In this paper a summary of recent research results on the assimilation of all-sky radiance (ASR) products from Meteosat-9 SEVIRI observations into the ECMWF four-dimensional variational assimilation (4D-Var) will be presented. The overcast cloudy scheme used operationally at ECMWF to directly assimilate cloud-affected infrared radiances from AIRS, IASI and HIRS polar orbiter data was extended to make use of the all-sky radiance products produced by EUMETSAT from Meteosat-9 SEVIRI data. Cloud cover and height are diagnosed from the data and in overcast scenes, cloud parameters are adjusted simultaneously with atmospheric temperature and humidity during the 4D-Var. The initial cloud parameters derived from the ASR SEVIRI observations agree well with EUMETSAT’s independent evaluation of the cloud conditions. The main objective of this study is 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. Experiments were performed with Meteosat-9 overcast cloudy data assimilated in addition to the clear-sky radiances (CSR) from the two water-vapour (WV) channels. The impact of all-sky geostationary radiances on wind analyses has been further investigated and results quantifying the impact of the ASR on the wind analysis will be presented and compared with the impact of CSR and cloudy atmospheric motion vectors (AMVs).

1. INTRODUCTION

In recent years, progress has been made in developing the capability to assimilate infrared cloud-affected radiances in several NWP centres. At ECMWF cloud-affected infrared radiances in overcast conditions over the ocean from hyperspectral sounders such as AIRS and IASI are assimilated in an operational context (McNally, 2009). In this framework, the 4D-Var analysis control vector was extended to include cloud parameters - cloud top pressure and effective cloud fraction - and they are simultaneously estimate together with temperature and humidity inside the main analysis. The present study extends that work by assimilating all-sky radiance product produced by EUMETSAT from Meteosat-9 SEVIRI data directly in 4D-Var. Hourly disseminated ASR contains brightness temperatures information from all water vapour and infrared channels averaged over all pixels within a processing segment as well as clear- and cloudy-sky brightness temperatures averaged over all clear and all cloudy pixels, respectively. Along with the averaged ASR, the percent of pixels flagged as clear sky and cloudy considering three types of layer clouds (high, middle and low) are also given by EUMETSAT.

Currently the radiance observation operator RTTOV-9 (Radiative Transfer for TOVS) is able to compute cloud-affected radiances using additional inputs of single-layer cloud-top height and fraction of opaque cloud. Background estimates of the additional analysis variables that describe clouds are diagnosed from the observations, not taken from the NWP model. Following the approach introduced by Eyre and Menzel (1989) the estimation consists in minimizing the sum of the squared differences between observations and simulated cloudy radiances through the following cost function $J$:

$$J = \sum_{i=1}^{N} [R_{OBS} - R_{CLD}(C_P, C_F)]^2$$
where $R_{\text{OBS}}$ is the observed radiance and $R_{\text{CLD}}$ is the cloudy radiance defined by a linear combination of overcast $R_O(C_P)$ and clear-sky radiances $R_{CR}$ using the following equation:

$$R_{\text{CLD}}(C_P, C_F) = (1 - C_F) R_{CR} + C_F R_O(C_P)$$

For SEVIRI radiances, the channels used to define background estimates of cloud parameters are the 10.8 and 13.4 μm. A value of 5 hPa has been used for the background error in cloud-top pressure.

Section 2 describes an initial evaluation of overcast SEVIRI data using the ECMWF Integrated Forecasting System (IFS). In Section 3, CSR, overcast and cloudy AMVs SEVIRI observations have been introduced into a baseline (observation depleted assimilation system) in order to assess the impact on NWP wind analyses. The conclusion and discussion follows in Section 4.

