

# Wind tracing from SEVIRI clear and overcast radiance assimilation

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## **Abstract**

The ECMWF 4D-Var analysis system has been successfully extended to directly assimilate cloud-affected geostationary radiances in overcast conditions, in addition to the clear radiances from Meteosat-9. Experimentation with the assimilation of cloud-affected SEVIRI radiances in the context of no-satellite baseline experiments have revealed the potential of overcast images for improving the wind tracing capability of SEVIRI radiances in 4D-Var. We will summarise recent research results to characterise how these radiances affect the wind analysis, and compare the impact to that of the assimilation of clear-sky radiances and cloudy AMVs from SEVIRI. The potential operational benefits of directly assimilating clear and overcast radiances from Meteosat-9 in ECMWF's 4D-Var has been assessed in a full system where all routinely available observations are used. Results of the assimilation experiments show that the use of combined clear and overcast radiances in water-vapour channels could be beneficial to the quality of 4D-Var analyses and subsequent forecasts.

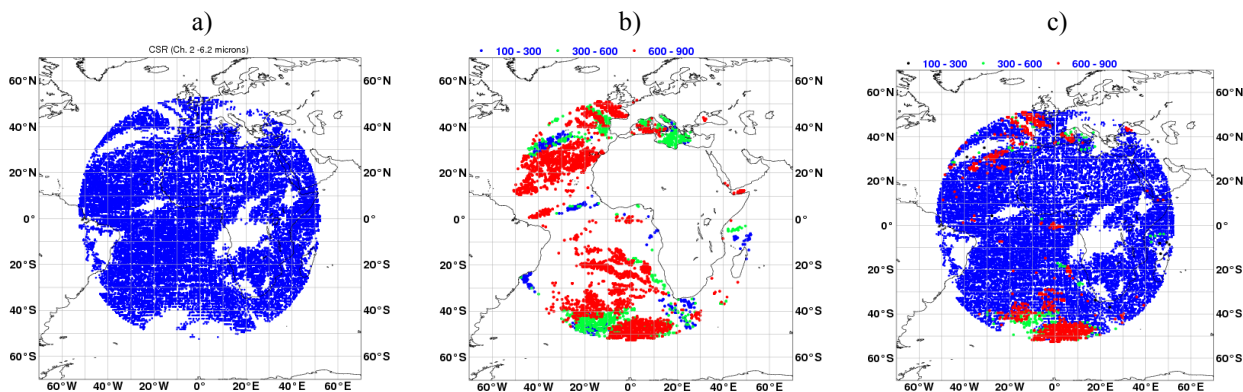
## **Motivation**

Water vapour clear-sky radiances (CSR) from geostationary satellites provide humidity information in the middle and upper troposphere. Previous studies have shown that the assimilation of high frequency CSR from geostationary satellites affects the 4D-Var wind field. Peubey and McNally (2009) have been demonstrated that the most important mechanism through which the assimilation of CSR constrains the analysis is the humidity tracer advection induced by 4D-Var which clearly dominate over the effects of balance constraints imposed on the analysis and model cycling. The process of model cycling is however important to propagate the benefits of tracer advection throughout the troposphere. SEVIRI CSR leads to an improvement in ECMWF's 4D-Var wind analyses throughout the troposphere, with the strongest signal in the middle and upper troposphere.

The main objective of this study was to extend the humidity tracing capability, previously demonstrated only in clear-sky, to cloudy regions, to obtain an all-sky constraint on the atmospheric wind field with geostationary radiances.

