TECHNICAL MEMORANDUM

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Comparison of ODYSSEY precipitation composites to SYNOP rain gauges and ECMWF model

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February 26, 2014

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

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Abstract

A systematic comparison of ODYSSEY European precipitation composites with both synoptic station rain gauge observations and ECMWF short-range forecasts was carried out over the period March 2012 to October 2013. Statistics indicate that the agreement between ODYSSEY and the two other datasets has been substantially improving over Western Europe during this period, while some issues remain especially over Eastern European countries and over mountainous regions. Indeed, interferences with other microwave sources are still present, even in recent composites, which leads to an obvious degradation of quality over these regions. Furthermore, large systematic positive biases over southeastern Europe would also suggest that S-band radars are not handled as well as C-band radars in the compositing process. Persistent contamination from ground-clutter echoes also appeared in spring 2013 for several weeks over the Netherlands, leading to a dramatic degradation of the agreement between ODYSSEY and the two other datasets. Lastly, the inadequacy of ODYSSEY's current Z-R relationship in snowfall situations causes a systematic large underestimation of precipitation in the wintertime over colder regions. Ongoing efforts by the OPERA community to improve the quality and homogeneity of precipitation composites are strongly supported by ECMWF because the assimilation of radar data on the European scale might be beneficial to operational global numerical prediction, as it is already the case with NCEP Stage IV composites over the United States.

1 Introduction

High spatial and temporal resolution estimates of precipitation are now available from several ground-based networks of meteorological radars around the world. In particular, continental-scale coverage is already provided by the three networks of the U.S.A. (NEXRAD[1]; Fulton *et al.*1998), Europe (OPERA; Huuskonen *et al.* 2014) and China (Bai 2013). Each of these networks comprises between 160 and 200 radars.

In the United States, the great homogeneity of the NEXRAD network (in terms of radar frequency, types and brands as well as in terms of measurement processing algorithms) quickly led to the operational production of continental precipitation composites (NCEP Stage IV dataset; Lin and Mitchell 2005). In Europe, by contrast, the variety of instruments and algorithms used to process the observations as well as occasional issues of international data exchange policy have slowed down the progress towards the delivery of reliable European precipitation composites.

However, since 1999, the OPERA programme led by EUMETNET has been constantly progressing towards the unification of radar data usage among 30 European countries. In 2008, the OPERA Pilot Data Hub was able to deliver two-dimensional (2D) rain composites over Europe, but the inhomogeneous handling of national data turned out to be detrimental to the quality of the product (Lopez 2008). The establishement of ”ODYSSEY” (OPERA Data Centre) in February 2012 constituted a new step towards the improvement of European 2D precipitation composites, with a centralized and harmonized processing of raw data from individual radars. It should also be noted that volumetric reflectivity and (to a lesser extent) Doppler-wind data will be made available from ODYSSEY, with access granted to OPERA members only. These data will be used by most European limited-area modelling consortia for the purpose of data assimilation.

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[1] See list of acronyms in Appendix 1

As a natural continuation to the assessment of the Pilot Data Hub 2D precipitation composites presented in Lopez (2008), the work described here was aimed at evaluating the evolution of the quality of ODYSSEY precipitation composites against synoptic station (SYNOP) rain gauge observations and ECMWF model outputs. The potential benefit from such study is threefold. First, improving our knowledge on the quality of the ODYSSEY product should help to determine whether these data can be used in meteorological applications such as model validation and data assimilation. The excellent spatial and temporal sampling of radar composites is clearly an advantage compared to rain gauge point measurements, the representativity of which can be sometimes questionable. Since the assimilation of NCEP Stage IV 2D precipitation composites in ECMWF's operational 4D-Var system since November 2011 (Lopez 2011) was proven to be beneficial to some aspects of atmospheric analyses and forecasts, the assimilation of European composites might also contribute to a similar improvement in the quality of numerical weather prediction (NWP). Secondly, feeding deficiencies found in ODYSSEY composites back to the OPERA community might provide some hints on how to reduce errors in radar data by improving the quality control and compositing software used in ODYSSEY. Thirdly, highlighting the improvements achieved since the creation of ODYSSEY could also give some confidence in the success of past developments.

It should be stressed that the focus in this study has been laid on 6-hour precipitation accumulations since this corresponds to the optimal accumulation length used for assimilating NCEP Stage IV rain composites in ECMWF's 4D-Var system. Another reason for this choice is that the accumulation length of SYNOP rain gauge observations is most commonly set to 6 hours over most of Europe. Only a few countries currently provide hourly accumulations.

The datasets used in this study are described in section 2. Results of the comparison of ODYSSEY composites against the two other datasets are presented in section 3. The most outstanding remaining issues are then reported in section 4. Section 5 summarizes the main findings of this study and provides an outlook on the quality requirements and potential usage of ODYSSEY data.

2 Datasets

2.1 ODYSSEY precipitation composites

In this work, ODYSSEY 2D precipitation composites were obtained from both the official OPERA Data Centre hosted at the Met Office (UK) and Météo-France (for dates after 25 March 2013; in BUFR format) and from FMI (for earlier dates; in HDF5 format). Note that FMI data were kindly provided by Dr Elena Saltikoff as a workaround to a rounding problem which was identified in BUFR data prior to 18 February 2013. The period of interest in this work runs from March 2012 (i.e. the beginning of the operational ODYSSEY archive) until October 2013. The original composites are available every 15 mn on a Lambert azimuthal equal area grid with a spatial resolution of 2 km. For motivations detailed earlier, these data were accumulated over 6-hour periods (ending at 00Z, 06Z, 12Z and 18Z) prior to statistical computations. Only pixels that were flagged as valid rain data (i.e. not labelled as 'no data' or 'undetected') were retained in the accumulations. This deliberate choice of rejecting data labelled as 'undetected' is justified by the fact that this category of pixels currently encompasses not only those for which the echoe returned to the radar was below the detection level, but also those points affected by ground clutter.

2.2 SYNOP rain gauge observations

The second precipitation dataset used in this study are 6-hourly accumulations measured by the European network of synoptic stations. These data are routinely received at ECMWF through the Global Telecommunication System (GTS). It should be emphasized that SYNOP rain gauge data will be regarded here as the most reliable source of information available on precipitation. However, one must also keep in mind that SYNOP rain gauge data may occasionally suffer from significant biases, particularly in strong wind conditions or snowfall situations, in which a systematic undercatch occurs. Rain gauge observations can also be affected by the lack of spatial representativity associated with point measurements, especially in meteorological situations characterized by unorganized convection. However, the fact of considering relatively long precipitation accumulations (6 hours) is expected to reduce the importance of the representativity issue, as a result of the displacement of cloud systems. Furthermore, the comparison of ODYSSEY composites with SYNOP data has been performed by identifying the ODYSSEY pixel nearest to the exact location of each raingauge, thereby minimizing spatial mismatches.

