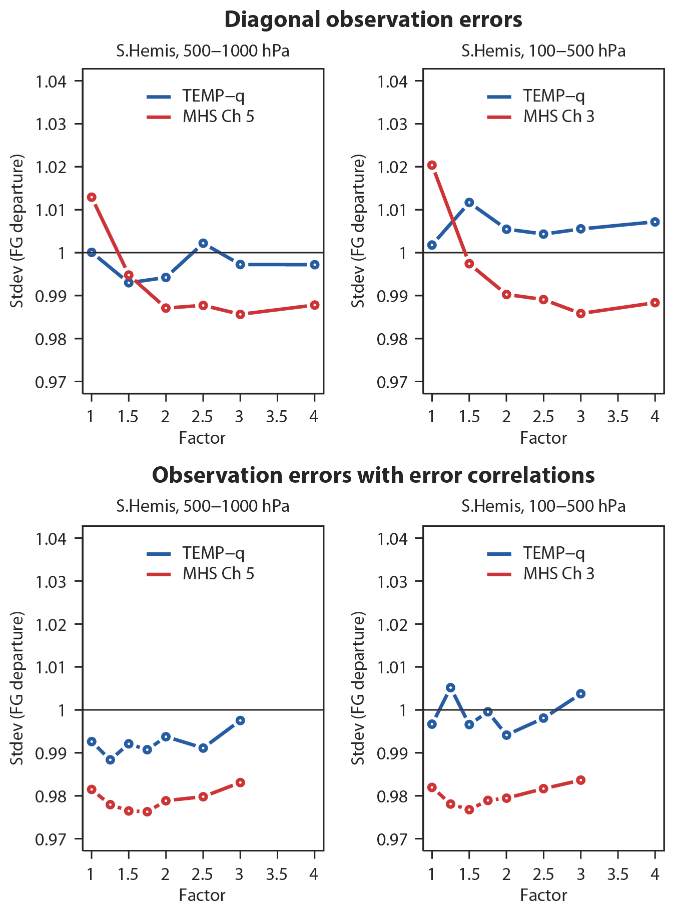

Figure 18 *Standard deviations of background departures over the Southern Hemisphere for humidity observations from radiosondes (blue) and MHS observations (red) as a function of the scaling factor applied to the diagnosed observation errors for AIRS and IASI. The standard deviations are normalised to 1 for the experiment in which AIRS and IASI are denied. Data are for 15 December 2011 – 14 January 2012. Top: diagonal observation errors are assumed; bottom: error correlations are taken into account. The departure statistics have been combined in the approximate layers indicated above the panels.*

It has been shown that the assimilation of AMVs can be significantly improved through a better scene dependent error model and quality control. Errors in the AMVs originate mainly from two sources: errors in the height assignment and errors in the wind vector tracking. The former is considered to be the dominant source of error and its impact is highly situation dependent. It can be very significant in regions where wind shear is strong but on the other hand it is less relevant in areas where there is not much variation in wind speed with height. These error characteristics can be accounted for in data assimilation by estimating the tracking error and the error in wind due to the error in height assignment separately and combining the estimates as a total, situation-dependent observation error for each AMV. This approach has been investigated in the ECMWF system.

AMV producers are currently not providing estimates for the height errors operationally. Thus, the height errors have been estimated based on model best-fit pressure statistics in the ECMWF system. Typical values for the height errors are of the order of 70 to 110 hPa. Comparison of best-fit pressure statistics for the ECMWF and Met Office Systems shows that the statistics are very similar for both systems. This increases confidence that the best-fit pressure is a useful concept in estimating the magnitude of the height errors. The estimated height errors are translated to wind errors using the background wind profile following the approach introduced in Forsythe and Saunders (2008). Tracking errors have been estimated from observation minus model background statistics by selecting cases where the wind error due to error in the height is small. The defined tracking errors vary from 2 to 3.2 ms^{-1} depending on height and satellite. The final observation error for each AMV combines the tracking error and the error due to error in height assignment, resulting in a highly situation dependent observation error. The new observation errors are on average of the same magnitude or slightly larger than the current operational observation errors which vary only according to the observation height.

