IMPACT OF ATMOSPHERIC MOTION VECTORS ON GLOBAL NUMERICAL WEATHER PREDICTION

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Abstract

The importance of satellite data at large is now such that they provide the main sources of information for numerical weather prediction (NWP) models. However, the role played by Atmospheric Motion Vectors (AMVs), evaluated via a series of Observing System Experiments (OSEs), remains essential in the Global Observing System (GOS). It is in particular shown that geostationary AMVs contribute to the reduction of humidity forecast error in the Tropics.

Polar AMVs derived from tracking clouds and water vapour features with MODIS onboard AQUA and TERRA continue to contribute significantly to the reduction of forecast error, especially in the Southern Hemisphere for the period under investigation.

It is finally shown that MODIS IR winds alone have a positive impact on the ECMWF forecasting system, giving some prospect and incentive to the Space Agencies for deriving polar AMVs from current and future imagers that will embark on the operational METOP (AVHRR) and NPOESS (VIIRS) satellites.

INTRODUCTION

Over the past few years, the importance of satellite data has progressively increased, to the extent that satellite systems now provide the main sources of information for NWP data assimilation systems. Satellites have the advantage of providing dense coverage in regions of the globe where in situ observations are lacking, such as the poles, oceans and Southern Hemisphere. The last decade in particular has seen significant progress, with the advent of new sensors offering greatly improved performance, the increased ability of numerical models to represent measured phenomena, a wealth of satellite observations (figure 1) and enhanced data handling and assimilation procedures. At ECMWF, around 30 satellite sources provide more than 90% of the over 6 millions of data assimilated daily. The increasing role of these satellite data in improving weather forecasts is illustrated in figure 2 (updated after Simmons and Hollingsworth 2002), which displays the running annual-mean anomaly correlation of 500 hPa height for ECMWF's operational three-, five- and seven-day forecasts for the extratropical Northern and Southern Hemispheres for the period from January 1980 until April 2006. Besides an overall and regular improvement in forecast quality over the years (reflecting the combined effect of better models, more and better observations, and better data assimilation techniques), the much faster rate of improvement in forecasts for the Southern Hemisphere where in-situ data coverage is sparse, clearly shows a signature of satellite data that are more abundant and being better used in the ECMWF system, leading to medium-range forecast quality that is now comparable in both Hemispheres.

OSEs are carried out at ECMWF on a regular basis, in support to Space Agencies and/or as a sanity check of the operational data assimilation system. A recent set of OSEs has recently been performed in collaboration with EUMETSAT and EUCOS to assess the contribution of various components (space and terrestrial) of the GOS to the skill of the ECMWF numerical forecasts. Within this framework, a special emphasis has been drawn towards assessing the contribution of the AMVs to the GOS (see Delsol et al. 2006 for their use at ECMWF), in a context overwhelmed by the assimilation of a wealth of radiance data from sounding instruments onboard polar satellites.

OBSERVING SYSTEM EXPERIMENTS FRAMEWORK

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

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

Assimilation experiments have been performed over a winter period, from 20041204 until 20050125. The first 10 days are excluded from the verification to ensure a reasonable warm-up phase for each assimilation scenario.