2.3 ECMWF model data

The third precipitation dataset consists of short-range forecasts obtained from ECMWF's operational forecasting system, which is described in Courtier *et al.* (1994). The forecasts used here were all initiated at 00Z, and 6, 12, 18 and 24-hour forecast ranges were retrieved to match the corresponding ODYSSEY 6-hourly precipitation accumulations (see section 2.1). Forecast data were produced at the operational horizontal spectral resolution of T1279 (i.e. roughly 16 km) and with 137 levels in the vertical. In the comparison of ODYSSEY with ECMWF model data, precipitation amounts at ODYSSEY 2-km pixels were averaged over each ECMWF model grid box ($\approx$16-km) to avoid spatial representativity issues. Even though ECMWF precipitation forecasts are likely to be usually less accurate than SYNOP observations, they are used here in order to assess the significance of the differences found between ODYSSEY and SYNOP data. For instance, the occurrence of large departures between ODYSSEY and both SYNOP and ECMWF model data is a clear indication of biases in the ODYSSEY composites.

3 Results

Monthly statistics of ODYSSEY composites versus SYNOP and ECMWF data were computed in terms of mean and root-mean-square differences, correlations and threat scores, for the period March 2012 - October 2013. Statistics included land points only and were calculated over various European subdomains shown in Fig. 1.

3.1 Monthly time series

Figure 2 displays time series of monthly normalized mean bias (NMB) and mean correlation between ODYSSEY and SYNOP rain gauges, for the whole of Europe and for each subdomain defined in Fig. 1. The legend of each panel indicates which domains are shown. Note that the normalized mean bias for a given month is defined as the mean bias divided by the mean precipitation amount computed over ODYSSEY and the other dataset. It is therefore unitless and can vary between -2 and +2. For instance, a value of +0.2 would indicate that OPERA composites have a positive bias of 20% relative to the mean

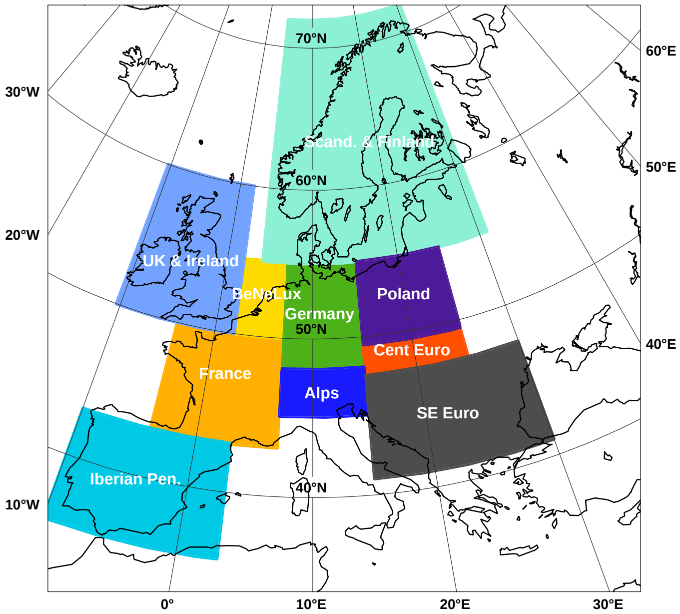

Figure 1: Geographical subdomains used in statistical computations.

value of ODYSSEY and SYNOP data. Figure 3 shows the same statistical results, but when comparing ODYSSEY to ECMWF model forecasts.

3.1.1 Normalized mean biases

The first general feature to be noted is the frequent similarity in the sign of *NMB* values of ODYSSEY composites versus SYNOP and ECMWF model, for most domains. For instance, the green curves for Germany in panel (c) of Figs. 2 and 3 exhibit similar relatively large negative values from March 2012 to February 2013 and values much closer to zero for the rest of the period. More generally, the fact of finding the same signal with respect to two independent datasets (SYNOP gauges and ECMWF model forecasts) can be used as an indicator that a significant positive or negative bias exists in ODYSSEY data.

Panel (a) of Figs. 2 and 3 suggests that over Europe as a whole, ODYSSEY composites tend to underestimate ($NMB < 0$) precipitation amounts by up to 25%. However, individual subdomains exhibit a large variety of behaviours. From panel (b), there seems to be a clear trend towards reduced *NMB* values over France and Germany, particularly at the end of 2012. The early overestimation over France and underestimation over Germany have almost vanished in 2013. On the other hand, the ”UK+Ireland” subdomain is characterized by smaller biases right from the start of the period.

Panel (e) of Figs. 2 and 3 shows that except in July 2013, ODYSSEY strongly underestimates precipitation over the Iberian Peninsula by roughly 50% on average. Conversely, ODYSSEY overestimates rainfall amounts over southeastern Europe by 20% with respect to SYNOP and by around 50% compared to ECMWF forecasts (see section 3.2 for a possible explanation). Except for the sudden large positive *NMC* values found in spring 2013 over the BeNeLux (these will be explained in section 4.1), this region usually suffers from an underestimation of around 20% in ODYSSEY composites.

As seen from panel (g) of Figs. 2 and 3, Nordic countries, the Alps and Poland are all characterized by a systematic strong underestimation in ODYSSEY (about 60% on average) which persists throughout