Introduction of the situation-dependent observation errors can also improve the background check for AMVs. The background check for AMVs has traditionally been very strict in the ECMWF system using rejection limits for AMVs three times tighter than for conventional wind observations. Ad-hoc geographical dependencies have also been used. In addition an asymmetric background check has been applied to ensure that AMVs do not slow down the extra-tropical jets. However no such asymmetric check has been applied for conventional winds. The left-hand panel of Figure 19 illustrates the result of applying the asymmetric background check for Meteosat-10 cloudy water vapour AMVs at 100-400 hPa. The impact of the asymmetric check is seen and only data very close to background is retained (in the raw data some very large departures are found). The situation dependent observation errors allow a reduction in the weight given to observations in areas where wind shear is strong and the error in the height assignment can have a large impact. The right hand panel of Figure 19 shows the scatterplot using situation-dependent observation errors and a symmetric background check for AMVs and without using geographical dependencies in the rejection limits. The outliers are still effectively removed but the spread in the scatter plot is notably wider and there is no asymmetry in the observation departures.

In addition, a new quality control criterion has been investigated. The criterion limits the magnitude of the observation error due to error in height assignment to be smaller than 4 times the tracking error. The criterion is motivated by the fact that the height assignment errors are likely to be more correlated spatially and such correlations are currently neglected. The value 4 has been chosen after trial and error based on a set of model experiments. This allows AMVs with an observation error up to 8 -13 ms^{-1} enter the analysis, depending on height. The criterion rejects on average 1% of the AMVs on top of the revised background check. Overall, in the revised system the number of used AMVs is increased by about 4% compared to the current operational system. The increase is seen mainly in the mid and high levels.

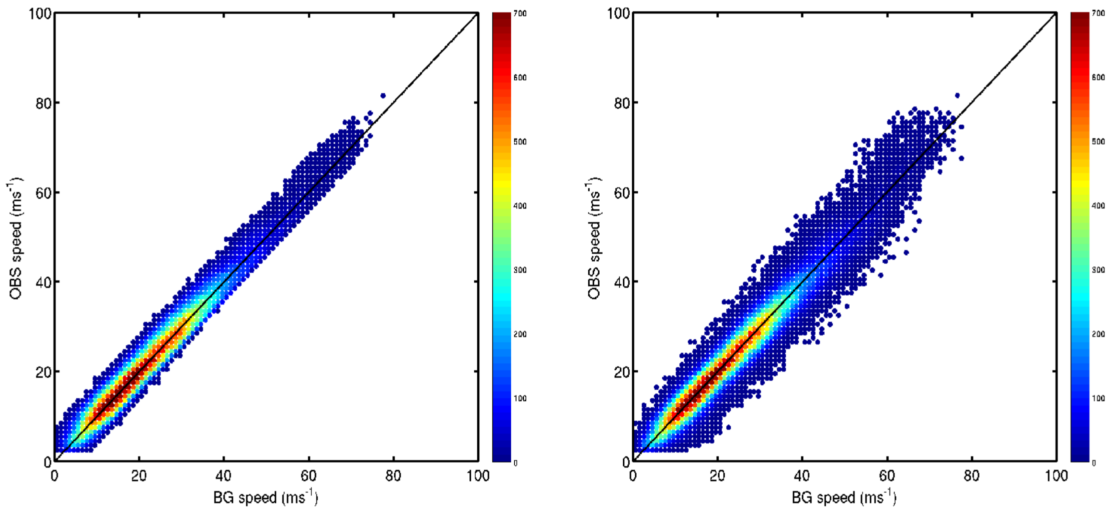

Figure 19 The left panel panel displays the Meteosat-10 cloudy water vapour AMVs at 100-400 hPa heights after applying the strict and asymmetric background check and the right hand panel shows the same using the symmetric check with situation dependent observation errors.