Typical data coverage maps of each of the assimilated CSR, overcast (OV) and combined clear plus overcast (CSR+OV) from SEVIRI in water vapour channel at 6.2  $\mu\text{m}$  are shown in figure 1 for the 00

UTC 10 February 2010. CSR data from the 6.2  $\mu\text{m}$  water vapour channel of Meteosat-9 provide a good coverage over oceans and land within about 50 latitude of the Equator, with gaps in cloudy regions (fig.1a). Figure 1b displays the distribution of the overcast scenes from SEVIRI separated into three categories depending on cloud height. The quality control decisions applied to overcast data leads to a rather low yield in terms of active observations available to the analysis. The overcast low clouds with the cloud top pressure between 600 and 900 hPa account for the majority of overcast scenes. As dynamically active areas are known to be mainly cloudy, current aims in Numerical Weather Prediction (NWP) centers are to continue improvements in the assimilation of cloud-affected infrared radiances both in polar and geostationary orbits, with the idea that this is necessary for continuing gains in NWP skill. An example of the coverage provided by the use of CSR and overcast from SEVIRI is shown in Figure 1c. It can be seen that the retained overcast data cover the areas where CSR are not available.



**Figure 1:** Typical data coverage maps of each of the assimilated: a) CSR, b) overcast (OV) and c) combined clear plus overcast radiances (CSR+OV) from SEVIRI in water vapour channel at 6.2  $\mu\text{m}$  for the 00 UTC on 10 February 2010. The overcast cloudy scenes are separated into three categories depending on cloud height.

### Baseline experiments:

#### Analysis impact of each of SEVIRI radiances (CSR, OV and combined clear and overcast) and SEVIRI cloudy AMVs

The results presented in this section were derived from experiments carried out with the ECMWF Integrated Forecasting System version CY36R3 at T511 resolution ( $\sim 40$  Km), 91 vertical levels and 12 hour 4D-Var for the period 10 February 2010 to 10 March 2010. SEVIRI CSR, OV, combined clear and overcast radiances and SEVIRI cloudy AMVs observations were each added to a base experiment that uses a depleted observing system. The base has been initialized with the ECMWF operational analysis on 2 February 2010 and the only observations assimilated are conventional data from radiosondes, aircraft and surface observations.

We display the analysis impact of each of SEVIRI CSR, OV, clear and overcast radiances and SEVIRI cloudy AMVs in terms of the root-mean-square (RMS) of analysis increments difference with respect to the Base assimilation in figure 2. These are shown as vertical profiles on pressure levels between 1000 hPa and 1 hPa for Meteosat-9 disc area. In the following, we will quantify the magnitude of each of the

CSR, overcast (OV) and combined clear and overcast radiances wind impact on isolation and compare results with the cloudy AMVs wind impact.