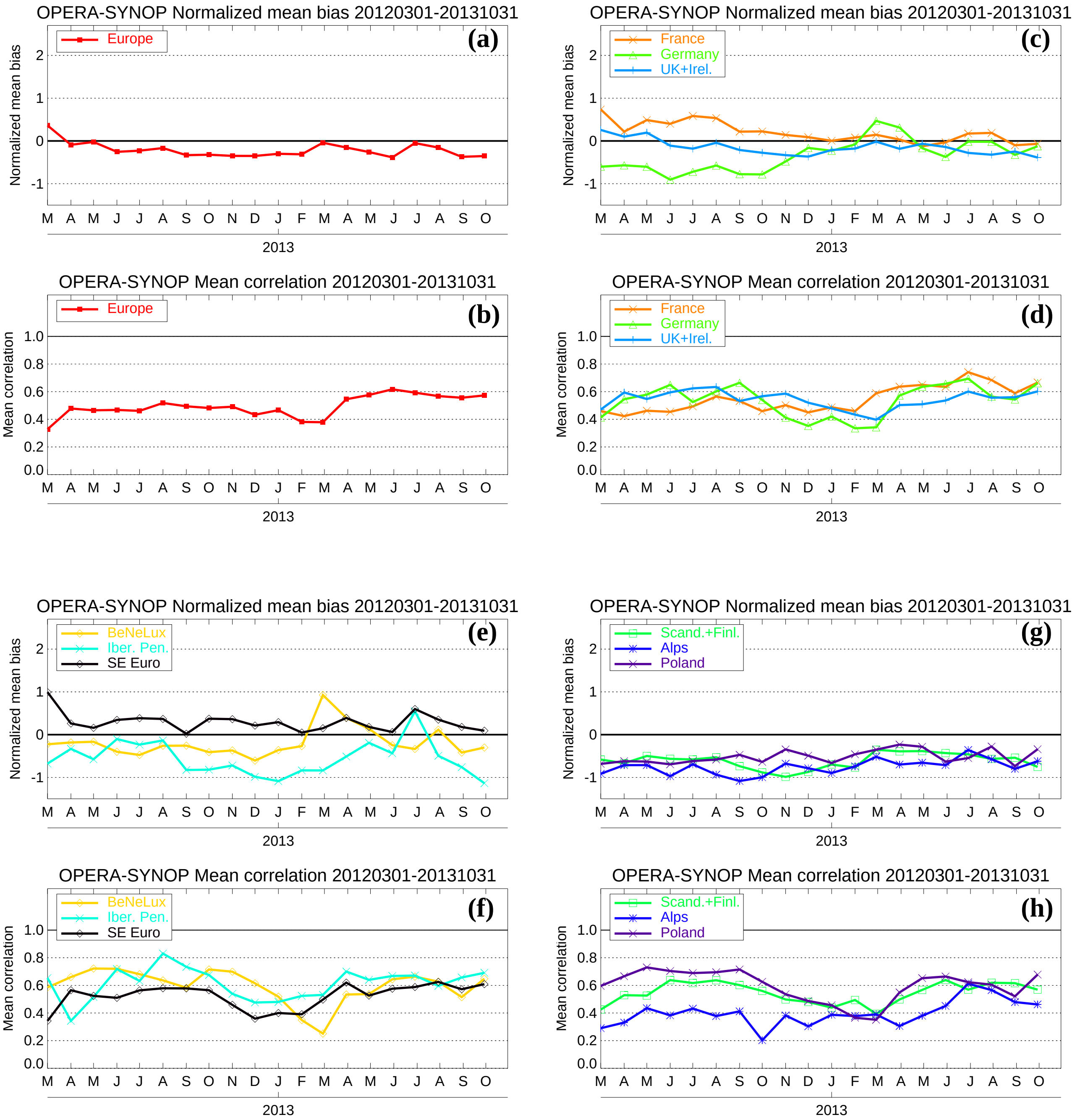

Figure 2: Time series of monthly normalized mean bias and mean correlation between OPERA composites and SYNOP rain gauges for the whole of Europe and for each of the European subdomains defined in Fig. 1. The period for the statistics is March 2012 to October 2013. Statistics shown along the y-axis are all unitless. The legend in each panel indicates the domain names with their associated line colours.

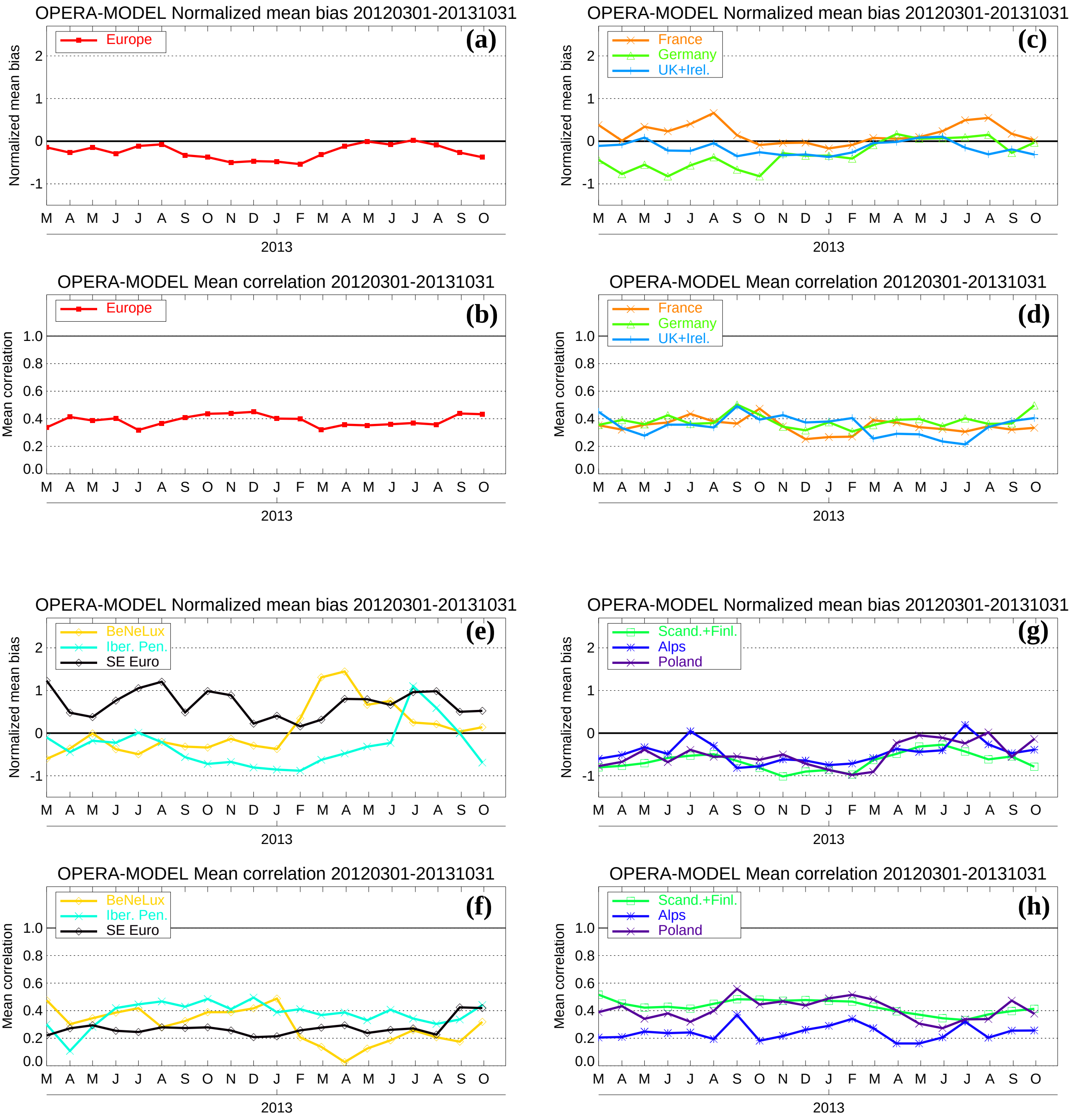

Figure 3: Same as in Fig. 2, but against ECMWF model forecasts.

the period. However, for Poland and the Alps, there is a hint of a reduction of the negative bias after March 2013, particularly compared to ECMWF forecasts (Fig. 3.g). It should also be stressed here that the frequent occurrences of snowfall over these three regions during the cold season might make SYNOP rain gauge measurements less reliable.

3.1.2 Mean correlations

As far as mean correlations are concerned, Fig. 2.b indicates that the correlation between ODYSSEY and SYNOP over Europe has slowly increased from less than 0.4 in March 2012 up to around 0.6 by the end of 2013. Figure 2 also evidences the systematic dip seen in the correlation with SYNOP in the wintertime over most subdomains. Given that no such dip appear in Fig. 3, these lower correlations might very well be due to the reduced reliability of rain gauges for measuring snowfall.

By comparing panels (b),(d),(f),(h) of Figs. 2 and 3, one can easily see that ODYSSEY correlations are systematically higher with respect to SYNOP data than against ECMWF model data by roughly 0.2. This is not surprising since one can reasonably assume that rain gauge observations are likely to be more accurate than precipitation forecasts, except maybe in snowfall conditions.