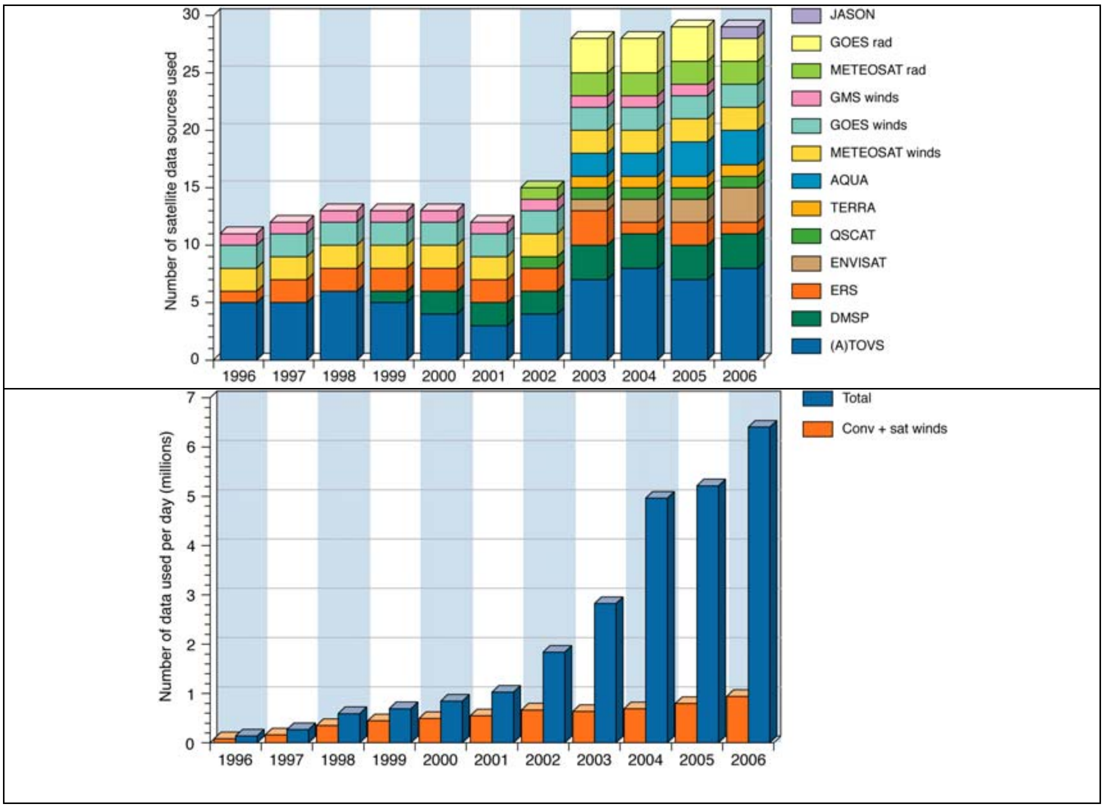

Figure 1: **Evolution over the last 10 years of the number of data sources used daily at ECMWF (figure 1.a). Evolution over the same period of the daily active data counts (figure 1.b: orange--conventional observations+ satellite winds, blue--total)**

Following the guidance from one of the outcomes of the Third WMO Workshop on the Impact of Various Observing Systems on NWP, it was accepted that due to a large degree of redundancy of the

GOS, performing impact studies by removing one element of the GOS can show very limited impact and does not necessarily highlight the intrinsic benefit of the element in question. Therefore scenarios in which the contributions of different elements of the GOS are investigated by adding data sets or combination of data sets to a baseline scenario have been preferred.

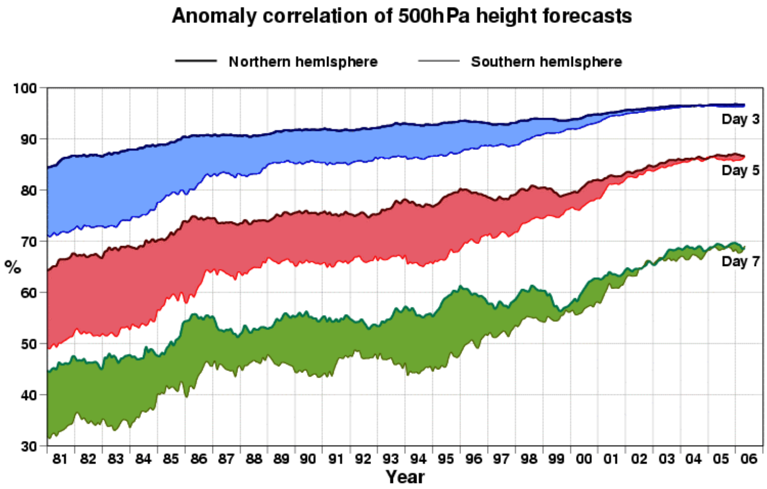

Figure 2: **Anomaly correlations of 500 hPa height for 3-,5- and 7-day forecasts for the extratropical Northern and Southern Hemispheres, plotted in the form of annual running means of scores for the period from January 1980 to April 2006.**

The list of assimilation experiments presented in this paper is described in the following table:

DESCRIPTION
BASELINE: all conventional observations (radiosondes+ aircrafts + profilers + synops +buoys + Ships)
BASELINE + GEO AMVs
BASELINE + GEO AMVs + MODIS AMVs
BASELINE + GEO AMVs + MODIS IR AMVs
BASELINE + GEO AMVs + MODIS WV AMVs
BASELINE + GEO Clear Sky Radiances **(CSRs)**
CONTROL: full operational system

***Table 1*: list of assimilation experiments**

GENERAL IMPACT OF SATELLITE DATA

Figure 3 displays the 500 hPa geopotential height root mean square forecast error (averaged over 43 cases) for the “**BASELINE**” (**blue curve**), “**CONTROL**” (**red curve**) and “**BASELINE + GEO AMVs + MODIS AMVs**” (**black curve)** experiments, in the Northern (1a) and Southern Hemisphere (1b), respectively. This figure consolidates previous results (Bouttier and Kelly, 2001), showing typically that without satellite data (difference between the blue curve and the red curve), the forecast skill is reduced at day 5 by half a day in the Northern Hemisphere, and by around two and a half days in the Southern Hemisphere, confirming the overwhelming importance of the space component of the GOS. This large impact is confirmed on figure 4 which displays the normalised difference (in %) of Z500 RMS forecast error between “**CONTROL**” and “**BASELINE**” at T+72h. Worth mentioning is that if the impact is obviously massive in the Southern Hemisphere (average 29% improvement), the impact of satellites is more modest in the Northern Hemisphere (13%) and mainly concentrated over the oceans.

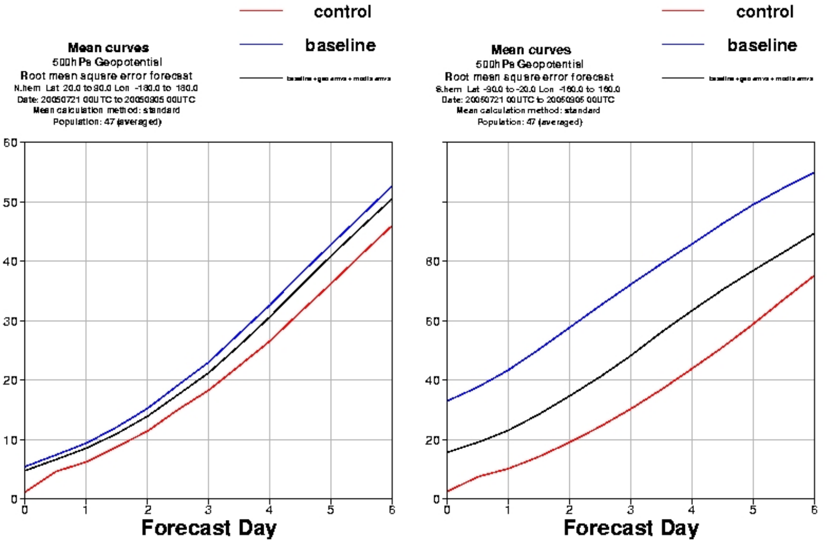

***Figure 3*: Mean (over 43 winter cases) Z500 RMS forecast error scores in Northern Hemisphere (left) and Southern Hemisphere (right) for experiments "BASELINE" (blue curve), "CONTROL" (red curve) and "BASELINE + GEO AMVs + MODIS AMVs" (black curve)**

