ON SEVERE CONVECTIVE STORMS OVER CENTRAL EUROPE: SATELLITE PRODUCTS WITHIN A CASE STUDY

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Abstract

The OASE (Object-based Analysis and SEamless prediction) - research group within the Hans Ertel Centre for Weather Research (HErZ) compared satellite products to numerical weather forecasts. A deep understanding of the development of severe convective storms over Central Europe is necessary for the improvement of fore- and nowcasting capabilities. Within a case study, the consistency of NWC-SAF (NoWCasting Satellite Application Facility) products derived from Meteosat SEVIRI is investigated. The severe convective storm on 22 June 2011 was chosen with a strong impact and significant damage in Central Europe. Using a radiative transfer model, synthetic satellite winds are derived from forecast data. The comparison of retrieved cloud winds to forecast wind velocities showed a systematic slow wind speed bias in the order of a few m/s. The height assignment was identified as major source of uncertainty which is especially poor in the complex cloud scenery present for severe summer convection.

INTRODUCTION

Object-based analysis and seamless prediction – OASE

The present investigation was carried out within the “object-based analysis and seamless prediction” (OASE) group which is a collaboration between the Leibniz Institute for Tropospheric Research, Leipzig, University of Bonn and the German Weather Service (DWD). OASE is part of the Hans Ertel Centre for Weather Research funded by DWD to enhance research in the field of weather forecasting with special focus on the understanding of forecast errors in cloud development and precipitation formation. As shown in Figure 1, the Hans Ertel Centre is a Germany-wide initiative which brings together scientists from various backgrounds of DWD interest. The topics of the OASE research group are described as follows:

- compositing of observables and derived data from multiple sources (satellite, radar, lightning) for monitoring of extreme events over Germany
- investigation of novel nowcasting techniques and object-based perspective on severe storms
- study of cloud life cycles and precipitation formation
- use of various products for nowcasting and data assimilation in numerical weather prediction

Mainly the last item is addressed in the present study. For assessing the quality and consistency of derived satellite products, the development of a test bed was started in which a selected product can be tested in a controlled environment via synthetic, model-generated measurements. Beside the evaluation of existing products, the future goal is also to participate in the development of robust satellite-based estimates of dynamical properties of mesoscale, convective systems.
Figure 1: Sketch of the network of the Hans Ertel Centre for Weather Research funded by the German Weather Service. The background image is the colour-enhanced brightness temperature of the MSG1-SEVIRI IR10.8μm channel for the 22 June 2011 at 12 UTC. All partners had been affected by severe weather at this particular day.

Synthetic Satellite Winds

The motion of clouds and water vapour disturbances is derived from subsequent images of the SEVIRI instrument aboard the geostationary satellite Meteosat-9. Atmospheric motion vectors, here also called satellite winds, contain extremely valuable information about the atmospheric flow especially in geographical regions which are not assessable by other methods, e.g. soundings. Satellite winds are commonly used in assimilation procedures for global weather prediction models (Bormann et. al., 2012), however, their utility for regional forecasts is still undetermined. The separation of systematic and random errors in wind retrievals from ageostrophic wind features established by mesoscale flow pattern remains a future challenge and mainly motivates the present study.

A controlled environment is needed for a deeper understanding of the quality and consistency of wind retrieval algorithms. Perfect model experiments in which synthetic satellite images and hence synthetic satellite winds are derived directly from numerical forecasts offer this opportunity. For instance, these have been used at ECMWF to assess the uncertainty in atmospheric motion vectors (von Bremen, 2008, Hernandez-Carrascal et. al. 2012, Lean et. al., 2012). In addition to the assimilation aspect, satellite winds are important for nowcasting of severe storms. They can be used to track cloud objects and to calculate time rates of the radiative properties of developing cells which are fundamental for the early detection and identification of rapidly developing severe thunderstorms (Mecikalski et. al., 2010, and references therein).