The Alps region (panel (h) of Figs. 2 and 3) exhibits the lowest correlations with respect to SYNOP gauges and ECMWF forecasts, with hardly 0.4 and 0.2, respectively, on average over the whole period. This highlights the difficulty to validate ODYSSEY composites over mountainous regions where radars can suffer from widespread beam blockage and precipitation enhancement effects. Furthermore, mountains are affected by snowfall in winter, which can be problematic for radars, rain gauges and model altogether. Mountains are also prone to intense convection during the warm season, a process which can be rather challenging for a global numerical model, even with a 16 km horizontal resolution. These issues affect not only the Alps, but also other smaller mountain ranges such as the Pyrenees or the Carpathians (see section 3.2). To qualify the poor result over the Alps, one must highlight the fact that the data coverage for the period of interest was degraded due to the lack of radar observations from Switzerland, Austria and Italy in the compositing process. The overall performance of ODYSSEY over the Alps would certainly have benefited from the inclusion of observations from these three countries in the composites.

Over BeNeLux, the marked drop in correlation in spring 2013 is associated with the sharp change in NMB values (panel (e) in Figs. 2 and 3) already mentioned in section 3.1.1. An explanation for this phenomenon will be given in section 4.1.

3.2 Statistical maps

To complement the time series of section 3.1, an example of maps of mean precipitation and NMB values are displayed in Fig. 4 for spring 2013. The top row shows mean SYNOP precipitation amounts for this season (left panel) and the corresponding ODYSSEY−SYNOP NMB (right panel). The bottom row shows the same but when using ECMWF model data instead of SYNOP rain gauges. Negative (resp. positive) NMB values are shown in blue (resp. red), indicating an underestimation (resp. overestimation) of precipitation in ODYSSEY. Also note that the small triangles plotted in the bottom panels correspond to the locations of all OPERA radars, with colour-coded information about their operating wavelength: C-band in red, S-band in black and X-band in dark blue.

First of all, one should note that the mean precipitation amounts shown in panels (a) and (c) are significantly higher than the values that would have been obtained if zero-rain events (i.e. ODYSSEY pixels flagged as 'undetected') had been included in the average (see section 2.1). Secondly, the comparison of panels (b) and (d) of Fig. 4 underlines the overall similarity of *NMB* patterns when ODYSSEY is compared to SYNOP gauges and ECMWF forecasts. For instance, a significant underestimation by ODYSSEY is obvious over mountains, particularly over the Alps, the Carpathians and the southwest of Norway. This is also true over the Pyrenees although the signal can only be seen in panel (d), given the absence of high-altitude SYNOP gauges in that region. The other striking feature is the strong overestimation in ODYSSEY composites over southeastern Europe, which might be related to the lack of treatment for artefacts specific to S-band radars (black triangles). This might also apply to S-band radars situated in southwestern France, since positive *NMB* values are found with respect to ECMWF model in Fig. 4.d, to a lesser extent though. As already suggested in panel (c) of Figs. 2 and 3, ODYSSEY is rather close to SYNOP gauges and ECMWF forecasts on average over Germany, France and southern Great Britain. Over Spain, there seems to be a rather systematic underestimation.

The *NMB* patterns identified in Fig. 4 for spring 2013 turn out to be rather robust throughout the year (not shown). The main difference that can be identified in other seasons is the strong underestimation of precipitation in ODYSSEY in the wintertime over Scandinavia, as illustrated in the time series of Fig. 5, with respect to both SYNOP gauges and ECMWF model. More generally, a large negative precipitation bias in ODYSSEY composites can be found anywhere as soon as snowfall is observed. An obvious explanation for this underestimation is the use of the traditional Marshall-Palmer Z-R relationship (Marshall *et al.* 1955: $Z = 200\ R^{1.6}$) across each ODYSSEY composite, which may be adequate for mid-latitude rainfall but is clearly unsuitable in snowfall conditions. Figure 6 displays a recomputation of the precipitation time series of Fig. 5 over Scandinavia using the Z-R relationship proposed by Saltikoff *et al.*(2010) for snowfall conditions over Finland ($Z = 100\ R^2$) rather than the default Marshall-Palmer relationship. The comparison of Fig. 5 with Fig. 6 shows that the agreement of ODYSSEY composites with the two other datasets is dramatically improved with the snowfall-specific Z-R relationship, even though peak values in ODYSSEY remain too low. Therefore, a more realistic description in ODYSSEY composites of the dependence of Z-R relationships on particle size distributions and precipitation types (convective/stratiform, rain/snow, etc...) would certainly be desirable.

3.3 Threat scores

Threat scores have also been computed between ODYSSEY and the two other datasets for each subdomain and for a set of various precipitation thresholds. The three scores that will be shown here are the equitable threat score (ETS), the probability of detection (POD) and the false alarm rate (FAR). Their mathematical definition is given in Appendix 2. ETS ranges from $-\frac{1}{3}$ up to 1, while POD and FAR both vary between 0 and 1. The higher POD and ETS (resp. the lower FAR), the better the agreement between ODYSSEY and the other dataset.

Figure 7 displays a sample of the most interesting score plots of ODYSSEY against SYNOP rain gauges, for the geographical subdomains of Fig. 2. The scores a shown for a precipitation threshold of 3 mm day^{-1} in panels (a)-(e) and 10 mm day^{-1} in panel (f). One should note that scores for thresholds below 2 mm day^{-1} were deemed inappropriate here given the radar detection threshold, the precision of ODYSSEY composites (0.1 mm h^{-1}) and the resolution of SYNOP rain gauges (typically not better than 0.2 mm for tipping bucket instruments).

Figure 7.a shows that POD over Germany has dramatically improved from a poor value of 0.24 in March 2012 up to 0.9 in recent months. In contrast, POD over France and "UK+Ireland" has remained above 0.8 throughout the period, which indicates a good level of detection in ODYSSEY. At the same time, FAR over Germany and "UK+Ireland" (Fig. 7.b) has stayed rather low (0.2-0.4) while over France it exhibited

