TECHNICAL MEMORANDUM

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Comparison of OPERA precipitation radar composites to CMORPH, SYNOP and ECMWF model data

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Abstract

The Pilot Data Hub of the Operational Programme for the Exchange of weather RAdar information (OPERA) across Europe is operated by the Met Office in Exeter (UK) and produces 4-km resolution European composites of radar precipitation rates every 15 minutes. The aim of this study was to obtain a preliminary assessment of the quality of OPERA precipitation estimates, for the prospect of their use in model validation or even radar data assimilation. OPERA data have been compared to three independent precipitation datasets: CMORPH (satellite based), SYNOP rain gauges and short-range forecasts obtained with ECMWF's operational model. Statistics in the form of mean maps, time series and skill scores over various regions in Europe have been computed for two months in spring 2008 and for precipitation accumulations over 6 hours.

OPERA precipitation rates exhibit systematic and consistent differences with respect to the three other datasets. These differences seem to be dependent on geographical location: OPERA tends to give less precipitation over most of Europe, except over France and the North Sea where a significant excess is found. Overall, the best agreement of OPERA with the other datasets is obtained over Germany, Belgium, the Netherlands, and to a lesser extent over France and Poland. Less satisfactory results are found over Scandinavia while a particularly unrealistic excess appears over the North Sea and a strong deficit is evidenced over the UK. The reasons for these latter departures could be clarified in the course of this study. The interpretation of other differences will require interaction with the OPERA community.

1 Introduction

Ground-based radars are already widely used for various meteorological applications such as nowcasting, hydrological forecasting (flood warnings), the study of hydrometeors inside precipitating systems, the validation of numerical weather prediction (NWP) outputs and even data assimilation.

The measurement principle is simple: the radar transmitter emits via a rotating antenna a series of electromagnetic pulses with a well-defined power, which propagate through the atmosphere. A fraction of each pulse is backscattered by particles (e.g. hydrometeors, cloud particles, aerosols, or even insects and birds) along its path and the corresponding signal is collected by the antenna and its power analyzed by the radar receiver. The reflectivity factor, Z, which is proportional to the ratio of the backscattered to the emitted power, together with the accurate measurement of the elapsed time between emission and reception, permits the quantification and precise localization of the scatterers along the radar beam. Since part of the emitted power is absorbed by scatterers, the radar pulse gets attenuated as it propagates away from the antenna. The size of scatterers that can be detected by a given radar as well as the magnitude of the attenuation mainly depend on the emitted pulse wavelength. For instance, S-band (8-15 cm wavelength) and C-band radars (4-8 cm) are mainly sensitive to larger hydrometeors (raindrops, snow flakes, hailstones) but not to smaller cloud particles, and are therefore labelled as precipitation radars. One of the main advantages of ground-based radars compared to rain gauges is their ability to deliver 360° azimuthal scans of the atmosphere at horizontal ranges of up to 200 km and with horizontal resolution of a few kilometers (degrading with range). Furthermore, when multiple beam elevations are used, 3D images of the atmosphere can be obtained within a few minutes. Radars with Doppler capabilities can also provide information on the radial component of the wind (isolated radar) or even on the full 3D wind field (several overlapping radars). Radars equipped with dual polarization can help identify the phase of hydrometeors (rain, snow, hail) as well as their characteristics (shape, size).

Despite the appeal of their extended and high-resolution spatial coverage, various errors can occasionally degrade the accuracy of weather radar measurements. Major sources of errors include:

- bad radar calibration,
- tilting and widening of beam with range,

- non-uniform filling of beam with scatterers,
- beam crossing the melting layer (bright band with sharp gradients of reflectivity)
- anomalous propagation (super-refractive/ducting conditions),
- beam blocking by large obstacles (orography) and ground clutter (echoes returned from ground itself, buildings, wind turbines,...),
- attenuation by scatterers (decreases with wavelength),
- echoes due to non-meteorological airborne scatterers (birds, insects,...),
- invalid Rayleigh approximation when hydrometeor size is not small compared to radar wavelength,
- uncertainties in Z-precipitation relationship, particle type and size distribution,
- orographic seeder-feeder precipitation enhancement,
- attenuation by water or dirt on radome,
- post-processing (e.g. averaging, compositing).