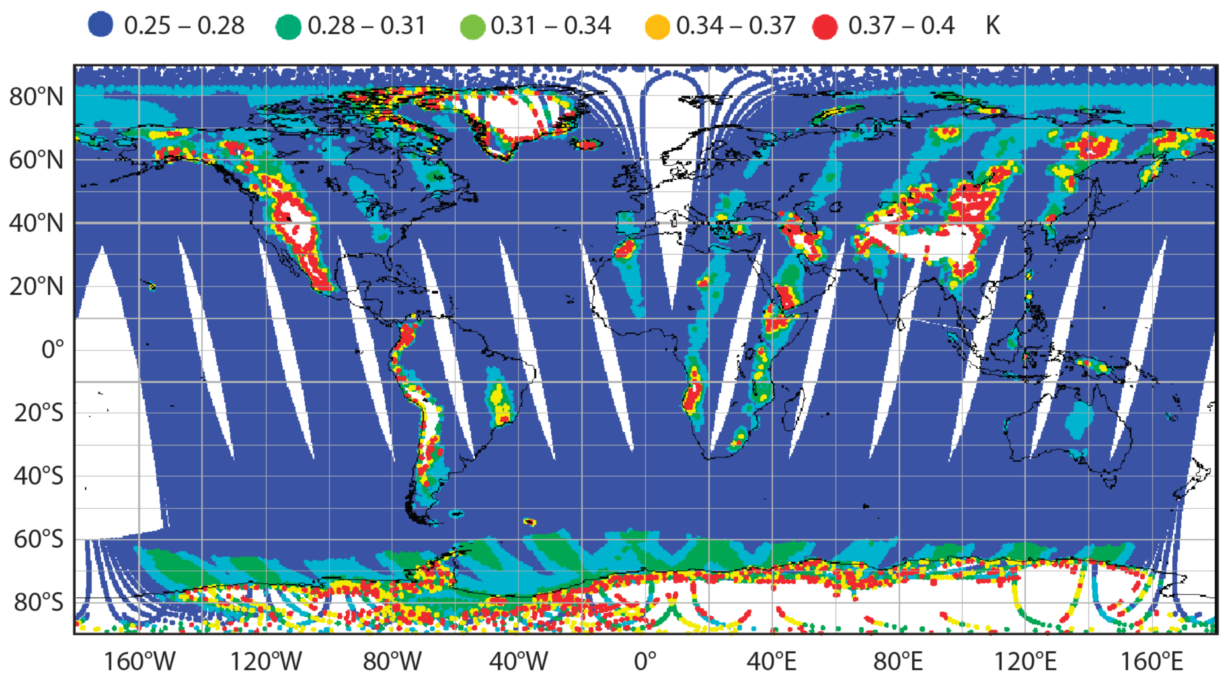

Figure 20 *AMSU-A channel 5 observation error, using a model allowing for surface type and atmospheric opacity.*

Overall the use of the situation-dependent observation errors and the revised background check clearly improves the use of AMVs in the ECMWF system with a positive impact on the model forecasts. The largest improvements are seen in the tropics at low levels but positive impact is evident also elsewhere. Verification against each experiment's own analysis indicates up to a 4% reduction in wind increments and in RMS wind errors for forecasts for forecast range up to 72 hours. For longer forecasts ranges the improvement is in the range 0.5 - 2% for most scores.

It is now recognised that improved observation error models may allow improved assimilation over land and sea ice where the observation operator error is strongly scene dependent. Early efforts focussed on extending the use of temperature sounding channels through improved emissivity estimation, and whilst this has allowed more data to be used the impact has been small in terms of forecast impact (e.g. Karbou, Gérard and Rabier 2005).. However Karbou *et al.* (2010) showed potential for improved humidity analysis over Africa through assimilation of microwave humidity sounder data over land. Effort at ECMWF has continued to look at the MHS and SSMIS instruments, the latter in the all-sky system, providing humidity sounding over land and sea ice. These efforts have proven successful, with positive impact clearly shown (Di Tomaso, Bormann and English 2013). There are many uncertainties in the treatment of the surface. Areas of debate have included whether to treat surface reflection as Lambertian or specular (Guedj *et al* 2010), whether we need to model emission better and how to improve the representation of surface skin temperature. English (2008) argued that to use AMSU-A channel 5 effectively needs an accurate surface skin temperature. There are also issues related to the representation of surface type variability and topography. Nonetheless little attention has been given to making the observation error scene dependent despite the fact some surfaces are much easier to model than others (in terms both of skin temperature and emissivity).

ECMWF have begun to investigate the sensitivity to modelling observation error scene dependence. Di Tomaso, Bormann and English (2013) developed a model for the observation error for AMSU-A channel 5. At nadir this channel peaks at around 750 hPa, but this rises towards the edge of the AMSU-A scan, due to increased atmospheric opacity. A simple model of the variation of observation error with scan angle and surface type can allow AMSU-A channel 5 to be assimilated in more areas. The new assumed error is shown in Figure 20; for reference the current operational assumed observation error at ECMWF is 0.28 K. It can be seen in Figure 20 that in some regions, for example on this day in large parts of the United States, a lower observation error can be assumed.

3.5 Other applications of satellite data

3.5.1 Land Surface Data Assimilation

The ECMWF Land surface Data Assimilation System (LDAS) aims at initialising the main surface prognostic variables that control the exchanges between the land surfaces and the lowest atmospheric level. In the last decade major progress has been made to improve the Land Data Assimilation System itself, as well as to develop the use of satellite data to initialise surface conditions, as discussed in Drusch et al., (2008) and de Rosnay et al. (2013a).