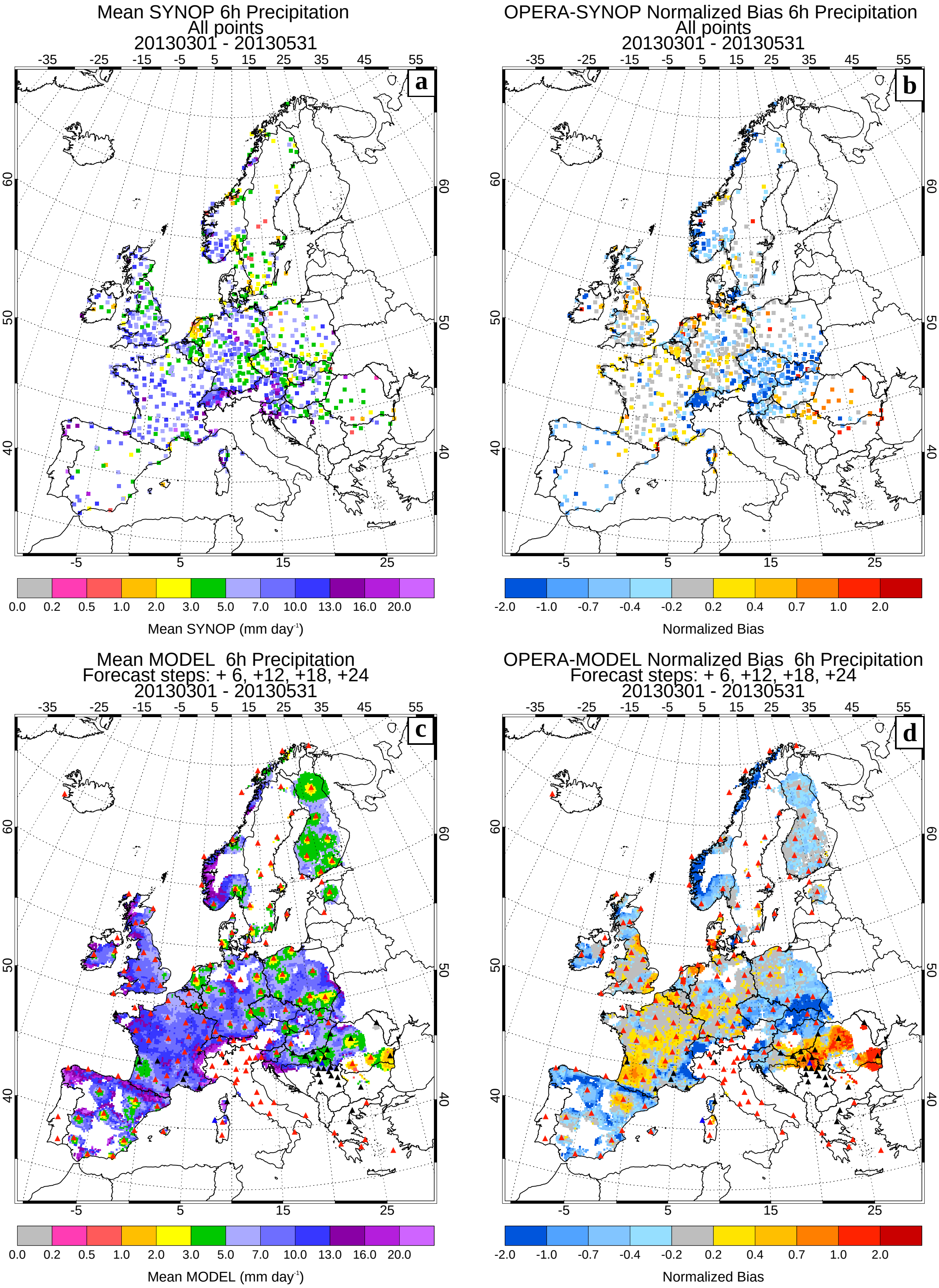

Figure 4: Maps of average precipitation amounts (left) and normalized mean bias (right) when comparing ODYSSEY precipitation composites against SYNOP rain gauges (top) and ECMWF short-range forecasts (bottom) over the period March-May 2013. Negative values (blue; unitless) on right panels indicate an underestimation in ODYSSEY composites relative to the other dataset. In bottom panels, OPERA radar sites are indicated by triangles which are colour-coded according to their wavelength: C-band (red), S-band (black) and X-band (dark blue).

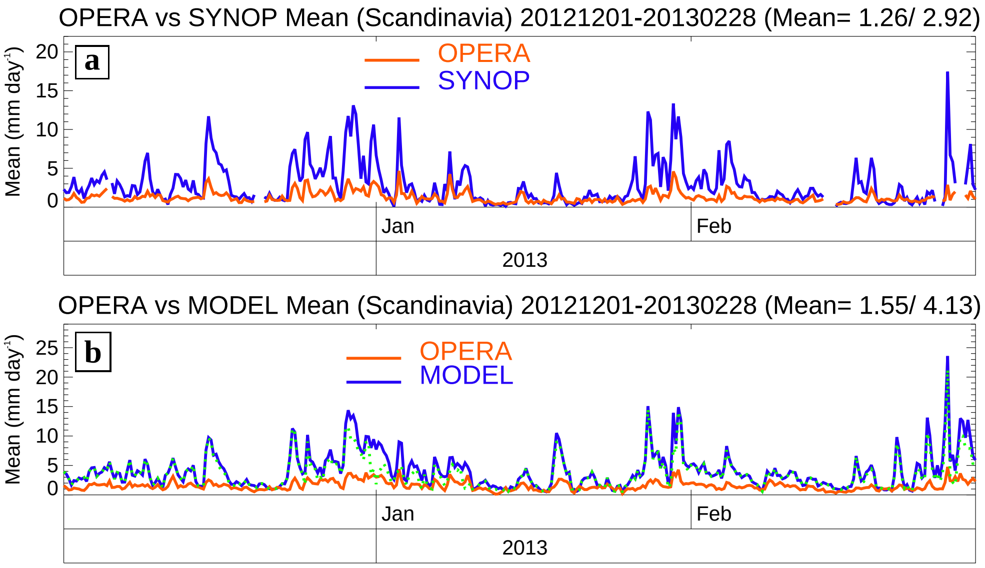

Figure 5: Time series of ODYSSEY versus (a) SYNOP and (b) ECMWF model 6-hourly precipitation accumulations averaged over Scandinavia between 1 December 2012 and 28 February 2013. Overall mean values are shown in the title in mm day^{-1} for ODYSSEY and the other dataset, respectively. The dotted green curve in panel (b) shows the amount of snowfall from the ECMWF model. Thus the vertical gap between the blue and green curves corresponds to the model's rainfall amount.

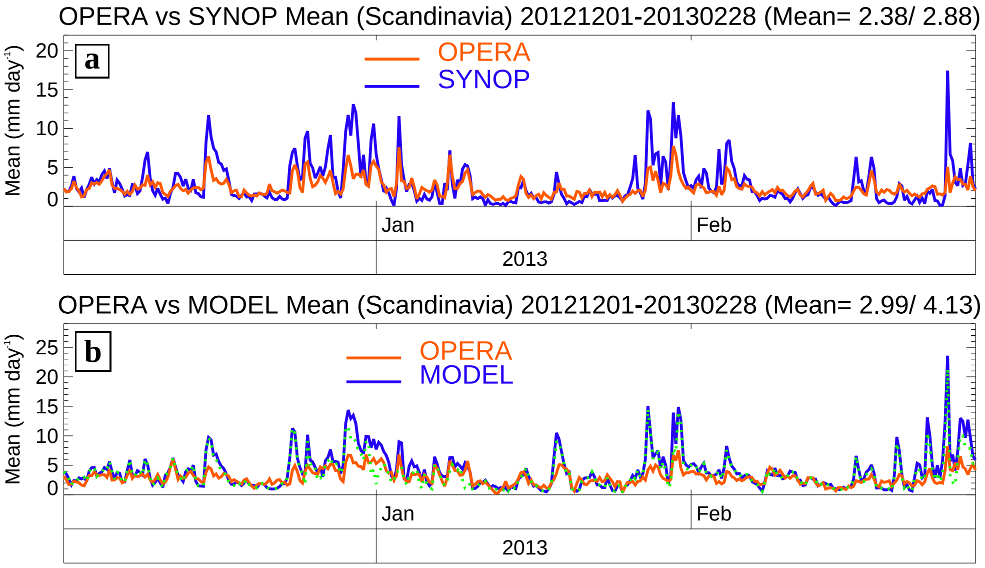

Figure 6: Same as in Fig. 5, but after the recomputation of precipitation rates using the Z-R relationship proposed by Saltikoff et al. (2010) for snowfall conditions rather than ODYSSEY's standard Marshall-Palmer formula.

peak values around 0.6 during both summers of 2012 and 2013, implying a systematic overestimation of the occurrence of rain rates above 3 mm day^{-1} in ODYSSEY composites.