A detailed discussion of weather radar errors can be found in Šálek *et al.* (2004).

Given the strong impact of precipitation on human activities and despite potential errors listed above, it is not so surprising that networks of ground-based precipitation radars have already been installed in the U.S.A, Europe, Japan, Australia, and more recently China. For many years now, data from the network of NEXt generation RADars (NEXRAD; S-band) have been combined with rain gauge measurements to produce quasi real-time precipitation analyses over the continental USA (Fulton *et al.* 1998). Similarly, the Operational Programme for the Exchange of weather RAdar information (OPERA; Holleman 2008), in the framework of the NETwork of EUropean METeorological services (EUMETNET), has taken up the challenge of combining ground-based radar information coming from 29 European countries into continental-scale precipitation composites. At present, OPERA composites gather data from more than 150 radars, mostly C-band.

Even though it should be stressed that the current version of the OPERA dataset is clearly intended to provide qualitative rather than accurate quantitative precipitation estimates, it seems interesting to establish a preliminary comparison of OPERA precipitation composites over Europe with three independent data sources. The first one is the satellite-based Climate Prediction Center MORPhing (CMORPH) rain rate dataset, the second consists of synoptic station (SYNOP) rain gauge measurements, while the third one involves precipitation fields from ECMWF's operational archive of short-range forecasts.

Section 2 describes in more detail the four datasets used in this study. The method for mapping OPERA data to each of the other dataset is presented in section 3, while the results of the comparison are detailed in section 4. Summary and conclusions are given in section 5.

2 Description of the precipitation datasets

2.1 OPERA composites

The OPERA Pilot Data Hub (Holleman 2008) is based at the Met Office in Exeter (UK) and provides 15-mn precipitation rates data obtained from about 150 operational ground-based weather radars available over the European continent. These European composites are produced in quasi-real time (within 30 minutes) by combining the data received from each individual countries, following the method described in Harrison *et* *al.* (2006). It should be noted that countries may send either single radar data or already processed national composites to the OPERA Pilot Hub, which might result in inhomogeneities in the final European composites. At the level of the Data Hub, quality control procedures are applied to single site data to identify and remove ground clutter, anomalous propagation and occultation occurrences, as well as to correct for vertical profile effects associated to bright band occurrence, resolution degradation with range and orographic enhancement of precipitation. On the other hand, no particular quality control is performed on the national composites other than the original one. The final OPERA composites are provided in BUFR format and on a Lambert's azimuthal equal area projection (tangent point 55°N and 10°E), with a pixel size of 4 km.

2.2 CMORPH

The CMORPH precipitation dataset is produced by combining measurements from passive microwave (PMW) instruments (SSM/I, TMI, AMSR-E and AMSU-B) on board various polar orbiting satellites (DMSP, TRMM, AQUA and NOAA, respectively) and by propagating this information in time between available orbits using motion vectors derived from geostationary satellite infrared (IR) data (Meteosat, GOES, GMS). A list of satellite acronyms is given in Appendix 1. Full detail on the CMORPH method can be found in Joyce *et al.* (2004). The technique combines the ability of PMW imagery to provide reasonably accurate retrievals of rain rates over polar orbits with limited coverage in space and time with the high temporal and spatial sampling of geostationary IR observations. The final CMORPH data consists of rain rate maps at a 30-min time frequency and with a horizontal resolution of 8 km, but these data are unfortunately only accessible for the previous four days. The actual CMORPH data that were retrieved from http://www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html are 3-hourly averaged precipitation rates on a 0.25° regular grid, between 60°S and 60°N. The global intercomparison performed by Dai *et al.* (2007) indicated that CMORPH is one of the best satellite precipitation retrieval algorithms over low- and mid-latitudes when compared to both weather reports and to the Global Precipitation Climatology Project (GPCP) dataset in terms of precipitation amounts, frequency and timing on both seasonal and daily time scales. In their two-year intercomparison of satellite surface rain retrieval algorithms and numerical models, Ebert *et al.* (2007) showed the good performance of CMORPH, especially in convective rain. However, since PMW precipitation estimates over land are solely based on the scattering by precipitating ice particles in the 85 GHz channel, it is difficult to distinguish between frozen precipitation and snow-covered surfaces. The accuracy of the CMORPH product is therefore expected to be degraded in snowy situations over land areas.