Concerning snow data assimilation, ECMWF has been assimilating both SYNOP *in situ* snow depth reports and the satellite-based NOAA/NESDIS multi-sensor snow cover extent product known as the Interactive Multi-sensor Snow and Ice Mapping System (IMS). Since 2010 the snow analysis has been continuously enhanced to replace the Cressman Interpolation by an Optimal Interpolation, to improve the multi-sensor snow cover product pre-processing and quality control and to use the IMS 4km product instead of the 24km product. Figure 21 shows that improving the IMS pre-processing and spatial resolution from 24 km to 4 km have a large impact on the 1000 hPa geopotential height forecast in the northern hemisphere. This significant and large-scale impact of the snow analysis on the atmospheric forecast illustrates the major importance of the snow analysis for Numerical Weather Prediction. Recent developments have focused on improving further the use of the IMS snow cover data with revised observations error specifications and implementation of snow depth and snow cover product monitoring in IFS cycle 40r1. Furthermore, as with the atmospheric observations, important work is undertaken with data providers to improve the quality and timeliness of their products.

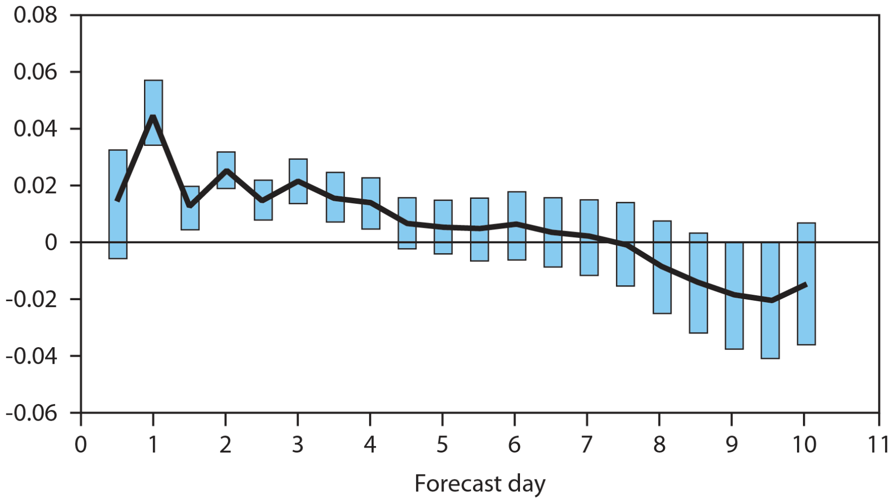

Figure 21 *Northern hemisphere 1000 hPa geopotential height impact of the IMS resolution and pre-processing upgrade (December 2009 to February 2010, days 1-10). Positive values indicate an improvement.*

Satellites products related to Snow Water Equivalent (SWE) would be very useful to further improve the snow depth analysis. SWE products based on passive microwave measurements are available. However, the observations are sensitive to many parameters such as snow grain size distribution and snow liquid water content, giving a highly ill-posed analysis problem for the frequencies used by currently available sensors. As a result SWE products have a limited accuracy, particularly for deep snow conditions (Takala et al. 2011). For this reason the ESA GlobSnow product also uses SYNOP snow depth reports in its retrieval algorithm. However the SYNOP data is already assimilated at ECMWF, so the GlobSnow product does not provide additional independent information. To improve, the ECMWF snow analysis will rely to a large extent on better observations, both *in situ* observations and dedicated satellite missions. The CoReH2O Earth Explorer proposal concept was designed to enable accurate retrieval of SWE, using dual polarisation and dual frequency measurements to analyse grain size and SWE. It reached the final stage of the ESA EE7 mission selection, but was rejected in favour of the BIOMASS mission. However it is likely that the CoReH2O concept will be considered again for future EE missions.

The ECMWF soil moisture analysis is based on a simplified Extended Kalman Filter approach (de Rosnay et al, 2011, 2013b). It relies on a screen level parameter data assimilation which is shown to improve both soil moisture and near surface parameter forecasts. ECMWF plays a major role in developing and investigating the use of new satellite data for soil moisture analysis. Satellite data from low frequency microwave sensors provide very valuable information on surface soil moisture conditions. The EUMETSAT ASCAT surface soil moisture product is the first operational soil moisture product available to the NWP community. ASCAT soil moisture has been monitored operationally at ECMWF since 2009. This monitoring was recently enhanced to also include Metop-B ASCAT soil moisture. In the context of EUMETSAT's H-SAF, an ASCAT root zone soil moisture profile product has been developed based on ASCAT surface soil moisture data assimilation in the ECMWF EKF Land Surface Data Assimilation System (de Rosnay et al, 2013b). The retrieved ASCAT root zone soil moisture, illustrated in Figure 22, is an optimal combination between the model background, the screen-level temperature and humidity analyses, and the ASCAT-derived surface soil moisture. This is propagated forward in time to the root zone profile. The ASCAT root zone soil moisture profile product is available for four soil layers from surface down to 3 meters, with a global daily coverage. It has been extensively evaluated against ground soil moisture measurements and showed to yield better estimates of soil moisture conditions when compared to model or satellite estimates alone (Albergel et al., 2012). The ASCAT root zone soil moisture profile retrieval algorithm is operational since 2012 as part of the H-SAF project.