METHOD: PERFECT MODEL EXPERIMENTS

Figure 2 gives an overview of the different steps within the perfect model framework. Regional forecasts from the numerical weather prediction model COSMO-DE operated by the German Weather Service were taken (Baldauf et. al., 2011). COSMO-DE has a horizontal grid resolution of 2.8 x 2.8 km² which is comparable to or even smaller than the resolution of the narrow-band spectral channels of the Meteosat SEVIRI instrument over Germany with roughly 4 x 6 km² per pixel. Each 3 hours, a new COSMO-DE simulation is initialized and performs a 21 hours forecast. The forecast data are operationally archived each 15 minutes which facilitates latter comparison of model predictions to the operational scan service of Meteosat-9 with the same scan frequency. Synthetic satellite images are derived from vertical COSMO-DE profiles of temperature, humidity, cloud liquid water, ice and snow
content using the very fast radiative transfer model RTTOV (Saunders et. al., 1999) which is operated and developed within the satellite facility for numerical weather prediction NWP-SAF. Please note that via RTTOV only the derivation of radiances in the thermal wave number range is possible. Cloudy radiances from visible and near-infrared channels of SEVIRI are not available from RTTOV and hence are ignored for the present study. The synthetic satellite imagery was kindly provided by the German Weather Service and is based on the method described by Keil et. al. (2006) which operationally uses RTTOV v9.3. The synthetic satellite images given on the COSMO-DE grid are projected and regridded to the Meteosat SEVIRI grid using nearest neighbour interpolation. The synthetic images are merged into the real SEVIRI measurements provided in the original HRIT files; resulting images are rewritten to the former input.

**Figure 2: A schematic view on the different step in the perfect model experiments.**

The high-resolution wind (HRW) algorithm from the satellite facility for nowcasting and very short-range forecasting (NWC-SAF) is applied to the synthetic SEVIRI images (García-Pereda, 2008). The software was configured to derive the cloud motion winds for the two water vapour channels WV6.2 and WV7.3 and the infrared split window channels IR10.8 and IR12.0, separately. Whereas the motion vectors from the latter mainly indicate motion of cloud tops, the former are also sensitive to structures in the water vapour fields and thus are used to derive upper tropospheric winds under clear sky conditions. The default HRW software operates in three stages: (i) possible targets are selected by gradients and edges in the images, (ii) tracer targets are identified in subsequent images using the maximal cross-correlation between two target boxes centred at the target pixel and with a box size of 24 x 24 pixels, and (iii) height is assigned to the motion vector. As this study is restricted to thermal infrared channels only, and the NWCSAF cloud typing products rely on the visible channels during daytime, we started with the simplest possible height assignment method, the brightness temperature interpolation method, in which the height of the motion vector is inferred from a temperature profile of an ECMWF forecast by matching to the brightness temperature of the IR10.8 channel. The method is known to give poor height estimates especially for semi-transparent and multi-layer clouds and will be replaced in future by the CCC technique described in Borde and Oyama (2008). In the output of the NWCSAF product the horizontal position and the pressure level of each cloud motion retrieval is given in addition to several other properties. For a point-to-point comparison between the original forecast wind velocity and the retrieved cloud motion wind, the COSMO-DE wind velocity is interpolated to the position of the cloud motion retrieval via linear interpolation in the vertical, and via nearest-neighbour interpolation in the horizontal. Note that for this point-to-point comparison difficulties arise because of (i) the horizontal extend of the HRW target box, i.e. the optimal displacement of the target box is not only affected by the cloud properties in the centre of the box, and (ii) the sensitivity to the vertical position, i.e. due to the appearance of the mid-latitude jet and the resulting strong wind shear small vertical displacements (errors in the height assignment) can lead to large changes in the estimated wind velocity at the retrieval position.
Within the OASE research group we selected a common case day at which most of Germany was affected by severe weather. The cloud development from morning at 9 UTC to evening 18 UTC is depicted as movie in Figure 3. It shows the time evolution of the IR10.8 brightness temperature with colour enhancement of temperatures below 240 K. The prevailing flow is from south-west to north-east. In the morning hours an isolated low developed in a pronouce convergence zone in Eastern France. The advection of warm, moist air ahead of the passing cold front led to a destabilisation and large-scale lifting of air. Severe convection developed over Germany in the course of the day leading to large hail, heavy rain, severe wind gusts and tornadoes.