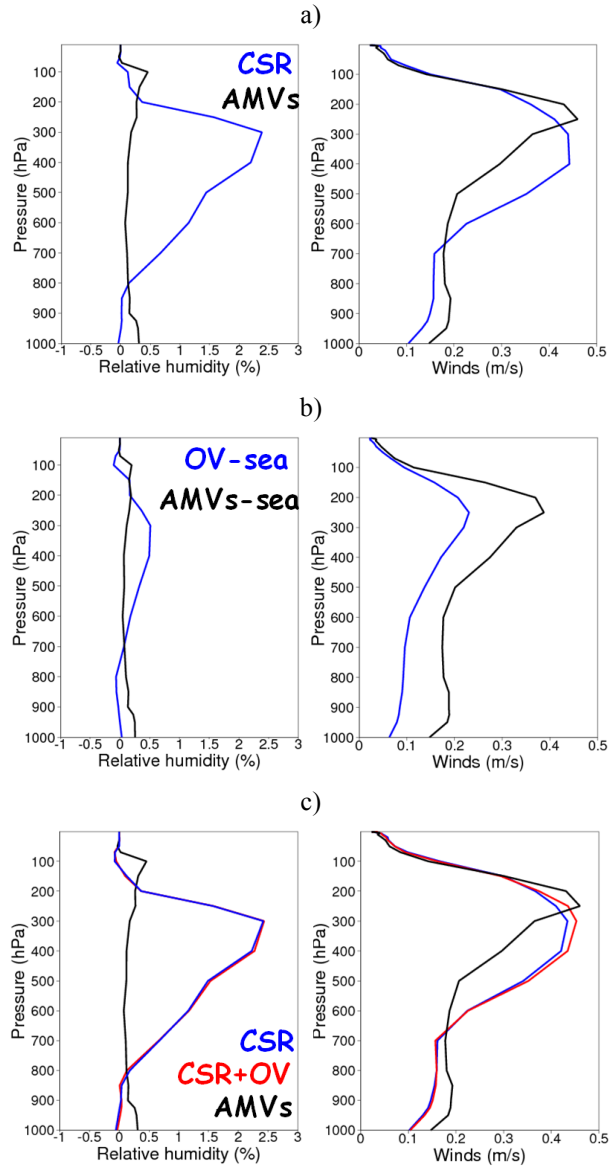
In figure 2a, the relative-humidity (left side) and wind impacts (right side), as provided by the RMS of the SEVIRI CSR experiment minus Base, is shown in blue line while the humidity and wind impact, as provided by the RMS of the SEVIRI AMVs experiment minus Base, is shown in black line. The vertical extent of the relative humidity increments, from WV CSR, typically between 100 and 800 hPa, and their peak, typically at 300 to 400 hPa, reflect the sensitivity of the WV channels. When the WV CSR are assimilated, the 4D-Var tracing mechanism fits the CSR by advecting deep layers of humidity and this leads to deeper layer adjustments of the wind field. For the cloudy AMVs the wind information is provided as a single level wind information and the structure functions of the background covariance matrix control the spread of this information on the vertical. SEVIRI AMVs data does not have significant impact on the relative humidity field. SEVIRI CSR and AMVs impact is complementary with respect to the magnitude of wind increments and the altitude range at which each observation type has maximum impact.

Figure 2b displays the relative-humidity (left side) and wind impact (right side), as provided by the RMS of the SEVIRI OV experiment minus Base (blue line) and SEVIRI AMVs experiment minus Base (black line). As the overcast radiances (with an effective cloud fraction equal at 1) from four channels (6.2, 7.3, 10.8 and 13.4  $\mu\text{m}$ ) are only used over sea, the AMVs dataset is also used here over sea but not over land. Wind speed vertical profiles from overcast radiances and AMVs assimilated over sea, are very similar in shape, showing a main peak at 250-300 hPa. The impact of AMVs is larger, as the number of completely overcast SEVIRI scenes is reduced comparatively with the number of cloudy AMVs. It appears that the vertical composite of relative-humidity changes is constrained particularly in the Southern Hemisphere where changes above the cloud top are observed from the use of overcast data (not shown).

The additional impact of the overcast SEVIRI radiances upon the assimilation system is illustrated in figure 2c as provided by the RMS of the SEVIRI clear and overcast experiment minus Base (red line). The blue and the black lines have the same meaning as described in figure 2a. CSR+OV and CSR wind speed increment are very similar in structure but a larger magnitude with a maximum at 300 hPa is obtained from the additional use of overcast scenes in CSR+OV experiment. This demonstrate the effect of humidity-tracer advection involved in the production of wind increment from the additional assimilated overcast SEVIRI observations.

## Wind analysis scores

Peubey and McNally (2009) used the analysis scores to compare the wind analysis impact of CSR and AMVs derived from geostationary satellites. In this work a similar comparison has been performed for all experiments assimilating overcast SEVIRI and AMVs data over sea. For each experiment, the wind analysis score is calculated inside Meteosat-9 disc by averaging over all  $m$  assimilation cycles as follows:



**Figure 2:** RMS of relative-humidity (left side, %) and wind speed (right side, m/s) increment differences between each of the experiments (e.g., CSR, OV and CSR+OV) and the Base experiment, for Meteosat-9 region, 10 February to 10 March 2010. The RMS of the SEVIRI CSR experiment minus Base is shown in blue line in a), the RMS of the SEVIRI OV experiment minus Base is shown in blue line in b), the RMS of the SEVIRI CSR+OV experiment minus Base is shown in red line in c) and the RMS of the SEVIRI AMVs experiment minus Base is shown in black line. In b), overcast and cloudy AMVs SEVIRI data were assimilated only over sea.

$$\Delta RMSE = \frac{\sum_{j=1}^m (RMSE_j^b - RMSE_j)}{\sum_{j=1}^m RMSE_j^b}$$

where  $RMSE_j$  and  $RMSE_j^b$  are the wind analysis error for experiment  $j$  and for the baseline, respectively.