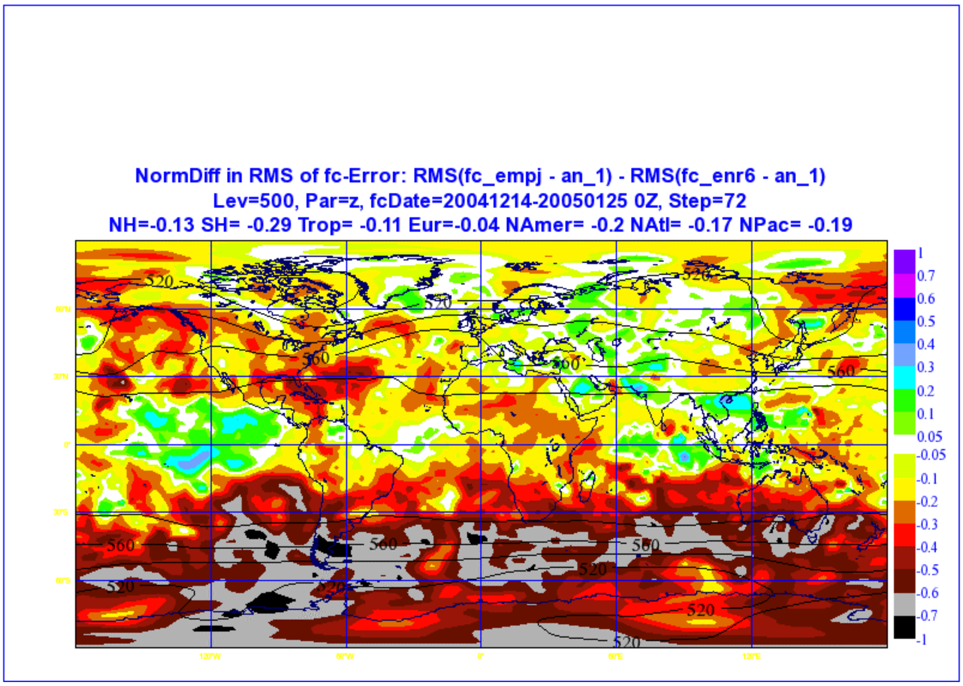

***Figure 4*: Normalised difference (in %) of Z500 RMS forecast error between "CONTROL" and "BASELINE" at T+72h (averaged of 43 winter cases)**

RELATIVE IMPACT OF AMVS

The black curve of figure 3 shows the net contribution of AMVs (polar and geostationary), in terms of forecast skill, to the idealistic degraded BASELINE scenario where only conventional observations are used. One can see that the gain provided by AMVs reaches typically, at day 5, 4 to 6 hours in the Northern Hemisphere, and 1.5 days in the Southern Hemispherere. Figure 5 shows the tropical wind scores at respectively 850 hPa (left) and 200 hPa (right), confirming the considerable impact of the geostationary AMVs in constraining the tropical wind field of the model forecast. More interestingly, figure 6 displays the 200 hPa relative humidity scores in the Tropics. Adding the AMVs to the **BASELINE** scenario clearly improves the tropical Upper Tropospheric Humidity forecasts (around 1/2 day at day 5), indicating that despite that AMVs essentially reflect small scale tracked cloudy features, the wind information provided by these observations has been globally ingested in a dynamically and physically consistent way in the NWP system.

Incidently, tropical UTH information is also provided by the 40 km Clear Sky Radiance (CSRs) products available from the METEOSAT and GOES satellites. An additional OSE has been performed in which CSRs have been added to the **BASELINE** scenario. It turns out that the improvement of the tropical UTH forecasts provided by these data is of very similar nature and magnitude as that provided by AMVs (not shown), indicating a good consistency in the 4D-Var assimilation between these two products of an a priori quite different nature.

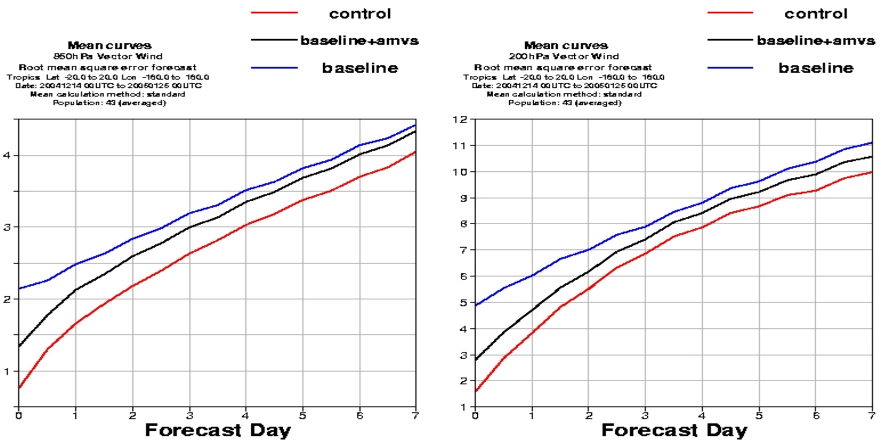

Figure 5: **Mean (over 43 winter cases) WIND RMS forecast error scores in the Tropics at 850 hPa (left) and 200 hPa (right) for experiments "BASELINE" (blue curve), "CONTROL" (red curve) and "BASELINE + GEO AMVs + MODIS AMVs" (black curve)**