**RESULTS: SYNTHETIC SATELLITE WINDS**

**Point-to-point comparison between forecast wind and retrieved cloud motion**

In Figure 4, a direct comparison is shown between the speed obtained from HRW retrievals on the x-axis and COSMO-DE wind velocity on the y-axis. Only the forecast for 12 UTC at the 22 June 2011 initialized at 0 UTC was chosen. The colour coding of the dots indicates the confidence level, a combination of different quality indices provided by the HRW software. Beside the temporal and spatial consistency, the confidence level also includes a check for the deviation of the wind retrieval from a given forecast. At the moment, we use the ECMWF forecast which introduces some inconsistencies in the present study. The corresponding quality check will be removed in future.

The wind retrieval for the infrared IR10.8 channel mainly accounts for the motion of cloud top and exhibits a symmetric spread around the diagonal. The average bias is negative and in the order of 2 m/s. The standard deviation is ~ 7 m/s. The winds obtained from the WV6.2 channel are affected by water vapour disturbances in the upper troposphere where the corresponding weighting function has a maximum in about 350 hPa (Schmetz et. al, 2002). Especially, a large portion of original forecast winds in the range between 30 m/s to 60 m/s is underestimated by the cloud motion retrieval. We speculate that clear-sky winds might negatively influence the wind retrieval statistics, but future refinement of the underlying error sources is needed. The average bias and standard deviation of the WV6.2 winds are -9 m/s and 11 m/s, respectively. The normalized bias and standard deviation of 20% to 40% are somewhat larger than reported in the HRW validation report. One of the primary causes might be that the cloud scenery in severe summer convection is much more complex than on annual average.
Figure 4: Retrieved cloud motion vs. forecast winds at cloud position for IR10.8 channel (a) and WV6.2 channel (b). Colour coding of the circles shows the confidence level obtained from a combination of different NWCSAF-HRW quality indices.

Profile analysis

To explain the impact of different cloud types on the IR10.8 wind retrieval, a few examples are shown in Figure 5. For four different locations in the domain, profiles of COSMO-DE wind velocity and mixing ratios of liquid and solid water content within the clouds at the centre of the HRW target box are related to the wind retrieval and its assigned height. Guided by the profiles of cloud properties, a pressure level is found manually in which the retrieved cloud motion fits best to the given forecast profile. Note that for the examples given here, the definition of the best-fit pressure level is not always obvious. If the best-fit pressure level is reasonably connected to the vertical position of a cloud layer than it can be used to quantify errors in the wind retrieval due to uncertainties in height assignment.

Figure 5(a) gives a typical example of a problem which occurs for multi-layer clouds. A very thin cirrus at about 200 hPa lays over an optically thicker water cloud at about 700 hPa. In this case (assuming that multi-layer structure at the centre point is representative for the whole target box) the radiative signal is composed of the signature of the very cold cirrus and the warmer liquid water cloud and the simple brightness temperature interpolation technique places the assigned height in the middle of the two. Visual inspection, however, makes it clear that the cloud motion derived from the IR10.8 images is dominated by the motion of the liquid water cloud underneath the cirrus. The same also happens in Figure 5(b). In Figure 5(c), the radiation of the semi-transparent cirrus double-layer is also affected by the warmer underground which leads in this case to an underestimation of the cloud motion height. At last, Figure 5(d) gives a positive example in which a wind retrieval obtained in a thicker cirrus gives a reliable estimate of the forecast wind speed. In summary, based on the presented examples the height assignment of the cloud motion is the most critical part in the wind retrieval algorithm and differences between the retrieved and best-fit pressure level up to 200 hPa appeared. It is expected that this error will be dramatically reduced when more sophisticated methods, e.g. the CCC method (Borde and Oyama, 2008), will be applied in future.
Figure 5: Profiles for multi-layer cloud scenes (a), (b), semi-transparent cirrus (c) and thicker cirrus (d). Each left plot shows the forecast wind speed (green squares) and horizontal wind direction (green arrows), cloud motion retrieval (red arrow), height estimate (red solid line), and intercept height (red dashed line). Each right plot shows ice (cyan) and liquid water mixing ratio (blue), and height (red solid line) and intercept estimates (red dashed line) of the cloud motion retrieval.