2.3 SYNOP

Six-hourly precipitation accumulations measured by rain gauges at SYNOP stations over Europe are routinely accessible via the Global Telecommunication System (GTS). Besides measurement errors in case of snowfall or strong winds, rain gauge observations suffer from their limited spatial representativeness (typically a few km^2), especially in convective situations and mountainous regions. Therefore, it may seem questionable to use them for comparison to other coarser resolution precipitation fields. For instance, the current ECMWF model grid mesh area (roughly 625 km^2) makes it difficult to compare model precipitation to individual rain gauge data, despite the smoothing caused by the accumulation in time. However, representativeness might be less of an issue when comparing rain gauges to co-located OPERA 4-km radar pixels.

2.4 ECMWF forecast model

Although the accuracy of model precipitation forecasts is known to be far from perfect, even at short ranges, it seems appealing to compare OPERA data with outputs from the ECMWF model. Model 6-hourly precipitation accumulations employed in this study are obtained from short-range forecasts (up to 24 hours) run with the operational ECMWF model at T799 spectral truncation (roughly 25 km resolution) and with 91 vertical levels. The ECMWF forecast model is a global semi-Lagrangian spectral model that include parameterizations of vertical diffusion, surface processes, gravity wave drag, radiation, convection and large-scale condensation. During model integration, temperature, specific humidity, vorticity, divergence, surface pressure, cloud liquid water, cloud ice, cloud fraction and ozone concentration are treated as prognostic variables. More information about the ECMWF forecasting system can be found in ECMWF (2006) . In the following, ECMWF forecast data will be referred to as ECMWF, simply.

3 Comparison methodology

Special care has been taken throughout the comparison to make sure that OPERA data and each other dataset had a similar spatial and temporal representativeness. In the case of SYNOP stations, the closest OPERA 4-km pixel has been identified and no spatial averaging has been performed to account for the very localized representativeness of rain gauge measurements, as underlined in section 2.3. For the comparison to CMORPH and ECMWF, 4-km resolution OPERA data have been averaged onto the CMORPH 0.25° regular grid and onto the model's T799 reduced Gaussian grid, respectively.

Timewise, statistical computations have been focused on precipitation accumulations over 6 hours. The minimum period of 6 hours corresponds to the shortest accumulation time common to all four datasets used in this study. For instance, the shortest accumulation period available from the ECMWF operational archive and with CMORPH data is 3 hours, but 6 hours for SYNOP station measurements, while OPERA data are produced every 15 minutes. A simple time averaging of precipitation amounts was therefore applied to match the target accumulation period of 6 hours, when needed.

The comparison of OPERA data with the three other datasets has been carried out for the period between 10 April and 8 June 2008 (60 days). The first date corresponds to the day when the automatic archiving of OPERA BUFR 15-mn composites began at ECMWF. Before this date, only images were being temporarily transferred from the Met Office for a running period of only 24 hours. In this study, the limitation to a 60-day period achieves a compromise between the computational cost of data processing and the significance of statistical results. For instance, processing of the 96 daily OPERA files involved BUFR decoding, conversion from cartesian to geographical coordinates, spatial averaging (w.r.t. CMORPH and model) or co-location (w.r.t. SYNOP) and time accumulation. Finally, it should be emphasized that the selected period in spring is meteorologically interesting since it combines various types of precipitation and weather regimes (stratiform and convective; rain and snow).

4 Results

It should be noted that, for convenience purposes, all precipitation rates and derived statistics will be expressed in mm day^{-1}, regardless of their period of accumulation. One should also emphasize that the CMORPH and SYNOP data (and even less the ECMWF model data) are in no way regarded as the truth here. However, the fact that OPERA systematically and significantly differs from all three other datasets is expected to betray a

Region	Area (km^2)	Mean number of SYNOP rain gauges per 6 hours
Europe	/	824
Alps	228172	98
CentEuro	591217	70
France SW	578754	99
FrBeNeLux	210617	63
Germany	404898	115
Poland	445949	36
Scandinavia	2583520	123
Spain-Port	915884	55
UK-Ireland	925585	105
North Sea	161699	0

TABLE 1: Area and mean number of SYNOP rain gauges per 6h period over each subdomain shown in Fig. 4.

genuine inaccuracy in OPERA.