2. ASSIMILATION EXPERIMENTS WITH OVERCAST SEVIRI RADIANCES

The first experiment is an overcast SEVIRI observations addition onto a no-satellite baseline experiment over a one-month period from 10 February to 10 March 2010. The baseline has been initialized with the ECMWF operational analysis on 2 February 2010 and the only observations assimilated are conventional in situ data from radiosondes, aircraft and surface observations. Allowing the system to degrade over a period of 8 days, the base is then used as initial conditions for all the experiments performed in this study. Both assimilation experiments used 12-hour 4D-Var, with a model resolution of T511 (~40 km), an incremental analysis resolution of T159 (~125 km), and 91 levels in the vertical up to 0.01 hPa. If the scene was determined as overcast in the initial estimation process, the cloud fraction was fixed at 1.0 and four channels (6.2, 7.3, 10.8 and 13.4 μm) were activated in the analysis. Overcast scenes over land and ice surfaces or with an unreasonable cloud-top pressure or when the cloud top is determined to be below 900 hPa are not used in the current system. The observation errors assigned to each channel for overcast radiances have been kept to the same values (2K) as those for operationally assimilated clear-sky data. Additionally, the bias correction is the same for cloudy as well as clear conditions. Observational biases are corrected using variational bias correction (Dee, 2004), employing a linear bias model that includes a global constant, total column water vapour, 1000-300 hPa and 200-500 hPa layer thickness from the first-guess as predictors for WV channels and a global constant offset predictor for channels at 10.8 and 13.4 μm. In this experiment, VarBC coefficients were inherited from the previous cycle of the operational suite at T511 resolution and they were updated at every analysis cycle.

Cloud fractions estimated within the ECMWF 4D-Var assimilation system from SEVIRI observations have been compared against independent estimates provided by EUMETSAT. Figure 1 shows an example of cloud fraction for the first 12-hours analysis cycle for high (100-300 hPa), middle (300-600 hPa) and low (600-900 hPa) clouds. Our estimation of effective cloud fraction, i.e., the product of fractional cloud cover and emissivity, (left side) agrees well with EUMETSAT independent estimation (right side), especially for the overcast scenes (red dots in figure 1).

Figure 2 (left side) displays the distribution of the overcast scenes from SEVIRI for the first assimilation window (00 UTC on 10 February 2010) 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. An example of the coverage provided by the use of WV CSR from SEVIRI (channel at 6.2 μm) is also shown in Figure 2 (right side). It can be seen that the retained overcast data cover the areas where CSR are not available.
Figure 1: The cloud fraction estimated within the ECMWF 4D-Var assimilation system from SEVIRI observations (left) and provided with ASR file produced by EUMETSAT (right). The cloud top pressure is between [100-300] hPa (top), [300-600] hPa (middle), [600-900] hPa (bottom). The colour of the dots is proportional with the estimated cloud fraction (red for overcast values \( C_f = 100\% \), while blue \( C_f = 0\%) \).
The differences between temperature, humidity and wind analysis increments in the SEVIRI overcast experiment and the baseline has been examined for the first 12-h analysis cycle. The increment differences at 300 hPa are shown in Figure 3 for temperature (left side) and humidity and winds (right side). The assimilation of overcast SEVIRI radiances affects temperatures, humidity and winds in areas where overcast observations are assimilated showing a good correspondence between the altitude where the changes occur and the diagnosed height of the overcast cloud. After many successive cycles of assimilation the changes due to the use of overcast radiances spread by advection into other areas.

Overcast cloud-affected infrared radiance data from SEVIRI have been introduced into the ECMWF Integrated Forecasting System following the approach used operationally to direct assimilate cloud-affected radiance from advanced infrared sounders. This has permitted a comparison of cloud parameters calculated within the ECMWF 4D-Var assimilation system from SEVIRI observations with EUMETSAT independent estimates as well as an initial assessment of overcast SEVIRI data on ECMWF 4D-Var analysis. Overcast SEVIRI radiances have been shown to provide temperature, humidity and winds increments in area where the overcast observations were assimilated.
3. IMPACT OF CSR, OVERCAST AND AMVs ON WIND ANALYSIS IN A 4D-Var CONTEXT

The assimilation of radiance data can influence the wind field through humidity tracer advection induced by 4D-Var. This is particularly true for high temporal density water vapour radiance information from geostationary satellites. It has been demonstrated by Peubey and McNally (2009) that a 4D-Var assimilation system can derive useful tropospheric wind information from humidity sensitive radiances by advecting humidity features to improve the analysis fit to observations.