Figure 7.c-d highlights the poor quality of ODYSSEY composites over southeastern Europe, with low ETS values, usually well below 0.3, and high FAR values between 0.4 and 0.85. This confirms the results of sections 3.1 and 3.2, for which a tentative explanation was the lack of treatment for specific S-band artefacts in ODYSSEY preprocessing. Over BeNeLux and the Iberian Peninsula, ETS and FAR exhibit values that fluctuate between 0.2 and 0.60. ETS value over the Iberian Peninsula tends to be higher (i.e. better) in spring and early autumn, while it is minimum in the summer, with a corresponding increase (i.e. degradation) of FAR. This summertime degradation over this region might be due to the enhanced variability of precipitation, which is mainly of convective type.

Figure 7.e points towards the existence of a seasonal cycle in the quality of ODYSSEY composites over Scandinavia, the Alps and Poland, with a clear minimum of ETS (down to 0.2) in the winter and a maximum (between 0.4 and 0.6) during the warm season. The Alps region is characterized by relatively low ETS values throughout the year, as a result of the many issues related to the use of radar data over mountainous terrain. Figure 7.f has been selected because it nicely illustrates the large uncertainty in ODYSSEY composites but also in SYNOP rain gauges when snowfall dominates, i.e. from December to March. This is particularly obvious for Scandinavia and Poland with FAR reaching 0.8, which indicates that precipitation rates above 10 mm day^{-1} occur much more frequently in ODYSSEY composites then in SYNOP gauge observations. As mentioned earlier, possible explanations could be the use of a Z-R relationship that is not valid for snow in ODYSSEY composites but also the effect of rain gauge undercatch in snowfall situations. The latter explanation is supported by the fact that FAR values relative to the ECMWF model do not show a similar increase in winter (not shown).

4 Remaining issues

This section will document two types of outstanding issues that were identified during the monitoring of ODYSSEY composites.

4.1 Ground-clutter contamination

Some contamination of composites by unfiltered ground-clutter was found over the Netherlands in early spring 2013, which led to spuriously large values of persistent and stationary precipitation, particularly obvious between 19 March and 31 March 2013. These can account for the sudden rise of NMB values and the drop in correlation seen over BeNeLux (yellow curve) in panels (e) and (f) of Figs. 2 and 3. Figure 8 displays the ODYSSEY composites valid at 1200 UTC 25 March 2013 and 1200 UTC 29 March 2013 over the Netherlands. Unrealistic stationary large precipitation values associated to ground-clutter can easily be identified in the vicinity of the Dutch radars at Den Helder (4.79°E, 52.95°N) and De Bilt (5.18°E, 52.10°N) (black triangles).

In the future, it is crucial that such spurious precipitation signals be completely eliminated from the composites, otherwise their effect could be disastrous for model validation, let alone data assimilation. This example also advocates the constant monitoring of ODYSSEY composites against other datasets, so that occasional deficiencies can be quickly detected and corrected. This sort of approach has been successfully applied for many years at ECMWF, for instance, to identify problems in satellite instrumentation by simply following the time evolution of model$-$observation mean departures in quasi-real time (e.g.

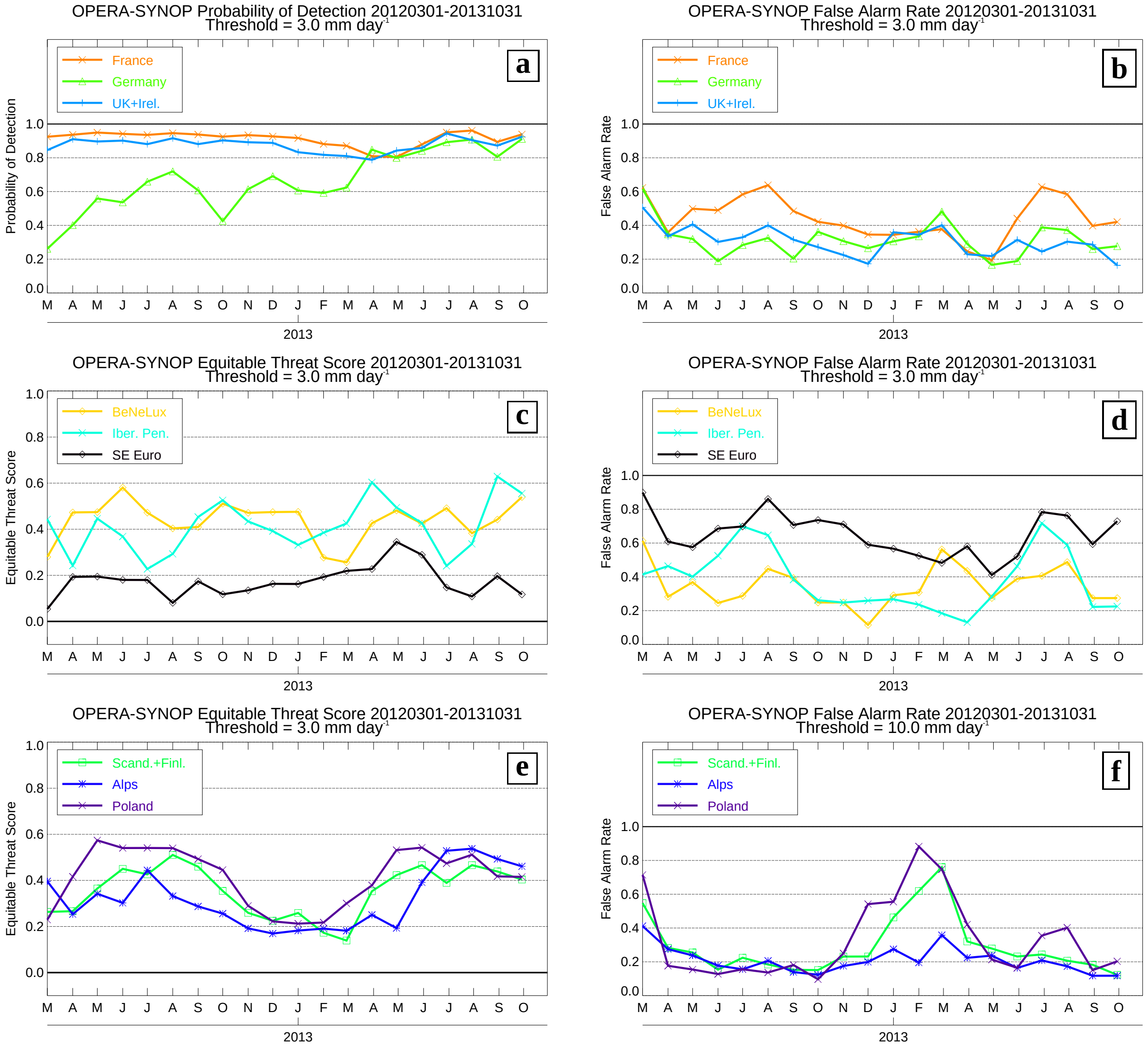

Figure 7: Time series of threat scores over various regions, as indicated in the legend and title of each panel. The precipitation threshold used to compute the scores is 3 mm day^{-1}, except in panel (f) where it was set to 10 mm day^{-1}. Months along the x-axis run from March 2012 to October 2013. The mathematical definition of threat scores can be found in Appendix 2.