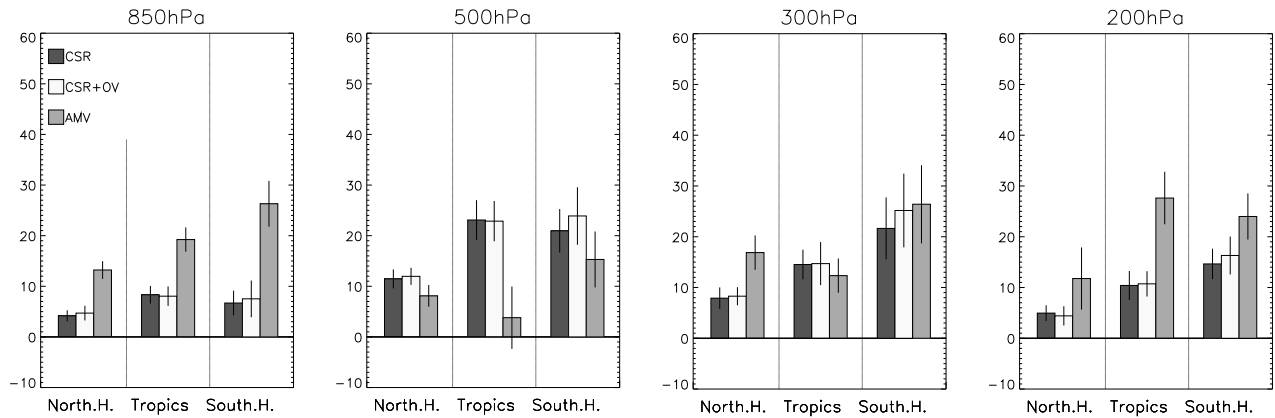
For every cycle  $j$ , wind analysis errors are calculated as departures from the ECMWF operational analysis (considered as the best available estimate of the true wind fields) that runs at T1279 resolution and assimilate the full observing system as:

$$RMSE_j^{(b)} = \sqrt{\frac{1}{n} \sum_{i=1}^n [(u_i^{(b)} - u_i^r)^2 + (v_i^{(b)} - v_i^r)^2]}$$

where  $u_i$  and  $v_i$  ( $u_i^b$  and  $v_i^b$ ) are the analysis values of the zonal and meridional wind components at a grid point  $i$  for the experiment (baseline),  $u_i^r$  and  $v_i^r$  are the corresponding values from the ECMWF operations and  $n$  is the number of grid points inside Meteosat-9 disc.

When a data set is added to the baseline the resulting analysis is always expected to perform better when compared to baseline. A zero value of the analysis score means no improvement over the baseline while the 100% value corresponds to an analysis that has no error with respect to the operational analysis.

Figure 3 shows the analysis scores of the wind speed for experiments assimilating SEVIRI CSR (dark bars), CSR+OV (white bars) and AMVs datasets. Vertical error bars superimposed upon the plot indicate 95% confidence interval for wind analysis scores and were calculated using the Student distribution as in Peubey and McNally (2009). In the context of no-satellite baseline experiment, CSR+OV have a positive impact on wind analyses through the upper-troposphere with better performance than CSR particularly over the Southern Hemisphere. Over the Northern Hemisphere and Tropics, wind analysis scores for the CSR+OV and CSR are very close, showing that in those regions, wind analyses only get benefits from CSR assimilation. However, over those regions the number of overcast scenes is limited. The impact of cloudy AMVs is significantly larger at 850 hPa and 200 hPa, owing to the large number of cloudy AMVs assimilated.