To investigate the impact of CSR, overcast SEVIRI and cloudy AMVs observations from Meteosat-9 on 4D-Var wind analyses, experiments are performed from 10 February to 10 March 2010 from a no-satellite baseline experiment on top of which CSR, overcast and cloudy AMVs observations are assimilated. To better understand the wind tracing capability of geostationary SEVIRI radiances in 4D-Var, detailed comparisons with AMVs have been performed to study how the wind information from both data sources is distributed in the vertical.

Figure 4 shows a vertical profile of the monthly averaged (inside Meteosat-9 disc) RMS humidity increment and wind speed differences between baseline+CSR and baseline experiment (blue line) and, respectively, baseline+AMVs and baseline experiment (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 radiance data by horizontally advecting deep layers of humidity and thus leads to deeper layer adjustments of the wind field. The CSR have a positive impact on wind analysis and the maximum was found at 300 hPa and 500 hPa. For AMVs the wind information is provided as a single level wind observation and the structure functions of the background error covariance control the spread of this information in the vertical. As shown in Figure 4, the maximum impact on wind analysis from AMVs is obtained at 250 hPa and 850 hPa.

Figure 5 displays the structure of analysis increments from overcast SEVIRI radiances (blue line) and cloudy AMVs used only over sea (black line). Small changes in monthly averaged humidity RMS increments above low clouds are observed from the use of overcast data. The vertical profiles of winds speed from overcast SEVIRI and AMVs assimilated over sea shown a main peak located at 250-300 hPa. However, the impact of AMVs is larger as the number of completely overcast SEVIRI scenes is reduced comparatively with the AMVs.

The impact of increasing the number of assimilated ASR was examined performing two additional experiments. The first experiment (hereafter, exp_ov1) is identical to the previous one (only completely overcast scenes was assimilated) except that a static VarBC was used. In the second experiment (hereafter, exp_ov2), the strict limitation of using only completely overcast situations
was relaxed by assimilating all scenes with effective cloud fraction greater than 0.99 and also, using a static VarBC.

Figure 5: Vertical profile of the monthly averaged RMS humidity (left side) and wind speed increments (right side) difference between the baseline+Overcast and baseline experiment (blue line) and baseline+AMVs and baseline experiment (black line). Overcast and cloudy AMVs SEVIRI data were assimilated only over sea.

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 cloudy AMV 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:

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

where $RMSE_{j}$ and $RMSE^b_{j}$ are the wind analysis error for experiment and for the baseline, respectively. For every cycle $j$, wind analysis errors are calculated as departures from the ECMWF operational analysis that runs at T1279 resolution and assimilate the entire observing system as:

$$
RMSE^b_{j} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [(u^b_i - u^f_i)^2 + (v^b_i - v^f_i)^2]}
$$

where $u_i$ and $v_i$ ($u^b_i$ and $v^b_i$) are the analysis values of the zonal and meridional wind components at a grid point $i$ for the experiment (baseline), $u^f_i$ and $v^f_i$ 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 6 shows the analysis scores of the wind speed for all experiments assimilating overcast SEVIRI and AMV data over sea. 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). The analysis scores indicate a positive impact of overcast SEVIRI data in the troposphere particularly over the Southern Hemisphere and over the Tropics at 500hPa. In the Tropics at 300 hPa, no improvement over the baseline is found when overcast data are assimilated and this is related to the limited number of overcast scenes assimilated. Relaxing the overcast limitation by assimilating all scenes with an estimate effective cloud fraction greater than
0.99, leads to an increase of number of overcast scenes assimilated and better wind analysis scores. It is worth noting that applying the simplified overcast approach to scenes with an estimate effective cloud fraction greater than 0.9 does not improve the wind analyses scores (not shown). The impact of cloudy-sky AMVs is larger than that of overcast data owing to the large number of cloudy AMVs assimilated.