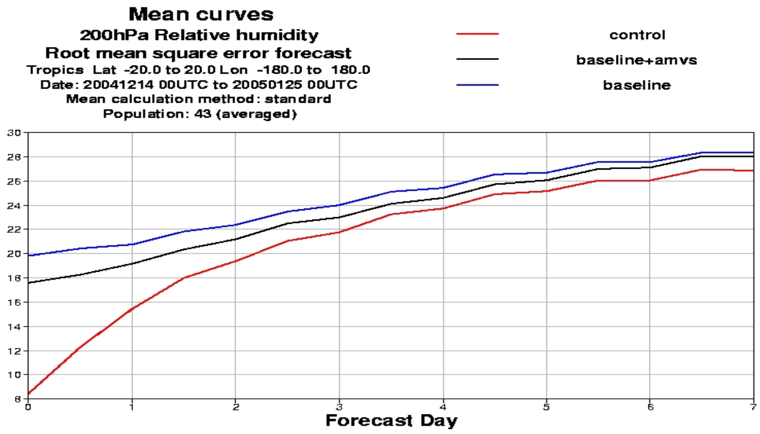

Figure 6**: as figure 5 but for Relative Humidity at 200 hPa in the Tropics.**

IMPACT OF MODIS POLAR WINDS

It has now widely been recognised that polar AMVS produced from the MODIS imager onboard TERRA and AQUA satellites have a positive impact on numerical forecasts (e.g. Bormann and Thépaut, 2004, Von Bremen et al., 2004), in particular due to their unique presence at these latitudes. The impact of this product has been reassessed within this OSE framework, by running a set of assimilations where only geostationary AMVs are added to the **BASELINE** scenario. Figure 7 displays the mean (over 43 cases) Z 500 hPa RMS forecast error scores in the Northern Hemisphere (top left)

Southern Hemisphere (top right), South Pole (bottom right) and North Pole (bottom left), and for experiments **BASELINE** (**blue curve**), **CONTROL** (**red curve**), **BASELINE + GEO AMVs** (**black curve**) , **BASELINE + GEO + MODIS AMVs** (**orange curve**). As we had seen in figure 3, the overall impact of AMVs in the Northern Hemisphere is generally fairly small (a few hours of skill added at Day 5). The relative impact of MODIS AMVS is itself quite small as well (difference between black and orange curve), although T-tests have been run and have shown that the small positive impact is statistically significant (with a confidence interval of 90% double sided) up to day 4. The impact of MODIS AMVs is much larger in the Southern Hemisphere, which is consistent with previous findings that MODIS winds had generally more impact in summer than in winter (recall that the period under investigation is 20041214-20050125). The zoom over the South Pole and North Pole confirms the very large positive impact of the MODIS AMVS in the summer Hemisphere, while the impact in winter remains small (see the North Pole superimposed curves). Note that wind scores have also been looked at (850, 500 and 200 hPa) and are very consistent with the geopotential scores (not shown).