Mean bias statistics

The mean bias and standard deviation of the wind retrievals obtained for four different SEVIRI channels is shown in Figure 6. The pastel-coloured curves give the respective statistical measure obtained from a domain average but for each hourly timeslot between 9 and 18 UTC separately. The curves in darker colours, however, show the temporal average of the former. Subsequently, wind retrievals with a confidence level lower than a certain value are removed from the analysis, e.g. for confidence level 90 only wind retrievals with a quality of 90 and greater are used. The results for the split window channels IR10.8 and IR12.0 are very similar, the mean bias is ~ -2 m/s and the standard deviation decreases from ~ 8 m/s to 3 m/s. The results from the water vapour channels WV6.2 and WV7.3 show larger deviations from the forecast values. The WV6.2 is more sensitive to higher altitudes and is more dominated by the wind jet than the WV7.3, a reason why also larger deviations arise for the former. Note that the spread between calculations at different timeslots is considerable even though several thousand retrieval points contribute to each statistical evaluation.

Figure 6: Mean bias (a) and mean standard deviation (b) of cloud motion vectors compared to forecast winds for different SEVIRI channels (colors). Temporal average (dark colors) and the values for individual time slots (pastel colors) for an interval between 9 and 18 UTC at 22 June 2011 are plotted.
CONCLUSIONS

We presented perfect model experiments in which synthetic cloud motion winds were derived from forecasts of the German regional weather prediction model COSMO-DE. The fast radiative transfer model RTTOV was utilized to derive synthetic satellite images for the infrared channels of the SEVIRI instrument aboard Meteosat-9. In the next step, the high-resolution winds (HRW) software developed and maintained by the EUMETSAT facility for nowcasting NWC-SAF was employed for the calculation of synthetic cloud motion winds. The retrievals were compared to the forecast wind velocity directly obtained from the model and interpolated to the retrieval position.

For the wind retrievals based on four infrared SEVIRI channels (WV6.2, WV7.3, IR10.8, IR12.0) we found a slow wind speed bias in the order of several m/s with lower deviations for the infrared split-window channels IR10.8 and IR12.0 and larger deviations for the water vapour channels WV6.2 and WV7.3. The standard deviation is also in the order of several m/s and quite similar for all of the four channels when a confidence level threshold of about 90 or greater is chosen.

In example plots, we highlighted that one major contribution to the wind retrieval error comes from the uncertainty in the height assignment of the retrieved wind vector (see e.g. Salonen et. al., 2012, and references therein). It was shown that due to the complexity of the cloud fields it is not always obvious how to choose a height in which the retrieved cloud wind fits best to the forecast velocity profile. The deviations of the retrieved pressure from the best fit can be 200 hPa or greater. Especially for semi-transparent and multi-layer multi-phase clouds the height assignment via brightness temperature interpolation gives poor results, and will be replaced by more advance methods in future. Our results emphasize the utility of synthetic studies in assessing the quality of existing satellite products especially when considering the inherent complexity of cloud structures in severe summer convection.

FUTURE CHALLENGES

The following items summarize the scientific questions which will guide our future work:

- What is the effect of cloud properties directly derived from forecasts on the wind product accuracy?
- What are special advantages and disadvantages of dynamic satellite products in severe storms?
- How can we learn more about problems in the assimilation of satellite winds with the help of synthetic measurements?
- How can we define appropriate measures of mesoscale circulations within the frame of synthetic satellite measurements?

REFERENCES