The ESA Earth Explorer SMOS (Soil Moisture and Ocean Salinity) mission was launched in 2009. Based on L-band passive microwave measurements, SMOS is the first mission dedicated to soil moisture remote sensing. The SMOS brightness temperature product has been monitored in near-real time since November 2010 (Muñoz Sabater et al., 2011a,b) and SMOS monitoring is operational since this summer with IFS cycle 38r2. SMOS monitoring statistics have been used to support the SMOS ground segment, for instance by identifying a systematic data loss of each day's last orbit worth of data, as well as areas affected by Radio Frequency Interference (RFI). The SMOS data implementation in the IFS was particularly challenging (Muñoz Sabater et al., 2011a). SMOS provides a new type of observations needing many new developments, including the radiative transfer model for low frequency microwave emission (de Rosnay et al., 2009), noise filtering and data thinning (Muñoz Sabater et al., 2011a,b,c). Preliminary impact studies were conducted with SMOS data assimilation in the IFS (Figure 23). A significant reduction of the RMSE of near surface temperature and relative humidity was found up to day five of the forecast, particularly in North America and Europe. However slight degradation was found in other regions, which may partly be due to RFI in these areas. The next stage of development for SMOS is to improve the error specification according to the soil and vegetation properties and B-matrix cycling.

ASCAT level2 surface soil moisture and SMOS near real time brightness temperatures are expected to be assimilated in operations in 2014 and 2015, respectively. Whereas the availability of the ASCAT soil moisture continuity is ensured through the Metop series, there is no operational follow up mission for SMOS. However ECMWF is already active in the preparation of the NASA SMAP (Soil Moisture Active and Passive) mission, to be launched in 2014. Beyond SMAP, there is unfortunately no plan yet for any continuation of the passive L-band data record. Both the hydrological forecast and NWP communities, which are strongly linked, would benefit from having long term continuity in SMOS and SMAP missions.

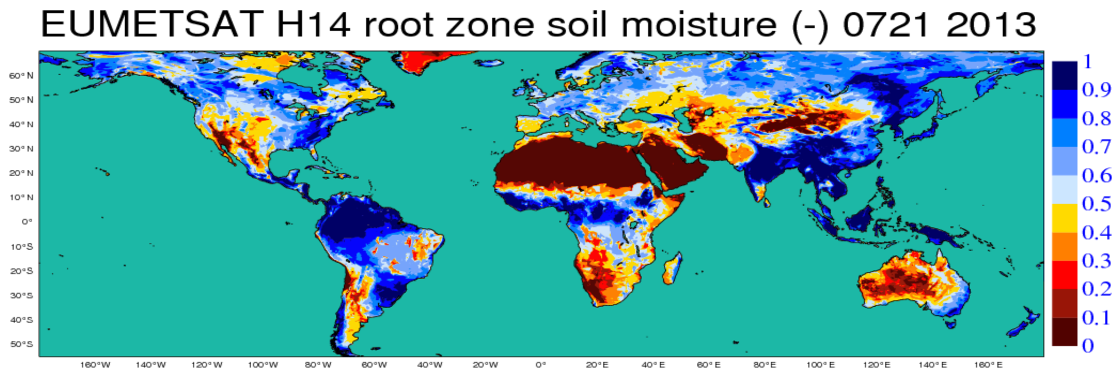

Figure 22 *EUMETSAT H-SAF root zone (0-1m) liquid soil moisture index produced on 21 July 2013 by operational ASCAT surface soil moisture data assimilation in the ECMWF RD Land Data Assimilation System.*