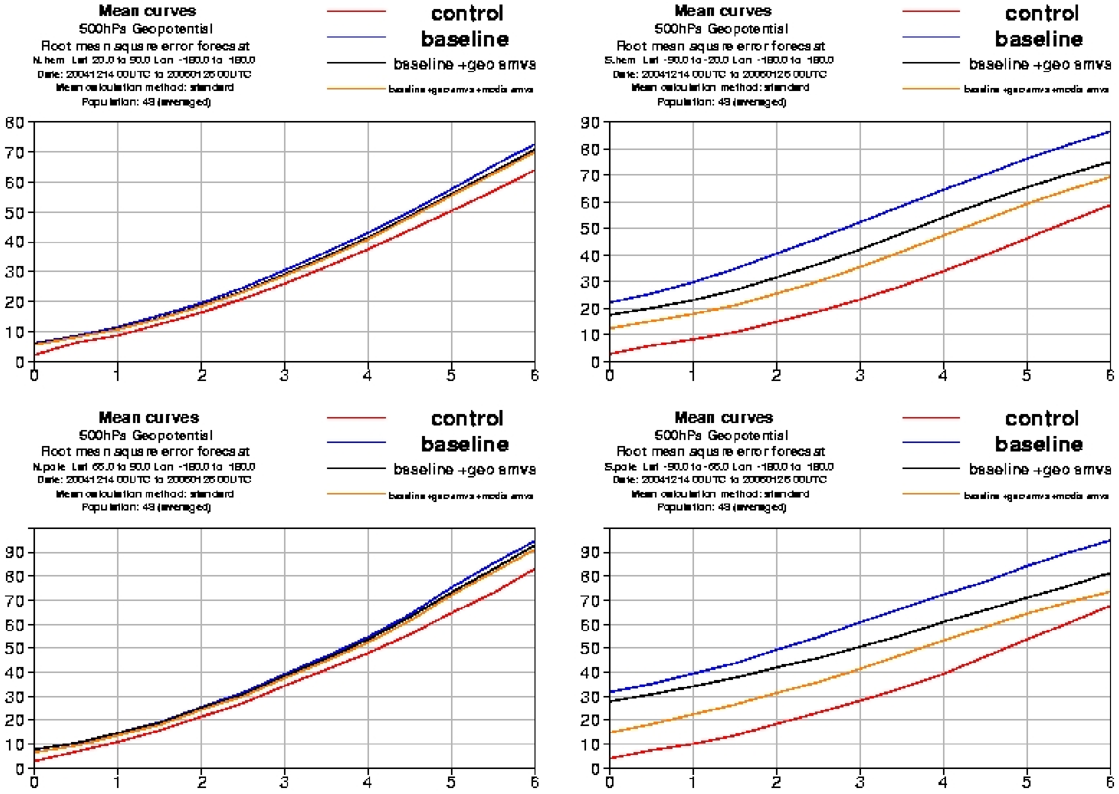

Figure 7: **see text for details**

Figure 8 displays the normalised difference (in %) of Z500 RMS forecast error between "**BASELINE + GEO AMVS + MODIS AMVS**" and "**BASELINE + GEO AMVS**" at T + 72h. The reduction of forecast error due to the MODIS AMVs is global, averaging 5% in the Southern Hemisphere and a modest 1% in the Northern Hemisphere. It is also noticeable that the induced reduction of forecast error spreads well into the mid latitudes at day-3 range.

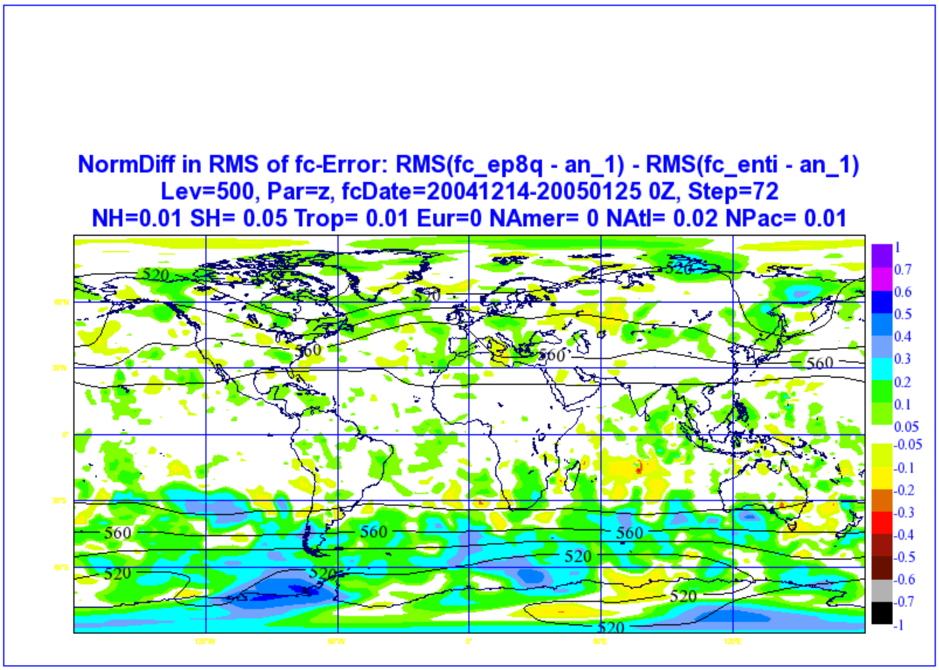

Figure 8: **Normalised difference (in %) of Z500 RMS forecast error between "BASELINE + GEO AMVS " and "BASELINE + GEO AMVS + MODIS AMVS" at T+72h (averaged of 43 winter cases)**