4.1 Mean differences, RMS differences and correlations

Figures 1-3 display maps of statistics computed over two months of OPERA versus CMORPH, SYNOP and ECMWF, respectively, in terms of precipitation amounts accumulated over 6 hours. Mean precipitation fields as well as mean difference (Diff) and root-mean-square differences (RMSD) are shown. Here, RMSD values have been calculated from the precipitation time series at each co-located point. Note that the mean OPERA precipitation in panel (a) of Fig. 1-3 depends on the other dataset involved in the comparison, due to the differences in the spatial processing as highlighted in section 3. In addition to maps, mean statistics are also presented for various geographical subdomains shown in Fig. 4 and Table 1 summarizes their respective area and the mean number of SYNOP rain gauges available inside each of them. Their shape was either defined to approximately match national boundaries or to highlight systematic differences that appear in Fig. 1-3. Table 2 summarizes the two-month mean statistics of 6h-accumulated precipitation over each subdomains as well as over the whole of Europe. Besides the mean precipitation for each dataset (Mean), these statistics also include mean OPERA-dataset Diff, RMSD and spatial correlations. To obtain the two latter statistical quantities, RMSD and correlations between 6-hourly precipitation maps have been averaged over the two-month period. In Table 2, mean correlations have been computed in two ways: the first option is obtained regardless of subdomain-averaged precipitation (P) amount while the second (value in parentheses) only includes time slots for which P exceeds 0.5 mm day^{-1}. With the second option, correlations are expected to be higher since correlations between different observation types are usually weaker for light precipitation events. Figure 5 provides a visual summary of the latter correlations (option 2) against mean relative differences between OPERA and each dataset for each subdomain shown in Fig. 4.

Particularly striking similarities can be found in Fig. 1-3 in terms of mean OPERA− dataset differences. For instance, OPERA precipitation rates are higher (positive differences) than in any of the three other datasets over subdomain ”France SW”, with maximum departures over Charentes, Massif Central and the Rhône delta. Table 2 indicates that over ”France SW”, OPERA exceeds CMORPH, SYNOP and ECMWF by 1.94, 1.65 and 0.31 mm day^{-1} (i.e. 79, 47 and 8%), respectively. The fact that the same signal is seen with respect to all datasets, in particular CMORPH and SYNOP, suggests that OPERA tends to systematically overestimate precipitation amounts throughout the two-month period. This will be confirmed by the examination of precipitation time series in subsection 4.2.

An opposite behaviour is found over regions ”Spain-Port” and ”Poland” where OPERA precipitation is usually in deficit by roughly 60% with respect to SYNOP and ECMWF, slightly less compared to CMORPH. Similarly,