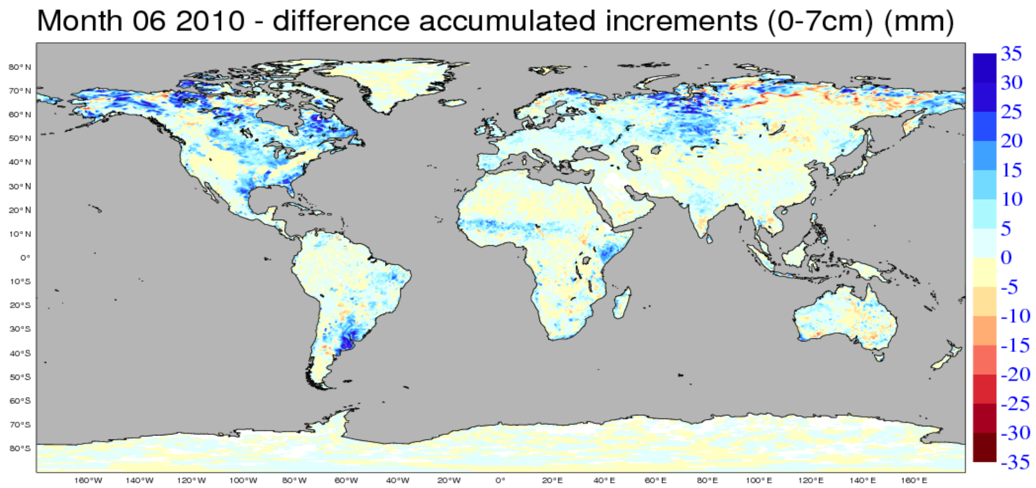

Figure 23 *Mean soil moisture increments at surface (0-7cm): difference in mm for June 2010, between SMOS experiment (assimilation of SMOS TBs combined with screen level parameters) and control (assimilation of screen level parameters only).*

3.5.2 Atmospheric composition

At present the only constituent (other than water vapour) analysed in the operational IFS is ozone. The use of data from infrared sounders and ultra-violet sensors gives a good ozone analysis that will be used in the future for radiation and dynamics within the IFS. However in the context of the European Union funded GEMS, MACC, and MACC-II projects, ECMWF has extended the IFS data assimilation system to also have the capability to model atmospheric composition and assimilate the relevant satellite data to constrain the model. ECMWF now routinely runs twice-daily the MACC-II pre-operational 4D-Var system with a 5-day forecast at T255L60 assimilating all operational meteorological observations as well as the extra satellite data for atmospheric composition. Work is also in progress to assess where the new capabilities for atmospheric composition can improve the operational NWP forecasting system. Because the data assimilation system for atmospheric composition is an extension of the meteorological IFS system, the basic principles for the assimilation of satellite data are in principle very similar to those described in this document. However, two aspects stand out as being different from normal NWP practice and are described below.

When in the 1980s satellite retrievals of temperature and water vapour were introduced in data assimilation for NWP, there was high expectation for significant improvements in forecast skill. However, only the southern hemisphere scores improved through the use of the satellite data; scores in the northern hemisphere were neutral or even worse. Kelly and Pailleux (1988) showed that the prior information used in these retrievals biased the retrievals with respect to the NWP model, which made the assimilation of these data far from optimal. Only when the change was made from satellite retrievals to direct radiance assimilation became the real added value of satellite observations obvious.

Most meteorological satellite observations are made in the infrared and microwave parts of the spectrum and the RTTOV fast radiative transfer model is used as part of the observation operator in the IFS. However, the observation of atmospheric constituents relies significantly on measurements in the ultra-violet, visible, and near-infrared parts of the spectrum. The radiative transfer of these latter parts of the spectrum are far more complex to model than the infrared and microwave and a mature and accurate fast radiative transfer model (with its adjoint) covering the whole electromagnetic spectrum does not yet exist.

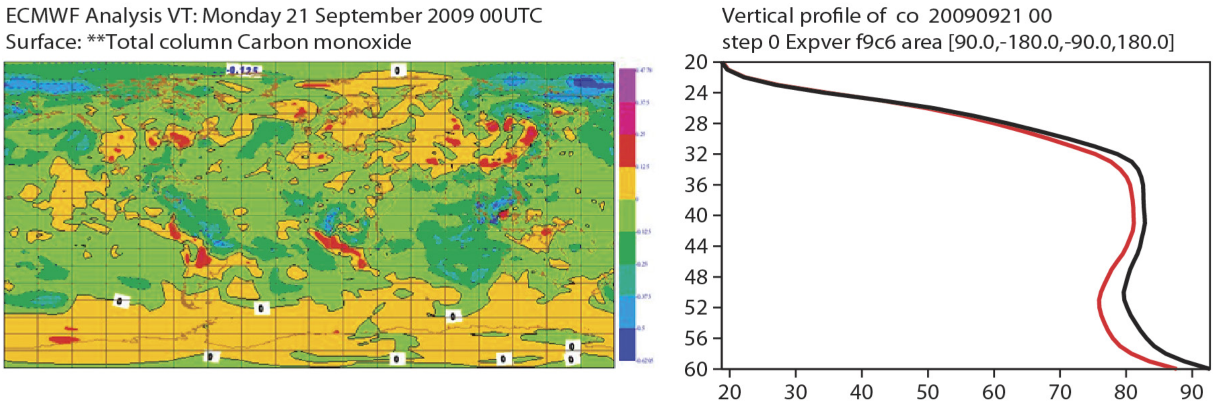

Figure 24 *The difference of carbon monoxide concentrations between a data assimilation experiment using averaging kernels and one without.*