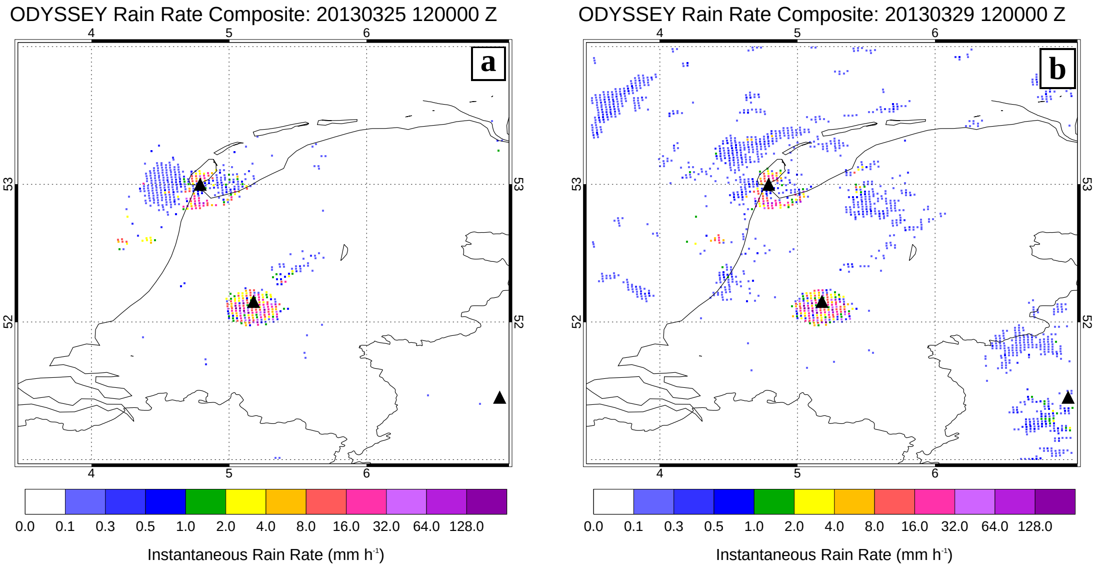

Figure 8: Precipitation rates from ODYSSEY composites over the Netherlands at 1200 UTC on (a) 25 March 2013 and (b) 29 March 2013. Black triangles indicate weather radar locations.

Geer *et al.* 2010).

4.2 Spurious precipitation patterns

Other unrealistic precipitation patterns were also detected in some ODYSSEY composites over eastern Europe. Figures 9 and 10 evidence two such patterns at 1700 UTC 20 May 2013 over Romania and at 1400 UTC 28 August 2013 over Slovakia. The first case in Fig. 9.a seems to originate from the erroneous superimposition of several radars during the generation of the precipitation composite. Figure 9.b shows that the reflectivity composite does not exhibit the same patterns, in good agreement with the corresponding Meteosat-10 10.8 μm image (Fig. 9.c). The second case in Fig. 10 is likely due to some interference with other local microwave emissions at the same wavelength as the nearby weather radar (Huuskonen *et al.* 2014). Note that in the interference case, the strange patterns are found in both the rain and the reflectivity composites. The interference problem is particularly frequent over eastern European countries, and will hopefully be solved via the enforcement of stricter frequency band restrictions. Again, it is worth stressing how harmful such erroneous precipitation patterns could be if carelessly included in a data assimilation system.

5 Conclusions

Six-hourly precipitation accumulations from ODYSSEY European radar composites have been compared to independent data from SYNOP rain gauge measurements and ECMWF short-range forecasts from March 2012 to October 2013. First, statistics computed against SYNOP rain gauges and the ECMWF model are usually consistent, which may give confidence in the existence of genuine biases in ODYSSEY composites. Secondly, statistical results indicate that the best agreement between ODYSSEY and the two other datasets can be found over Germany, the British Isles and France, with small mean biases and good threat score values. In fact, a substantial reduction of the mean bias in ODYSSEY data

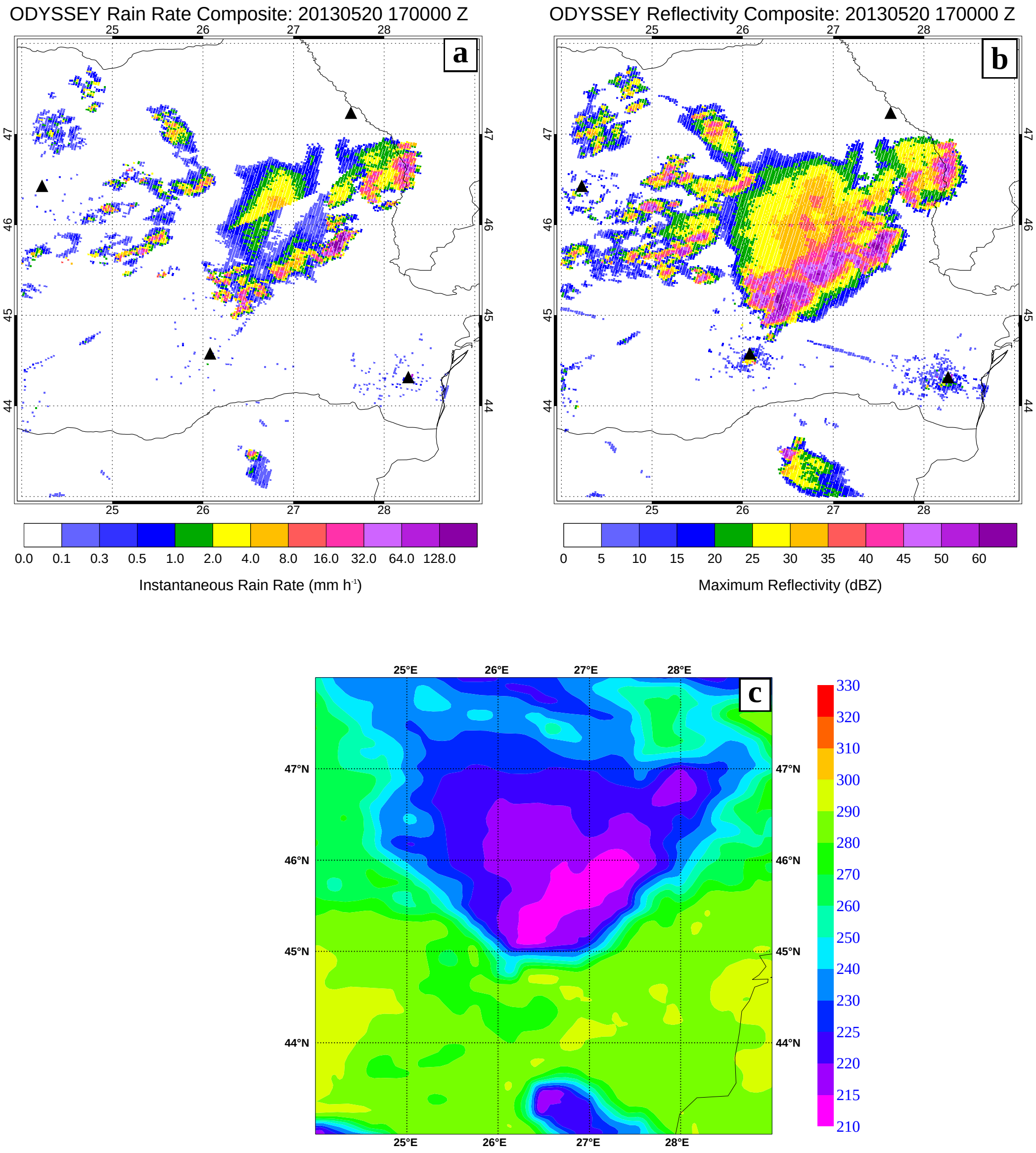

Figure 9: Example of spurious precipitation patterns in ODYSSEY rain composites at 1700 UTC 20 May 2013 over Romania (panel (a)). Panels (b) and (c) show the corresponding reflectivity composite and Meteosat-10 10.8 μm brightness temperatures, respectively. Black triangles in panels (a) and (b) indicate weather radar locations.