MODIS IR AMVS VERSUS MODIS WV AMVS

If the positive impact of MODIS polar AMVs is now well recognised, the perenniality of such data coverage beyond the life-time of the MODIS instruments is currently not secured. The imagers currently planned for Metop (AVHRR) and NPOESS (VIIRS) do not include a water vapour channel which for example provides 2/3 of the MODIS AMVs currently assimilated. Alternative AMV products are being derived at CIMSS from the AVHRR instrument and solely based on InfraRed (IR) channel information, and similar plans exist at EUMETSAT in the context of METOP. In support to these initiatives and to assess the intrinsic value of the IR AMVs, two additional OSEs have therefore been performed ("**BASELINE + GEO AMVS + MODIS IR**" and "**BASELINE + GEO AMVS + MODIS WV**").

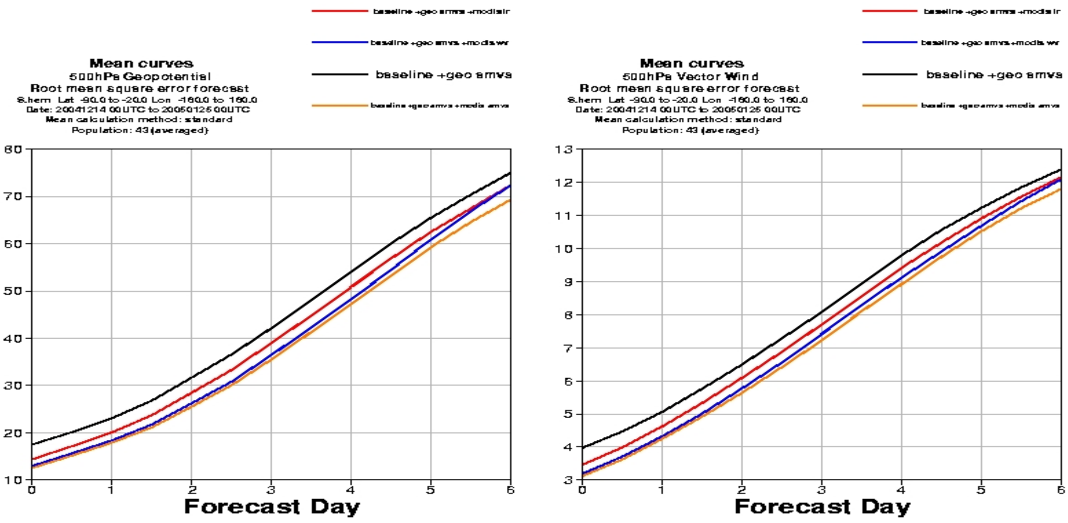

Figure 9**: see text for details.**

Figure 9 displays the mean (over 43 cases) Z 500 hPa (left) and Wind 500 hPa (right) RMS forecast error scores in the Southern Hemisphere, for experiments **BASELINE + GEO AMVs + MODIS WV** (**blue curve**), **BASELINE + GEO AMVs + MODIS IR** (**red curve**), **BASELINE + GEO AMVs** (**black curve**) , **BASELINE + GEO AMVs+ MODIS AMVs** (**orange curve**). Obviously, the MODIS WV AMVs (blue curve) provide the bulk of the forecast error reduction. However, the IR AMVs alone have also a significantly positive impact when added to "**BASELINE + GEO AMVs**". Although one has to be careful with these results as a fraction of the IR AMVs have used information from the water vapour channel for assigning their height (which of course would be impossible to do with the AVHRR instrument - study of the impact of IR AMVS in a cleaner context is currently underway -), the outcome of these OSEs is certainly very encouraging in the prospect of deriving polar AMVs from AVHRR and future IR operational imagers. Note that the impact noted in the Southern Hemisphere is statistically significant up to day 4 to 5 (see figure 10).