The approach has therefore been taken to go back to the assimilation of retrievals instead of radiances for most species and satellite instruments. This is possible because the theory for assimilation of satellite retrievals has significantly evolved during the past twenty years and it can now be shown that the assimilation of retrievals is equivalent to radiance assimilation under certain assumptions (see e.g., Migliorini, 2012). Averaging kernels, now implemented in the IFS, describe the full sensitivity of the retrieval values to both the real atmosphere values and the a priori constraint used in the retrieval, allowing a more optimal assimilation of the retrieval products. The contribution of the potentially biased a priori profile in the retrieval is effectively replaced by the assimilation model first-guess in the observation operator of the data assimilation system. Figure 24 shows the difference of carbon monoxide concentrations between a data assimilation experiment using averaging kernels and one without. There are clear geographic differences as well as differences between the global mean profiles, illustrating the potentially damaging impact of biased a priori in the satellite retrievals.

Using satellite retrievals also allows the use of the full expertise of the various data provider groups on the instrument and radiative transfer modelling for each specific instrument to extract the information from the measurements as accurately as possible. In the coming years, significant effort will be spent on further optimizing the retrieval assimilation framework and ensuring the conditions for accurate extraction of observational information are met. At the same time, discussions with space agencies and other data providers have been initiated to ensure that the correct information will be disseminated for use in the data assimilation system. This has the additional benefit that retrievals are in their own way a form of data compression, which will help with the near-real-time data dissemination of for instance the Sentinel-4 and 5 missions, both of which will be important for environmental monitoring and prediction.

A second issue is that the data assimilation of atmospheric composition is much less an initial value problem than it is for NWP. Anthropogenic emissions, natural carbon fluxes, fire emissions, volcanic emissions; all are boundary conditions affecting the atmospheric concentrations to a large extent. Therefore, if these boundary conditions are not accurately represented, the data assimilation will change the initial atmospheric conditions, and therefore the analysis, in an incorrect way. Research is already in progress and will continue over the next years to determine suitable solutions to this problem. Improved estimation of background errors, weak-constraint 4D-Var with model errors representing the uncertainty in these fluxes, including some of these boundary conditions in the control vector within the 4D-Var or possibly in a separate data assimilation step, are some of the options that are being considered. ECMWF is organizing a Research Department workshop in October 2013 on exactly this topic bringing together scientists with strong expertise in these areas. The workshop will hopefully provide some guidance on which techniques to explore further. Also, the atmospheric chemistry plays a significant role. Only a few species are being observed by satellites, but these species are all connected to many other chemical constituents through the many chemical reactions taking place. This means that optimally the background error covariance matrix should account for the chemical correlations between the species in the control vector. Furthermore, the chemistry scheme should ideally be part of the adjoint code. This is currently not the case, creating problems with the data assimilation of for instance NO2, which can be rapidly converted to NO and back within the time frame of a 12-hour 4D-Var window. Simple corrections for this rapid conversion are used in the observation operator, but this is far from ideal. Significant focus will therefore be given to this problem to find more satisfactory solutions.

4 Conclusions on priorities

For NWP centres it is a difficult judgement whether to build and test the infrastructure needed for satellite observations, especially from research satellites. It is not feasible with current resources to assimilate every satellite instrument that is launched. However a remarkable amount of satellite data is used and its impact is very large.

ECMWF have been pioneering in bringing benefits from new satellites to operations, including research satellites. For example the AIRS instrument on the Aqua satellite was launched 5 years ahead of Metop-A and gave NWP centres experience with handling high spectral resolution infrared data, allowing a much faster initial exploitation of IASI. However for other missions, notably ESA’s Earth

Explorers, it is a more difficult decision whether to invest resources, as there is no operational follow-on. Often these missions start with no plan for near real time dissemination and their potential impact on NWP is unknown. By establishing the technical framework for data dissemination, writing observation operators to be able to use the data in 4D-Var and to show the value of the data needs at least one NWP centre to take a lead. ECMWF have taken such a role for many missions, notably SMOS, Aeolus and EarthCARE. In each case ECMWF have worked closely with Space Agencies and other partners to test the new data in an assimilation framework.