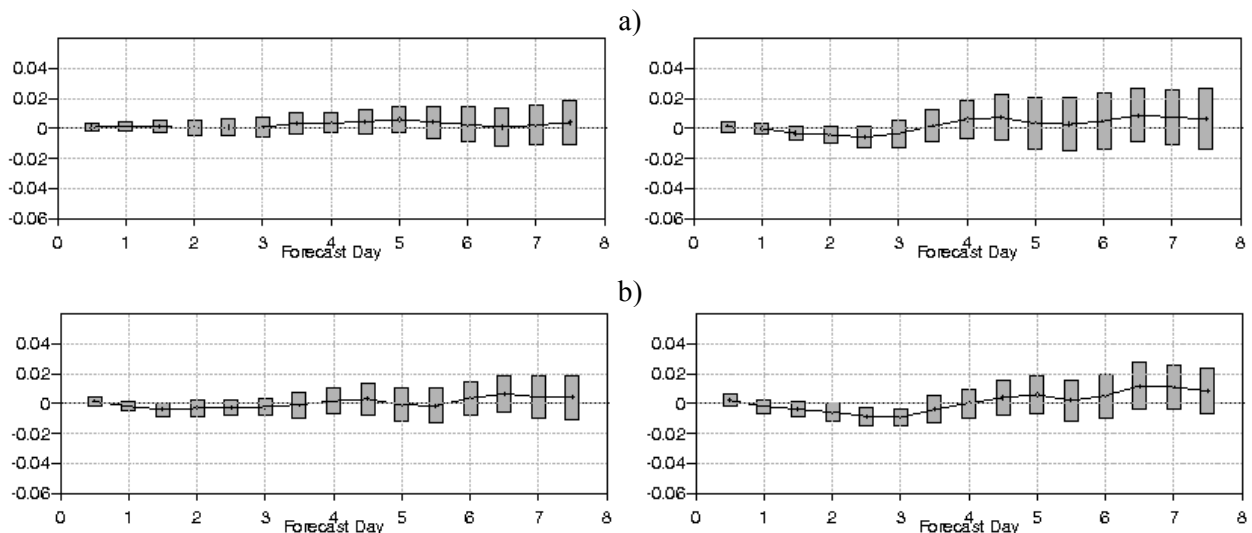
**Figure 3:** Wind analysis scores for the experiments assimilating SEVIRI clear-sky radiances (CSR), clear plus overcast radiances (CSR+OV) and cloudy AMVs data calculated inside Meteosat-9 disc over one month period (10 February to 10 March 2010) in the Northern Hemisphere [20°N-50°N], Tropics [20°S-20°N] and in the Southern Hemisphere [50°S-20°S].

## Full system experiments

A full system experiment was run over the period 1 January 2011 to 31 March 2011, using a T511 configuration of the ECMWF operational model. The clear and overcast scenes from the new Meteosat-9 ASR product were added to the full ECMWF system (Lupu and McNally, 2012). The OSEs carried out were therefore:

- **CTRL:** CY37R3 full system experiment with all available conventional and satellite data, including water-vapour Meteosat-9 CSR.
- **ASR:** CY37R3 full system experiment + clear and overcast SEVIRI radiances in water vapour channels (6.2  $\mu\text{m}$  and 7.3  $\mu\text{m}$ ) from the new EUMETSAT ASR product.