Figure 6: Wind analysis scores for the experiments assimilating overcast SEVIRI and cloudy AMVs data over sea 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]: exp_ov (C_F=1 and VarBC evolved, dark grey), exp_ov1 (C_F=1 and VarBC static, white), exp_ov2 (C_F>0.99 and VarBC static, light grey), exp_AMVs (AMVs over sea, hatched).

Using the new ASR product disseminated by EUMETSAT, the next step was to assimilate Meteosat-9 overcast cloudy data in addition to the WV clear-sky radiances from the two water-vapour channels (hereafter, experiment CSR+OV). When the scene is determinate as overcast (estimated effective cloud fraction greater than 0.99) four channels were activated in the analysis and assimilated only over sea. If the scene is not overcast, the cloud fraction is fixed at zero and the system reverts to a clear-sky treatment of SEVIRI data. In this experiment a static VarBC was applied to both clear- and overcast radiances.

Figure 7 shows preliminary analysis scores of the wind speed calculated over 9 days for three experiments assimilating: CSR+OV, CSR from ASR product and cloudy AMVs (same as ECMWF in operations). In the context of no-satellite baseline experiment, CSR+OV have a positive impact on wind analyses through the troposphere with better performance than CSR particularly over the Southern Hemisphere and Tropics at 300 hPa and 500 hPa.

Figure 6: Wind analysis scores calculated inside Meteosat-9 disc in the Northern Hemisphere [20°N-50°N], Tropics [20°S-20°N] and in the Southern Hemisphere [50°S-20°S] for the experiments assimilating CSR, CSR+overcast and cloudy AMVs SEVIRI observations for the first 9 days of the assimilation period (10 to 18 February 2010): CSR (black), CSR+OV (white), AMVs (dark grey).
Additionally, as discussed by Peubey and McNally (2009), 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.

The preliminary results reported here are encouraging. Once the assimilation experiments over all month period have been completed, we can validate the preliminary results presented in Figure 7 and also we can evaluate the impact of each dataset in forecast scores. However, it should be noticed that in the context of a no-satellite baseline experiment, analysis errors are larger than might be expected from a full observing system. Consequently, the improvement in wind analysis scores from CSR+OV dataset with respect to the CSR dataset may be larger than would be expected when those data sets are added to a full observing system.

4. CONCLUSIONS

In this paper we have described further progress toward the assimilation of cloud-affected radiances from Meteosat-9 SEVIRI in ECMWF 4D-Var analysis. Overcast SEVIRI radiances have been successfully introduced into the ECMWF IFS following the approach used operationally to direct assimilate cloud-affected radiance from advanced infrared sounders. Once we have completed the initial assessment of overcast SEVIRI data on 4D-Var analysis, the focus was to extend the humidity tracing capability, previously demonstrated only in clear sky, to cloudy regions, to obtain an all-sky constraint the atmospheric wind field with geostationary radiances.

As part of this study we investigated the impact of overcast geostationary SEVIRI data on the ECMWF 4D-Var wind field. Results using a no-satellite baseline have revealed the potential of overcast images for improving the wind analysis in a 4D-Var context, particularly over the Southern Hemisphere through the troposphere and over the Tropics at 500hPa. In general, low-level overcast scenes add most of the overcast situations to the system. It was also shown that the usage of more overcast scenes could also improve the wind analysis scores. The performance of clear-sky and overcast scenes (CSR+OV) assimilated in top of a no-satellite baseline experiment was found better than CSR performance particularly over the Southern Hemisphere and Tropics at 300 hPa and 500 hPa. Nevertheless, the improvement in wind analysis scores from CSR+OV dataset with respect to the CSR dataset may be larger than would be expected when those data sets are added to a full observing system.

In future, infrared soundings with high spectral resolution from the geostationary orbit at a high temporal and spatial sampling should greatly improve the capabilities of extracting wind information from the assimilation of geostationary data. The first opportunity for these observations may be on EUMETSAT’s Meteosat Third Generation mission.

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6. REFERENCES