ECMWF also have worked very closely with the Chinese Meteorological Administration (CMA) to evaluate the FY-3A/B satellite instruments (two microwave temperature and humidity sounders, one infrared sounder and one microwave imager). This collaboration has been extremely successful. With a strong input from ECMWF the CMA improved the calibration of the instruments to a level where they could be used operationally (Lu *et al* 2011). Unfortunately the MWTS instrument on FY-3A stopped scanning shortly before operational assimilation would have begun. The similar instruments on FY-3B are still under review.

The increasing skill of the background means that usually we are testing fine tuning, that can be incredibly important for specific events, as was seen in the Superstorm Sandy case, but on average has small impact. It is proving increasingly difficult to generate statistically robust samples for testing data assimilation changes. Increased reliance on data assimilation statistics, such as changes in background departures, combined with scientific insight, and at least neutral impact in forecast scores, has to be used to assess whether to introduce many changes. However when these small changes are aggregated together, the rate of improvement in forecast scores remains very impressive.

The range and diversity of satellite data being used is increasing. Observations of cloud and precipitation, once thought to be useful only for nowcasting and better understanding of processes, will be increasingly used in data assimilation to improve the initial conditions, with instruments like radar, lidar and all-sky radiances being more prominent. Also with increasing focus on atmospheric composition for environmental prediction, on land and marine surfaces and on the cryosphere new observations such as L-band radiometry, ultraviolet observations and limb sounders are becoming more widely used. The resources required to make effective use of all this new data are far higher than those currently available. And in providing resources to do new things it is vital to continue to properly maintain and understand the long standing meteorological observations, and indeed improve their impact. ECMWF has and will continue to provide global leadership in satellite data assimilation.

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Acronym list

AAPP	AVHRR and ATOVS Processing Package
ADM	Atmospheric Dynamics Mission
AIRS	Advanced Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
AMV	Atmospheric Motion Vector
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
ASCAT	Advanced Scatterometer
ATOVS	Advanced TIROS Operational Vertical Sounder
ATMS	Advanced Technology Microwave Sounder
AVHRR	Advanced Very High Resolution Radiometer
CHAMP	Challenging Minisat Payload
CMA	China Meteorological Administration
CNOFS	Communications/Navigation Outage Forecasting System
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CrIS	Cross Track Infrared Sounder
DMSP	Defense Meteorological Satellite Program (of the US Department of Defense)
DoD	US Department of Defense
EarthCARE	EARTH Clouds, Aerosols and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
EDA	Ensemble of Data Assimilations
ENVISAT	ENVIronmental SATellite (ESA)
ERS	European Remote Sensing Satellite (ESA)
ESA	European Space Agency
EUMETSAT	European Meteorological Satellite Organisation
FEC	Forecast Error Contribution

FY	Feng-Yun (CMA satellite series)
GCOS	Global Climate Observing System
GCOM	Global Change Observation Mission
GEO	Geostationary orbit
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite, owned by the US.
GOME	Global Ozone Monitoring Experiment
GOSAT	Greenhouse Gases Observing Satellite
GRACE	Gravity Recovery And Climate Experiment
GRAS	GNSS Receiver for Atmospheric Sounding, instrument on Metop.
HIRS	High Resolution Infrared Radiation Sounder
HY	Hai Yang (China National Space Administration)
JPSS	Joint Polar Satellite System
IASI	Infrared Atmospheric Sounding Interferometer
LEO	Lower Earth Orbit
LWC	Liquid Water Content
Metop	Meteorological Operational Satellite (operated by EUMETSAT)
MERIS	Medium Resolution Imaging Spectrometer
MHS	Microwave Humidity Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
MSU	Microwave Sounding Unit
MTSAT	Multi functional Transport Satellite
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data and Information Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NPP	NPOESS Preparatory Programme

NWP	Numerical Weather Prediction
OMI	Ozone Monitoring Instrument
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
POES	Polar Orbiting Environmental Satellites
RMS	Root Mean Square
RO	Radio Occultation
RTTOV	Radiative Transfer model for TOVS
SAC-C	Satélite de Aplicaciones Científicas-C
SAF	Satellite Application Facilities
SBUV	Solar Backscatter Ultra-Violet Spectral Radiometer/2
SCIAMACHY (ENVISAT)	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SMOS	Soil Moisture and Ocean Salinity Mission
SSMIS	Special Sensor Microwave Imager Sounder (on DMSP satellite)
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Monitoring Mission
WMO	World Meteorological Organization