The forecast verification results are now summarised. Figure 4a shows the normalised difference in root mean square error (RMS) of the 500 hPa geopotential between the ASR and the CTRL experiment as a function of forecast range in days for the Northern Hemisphere (left side) and the Southern Hemisphere (right side). Both experiments have been verified against own analysis. Negative (positive) values indicate a reduction (an increase) in forecast error for the ASR experiment. Error bars highlight the level of significance of the changes based on a 95% confidence level. The reader is referred to Geer *et al.*, (2010) for details on the method used to calculate RMS error and the statistical significance of the difference. Averaged over a three-month period, 500 hPa height forecast errors are, overall, not statistically significantly different for the ASR experiments and the CTRL. Some wind (figure 4b panel, left side) and temperature (figure 4b, right side) forecast improvements in the upper troposphere from the ASR experiment are present in the short range in the Southern Hemisphere at 200 hPa, but these improvements do not carry on beyond day 3.



**Figure 4:** Normalised difference in the root mean square error (RMS) of the: a) 500 hPa geopotential between the ASR and the CTRL experiment as verified against own analysis for the Northern Hemisphere (left side) and the Southern Hemisphere (right side); b) 200 hPa temperature (left side) and vector wind (right side) for the Southern Hemisphere. Negative values indicate a reduction in the forecast error from using the combined clear and overcast radiances compared to operational CSR. Error bars indicate 95%

confidence intervals.

## Conclusions

The use of cloudy radiances from satellite instruments in polar or geostationary orbit is still a great challenge for numerical weather prediction. Work is in progress to assimilate such data that should contribute to a more accurate description of the atmospheric state and increased accuracy in numerical weather prediction. In this work the focus was to investigate the analysis impact of each of the following observations types from Meteosat-9 SEVIRI: clear-sky radiances, overcast, combined clear and overcast and cloudy AMVs in a no-satellite baseline context. The geostationary overcast radiances were used only over sea while water-vapour clear SEVIRI radiances were used also over land. The analysis impact of each of those observation types was expressed in terms of the root-mean-square of humidity and wind speed analysis difference with respect to the baseline assimilation and was shown as vertical profiles on pressure levels between 1000 and 1 hPa inside Meteosat-9 disc area. The main results of this study are:

- When the water-vapour clear-sky radiances are assimilated, the 4D-Var tracing mechanism fits the radiances by advecting deep layers of humidity and this leads to deeper layer adjustments of the wind field. For the cloudy AMVs the wind information is provided as a single level wind information and the structure functions of the background covariance matrix control the spread of this information on the vertical. SEVIRI AMVs data does not have significant impact on the relative humidity field. SEVIRI clear-sky radiances have a positive impact on wind analysis and the maximum was found at 300 hPa and 500hPa, while for the cloudy AMVs the maximum impact on wind analysis was obtained at 250 hPa and 850 hPa.
- Wind speed vertical profiles from cloud-affected radiances in overcast conditions and from cloudy AMVs assimilated only over sea, are very similar in shape, showing a main peak at 250-300 hPa. The impact of AMVs is larger as the number of completely overcast SEVIRI scenes is reduced comparatively with the number of cloudy AMVs.
- Wind speed vertical profiles from the combined clear and overcast radiances are very similar in structure with those from the clear SEVIRI data, but a larger magnitude with a maximum at 300 hPa is obtained from the additional use of overcast scenes. This demonstrates the effect of humidity-tracer advection involved in the production of wind increments from the additional assimilated overcast SEVIRI observations.
- Wind analysis scores calculated, in a no-satellite baseline context, has shown that combined clear and overcast SEVIRI have a positive impact on wind analyses through the troposphere with better performance than clear SEVIRI data particularly over the Southern Hemisphere. Over the Northern Hemisphere and Tropics, wind analysis scores for the both datasets are very close, showing that in those regions, wind analyses only get benefits from the clear SEVIRI radiances assimilation. However, over those regions the number of overcast scenes is limited.

- Results with SEVIRI clear and overcast radiances in the full system provide a clear indication that the operational switch to ASR from Meteosat-9 in the next coming cycle (CY38R1) could be beneficial to the quality of 4D-Var analyses and subsequent forecasts.

## **Acknowledgements**

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## **References**

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