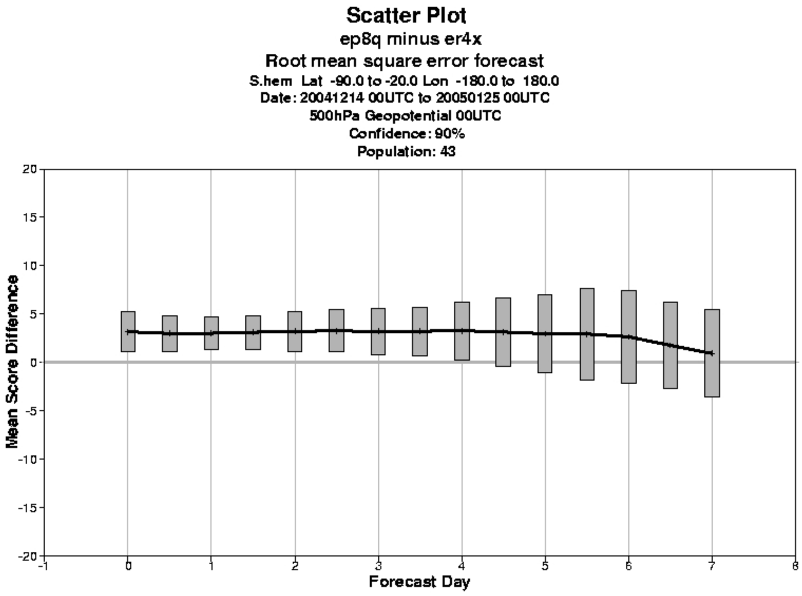

Figure 10: **mean (over 43 cases) Southern Hemisphere Z500 RMS forecast error difference between "BASELINE + GEO AMVS" and "BASELINE + GEO AMVS + MODIS IR". Confidence interval for error bars: 90%.**

The ranking of the respective impacts is similar in the Northern Hemisphere, but the magnitude is considerably smaller (not shown). Note that the positive impact of MODIS IR AMVs has also been noted by Riishøjgaard et al. (2006).

CONCLUSIONS

This paper has described the current impact of the AMVs in the global data assimilation and numerical weather prediction system at ECMWF. This impact has been evaluated in the context of OSEs where a given Observing System is added to a reference network. The period under investigation covers 20041204-20050125. Care has therefore to be taken in interpreting the results of these OSEs, due to the limited size of the sample (43 cases). At the time of writing, a summer period is being run (20050714-20050915) to consolidate these results.

With the caveat mentioned above, it has nevertheless been shown that despite the undeniable benefit of directly assimilating satellite radiances from polar and to some extent geostationary satellites, AMVs continue to play a major role in the GOS, with a substantial impact on the quality of numerical forecasts. It is particularly interesting to note that the use of AMVs improves the quality of the Upper Tropospheric Humidity forecast in the Tropics.

Over the sampled period, MODIS polar AMVs provide a significant reduction of forecast error, in particular over the Southern Hemisphere. Furthermore, it has also been shown that while MODIS water vapour AMVs are the main contributors to the forecast impact, infrared AMVs can have, on their own, a noticeable positive impact. This result is important as the data coverage of polar water vapour winds is under threat beyond the life time of TERRA and AQUA.

Finally, the results presented above should not hide the difficulties that NWP centres have to face with the assimilation of AMVs. The reader is referred to Bormann et al. (2006) in a companion paper, which addresses the main difficulties and challenges encountered by NWP centres in their treatment of AMVs (height assignment primarily but also quality control, spatial and temporal thinning, bias correction, observational error specification,…). As mentioned by Bormann et al. (2006), some of these issues will require more work on understanding the fundamental sources of error in AMV products and their proper specification in data assimilation. Progress in this area will certainly benefit from new validation opportunities with missions such as the recently launched CloudSat/Calipso, and even more with ADM-AEOLUS that will provide independent wind profile information from a Doppler Wind Lidar.

Further down the road, it is hoped that the accuracy of the height assignment of AMVs will be greatly improved with the forthcoming multispectral IR sounders that will hopefully fly on geostationary orbit at the horizon 2015-2020 (MTG/IRS, GOES-R/HES). It remains however open whether information from future geostationary IR sounders will be best assimilated in the form of radiances, AMVs or a combination of both.

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