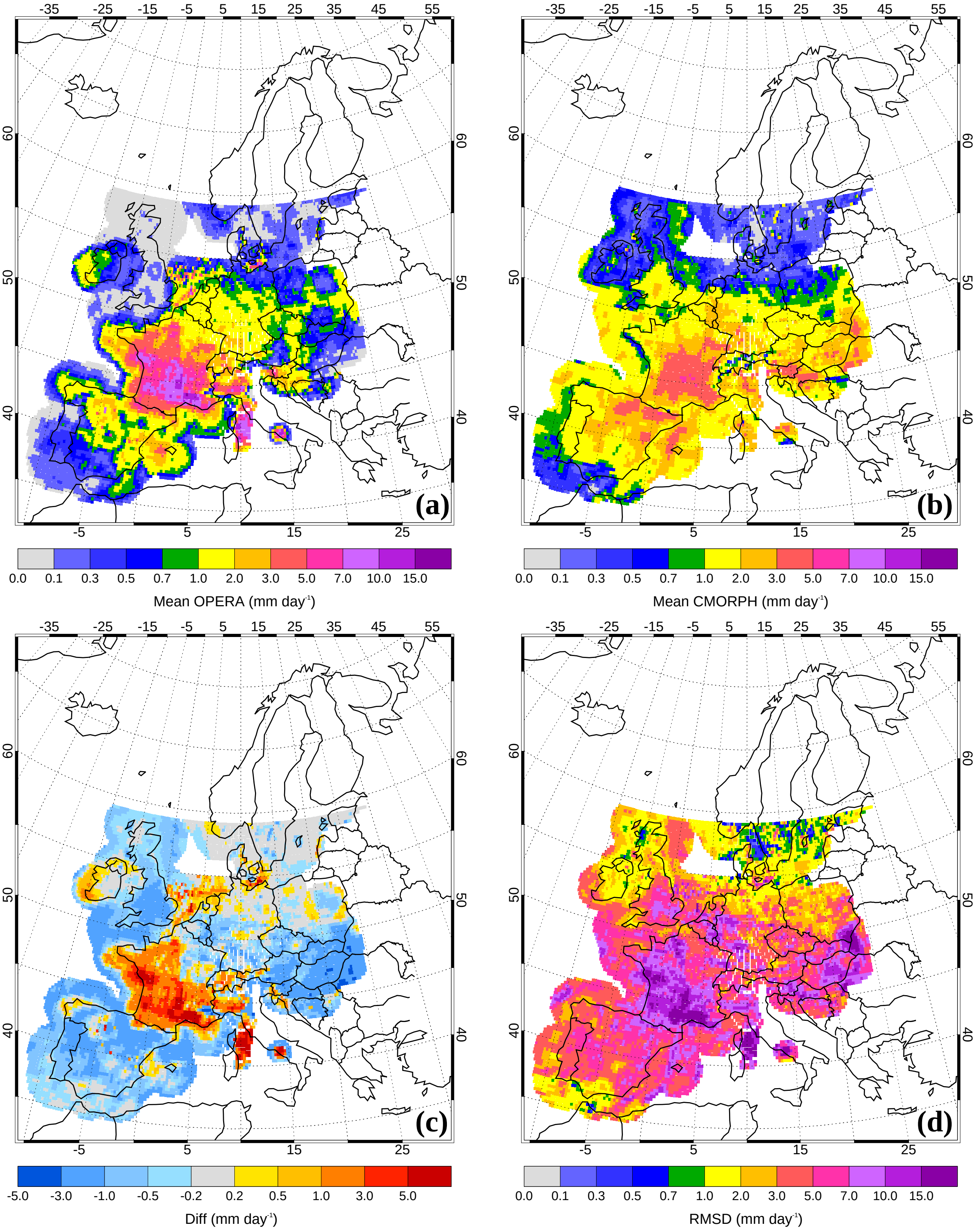


FIGURE 1: OPERA radar composite versus CMORPH 6h-accumulated precipitation: (a) mean OPERA, (b) mean CMORPH, (c) mean OPERA−CMORPH differences and (d) mean OPERA−CMORPH RMS differences, computed over the period between 10 April and 8 June 2008 (60 days). All fields are expressed in mm day^{-1}. White regions correspond to missing data.