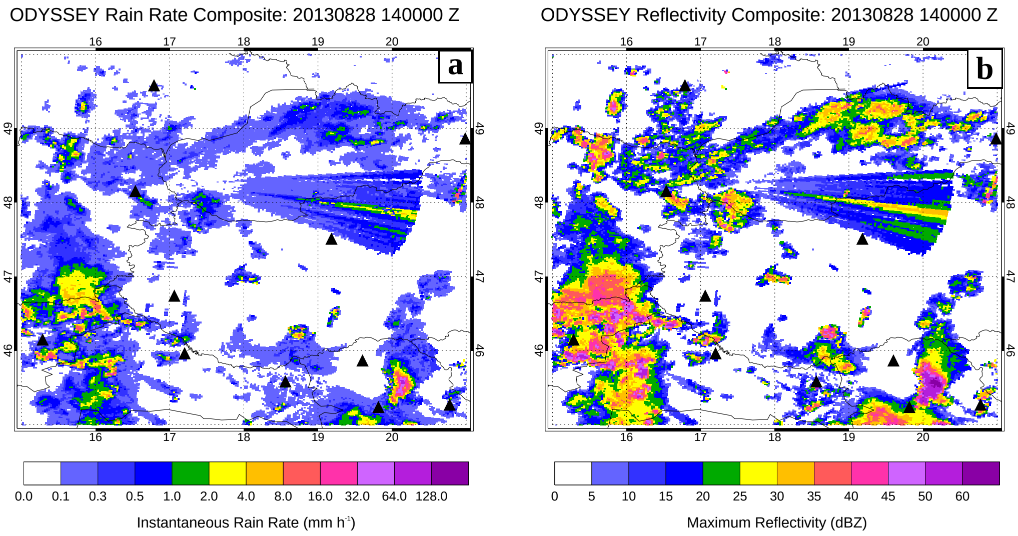

Figure 10: Example of interference patterns in ODYSSEY composites at 1400 UTC 28 August 2013 over Slovakia present in both (a) rain and (b) reflectivity composites. Black triangles indicate weather radar locations.

occurred over France and Germany at the end of 2012. Poland and Scandinavian countries also exhibit a rather good agreement with the two other datasets, but only in the absence of snowfall. In the wintertime, ODYSSEY systematically underestimates precipitation compared to both SYNOP gauges and ECMWF model. The single Z-R relationship currently used to produce the precipitation composites is clearly not suitable for snowfall conditions. Therefore, the inclusion of some dependence on precipitation types (e.g. convective/stratiform, rain/snow) would certainly be strongly desirable. The performance of ODYSSEY over the BeNeLux region was also rather good over the whole period, except in spring 2013, when the statistics were degraded because unscreened ground-clutter appeared around two Dutch radars for several weeks in a row. Over the Iberian Peninsula, a strong underestimation occurs during the rainy autumn and winter seasons, while threat scores seem degraded during summer (however most of the region usually receives very little precipitation in this season). The Alps as well as other mountainous areas suffer from a strong systematic underestimation of precipitation in ODYSSEY composites and from low correlation and ETS values with respect to SYNOP gauges and ECMWF model. This is not surprising given the multiple challenges imposed by radar beam blockage, precipitation enhancement effects, the occurrence of snowfall during the long cold season and the advent of convective events in spring and summer (high-spatial variability). However, the performance of ODYSSEY over the Alps might be improved, should data from Switzerland, Austria and Italy be included in the composites. Finally, poor statistical results are also obtained over southeastern Europe, which might result from the lack of treatment for specific S-band artefacts in the compositing process (although this remains to be confirmed).

Repeating this comparison exercise for hourly instead of six-hourly precipitation accumulations would be very interesting. However, while operational model outputs are now routinely archived every hour, most SYNOP rain gauge observations available from the GTS still come as 6-hourly accumulations, despite the widespread automation of most instruments. This is regrettable since hourly rain gauge observations would allow some further validation of model outputs, for instance in terms of the diurnal cycle of convection (Bechtold *et al.* 2014).

Before ODYSSEY composites can be operationally used in data assimilation, their overall quality should first be improved to a level similar to that of NCEP Stage IV composites over the United States, even though these two datasets may not be directly comparable because NCEP Stage IV composites unlike ODYSSEY also include rain gauge data. The statistics obtained here suggest that any first attempt to assimilate ODYSSEY composites in the ECMWF 4D-Var system should be focused on western European countries during the warm season and away from mountainous regions. Besides, the separate flagging of pixels affected by ground clutter contamination, by microwave interferences, by snowfall or hail, and by the lack of radar sensitivity (non-detection) would be highly desirable. It also seems crucial to eliminate the occurrence of the strange patterns apparently associated with the superimposition of individual radars (see Fig. 9). As a consequence, ongoing efforts by OPERA to improve the quality of their precipitation composites in terms of both the reduction of errors and the inclusion of quality information, essential for data assimilation purposes, are strongly encouraged by ECMWF.

Acknowledgements

I am very grateful to Dr Elena Saltikoff (FMI) for kindly providing ODYSSEY rain composites in HDF5 format from FMI's archive as well as for her helpful suggestions during this work. I would also like to thank Anton Beljaars (ECMWF) for his comments on the manuscript.

APPENDIX 1

List of acronyms used in the text

ECMWF = European Centre for Medium-range Weather Forecasts
EUMETNET = EUropean METeorological services NETwork
FMI = Finnish Meteorological Institute
NCEP = National Centers for Environmental Prediction (U.S.A.)
NEXRAD = NEXt-generation RADars (U.S.A.)
OPERA = Operational Program for the Exchange of weather RAdar information

APPENDIX 2

Precipitation scores used in this study are the Equitable Threat Score (ETS), the Probability Of Detection (POD) and the False Alarm Rate (FAR), which are defined as

$$ETS = \frac{H - H_e}{H + M + F - H_e} \quad (1)$$

$$POD = \frac{H}{H + M} \quad (2)$$

$$FAR = \frac{F}{H + F} \quad (3)$$

where H is the number of correct hits, M is the number of misses and F is the number of false alarms. H_e is the number of correct hits purely due to random chance and is computed as

$$H_e = \frac{(H + F)(H + M)}{N} \quad (4)$$

where N is the sample size.

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