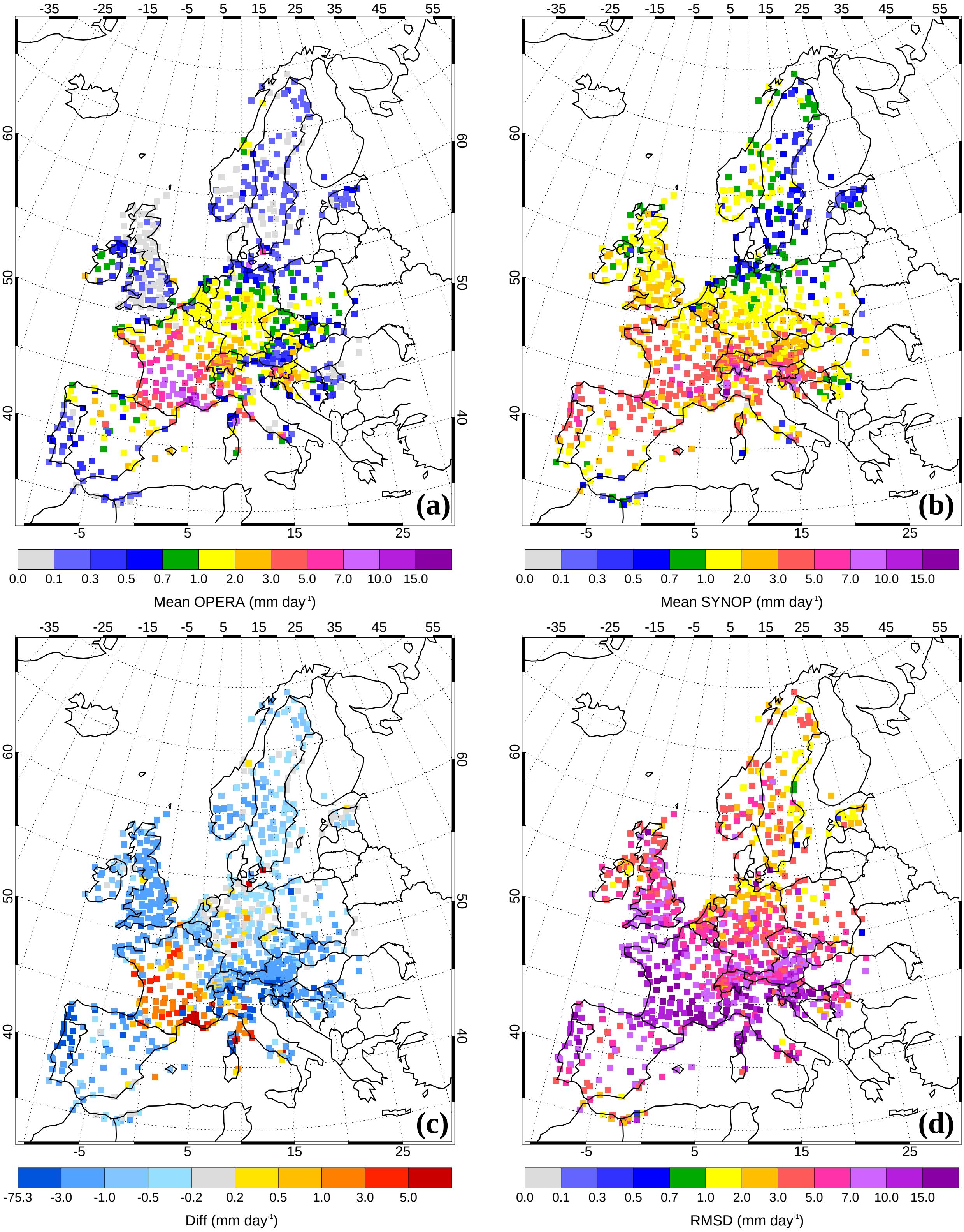


FIGURE 2: Same as in Fig. 1, but for OPERA versus SYNOP rain gauges.

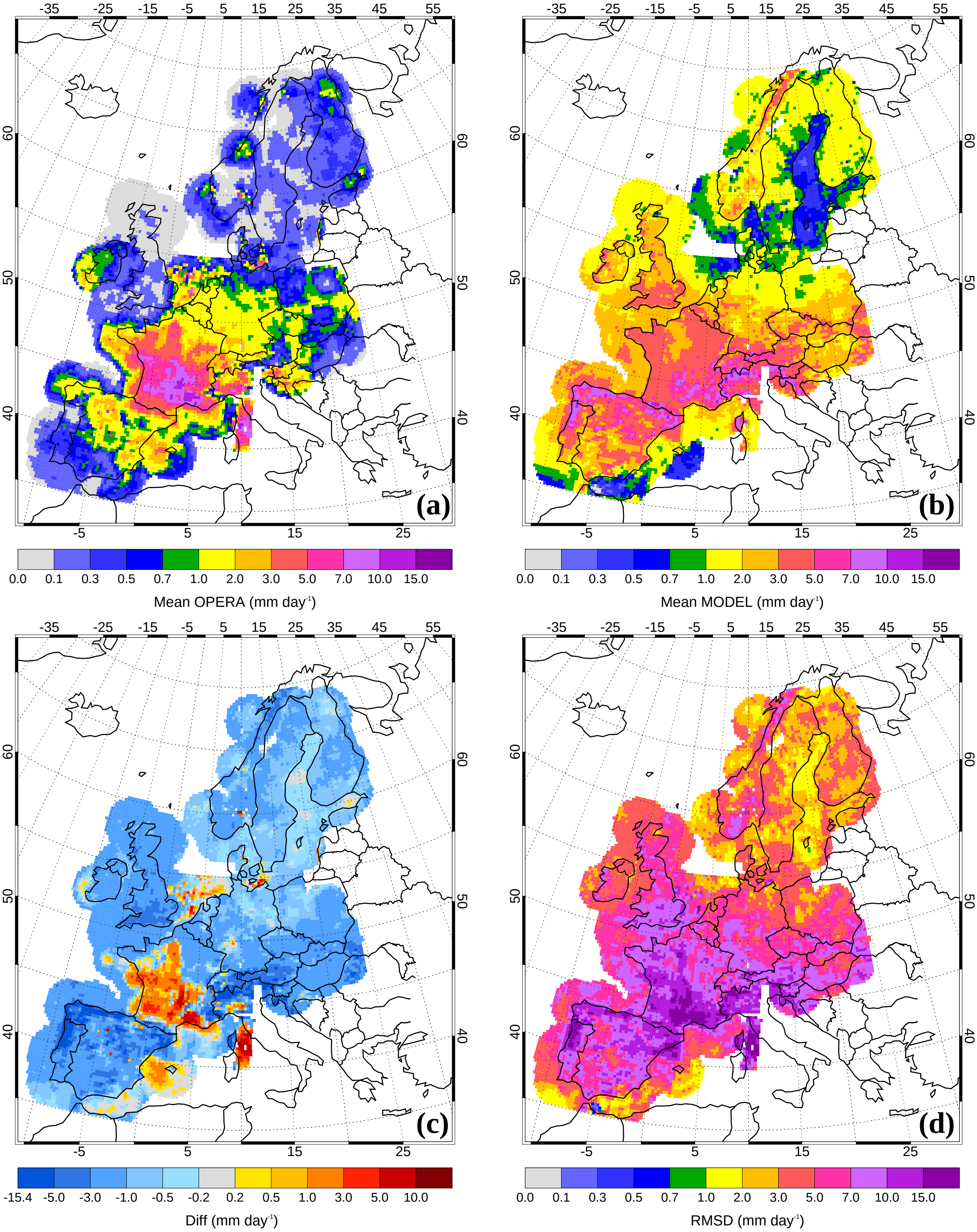


FIGURE 3: Same as in Fig. 1, but for OPERA versus ECMWF model data.

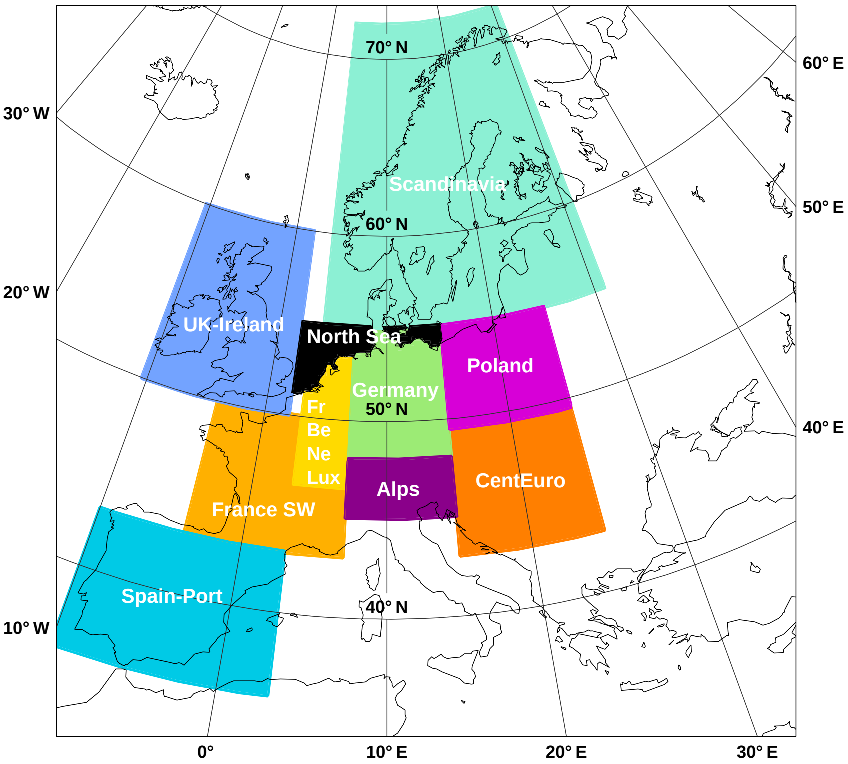


FIGURE 4: Geographical subdomains for statistical computations.

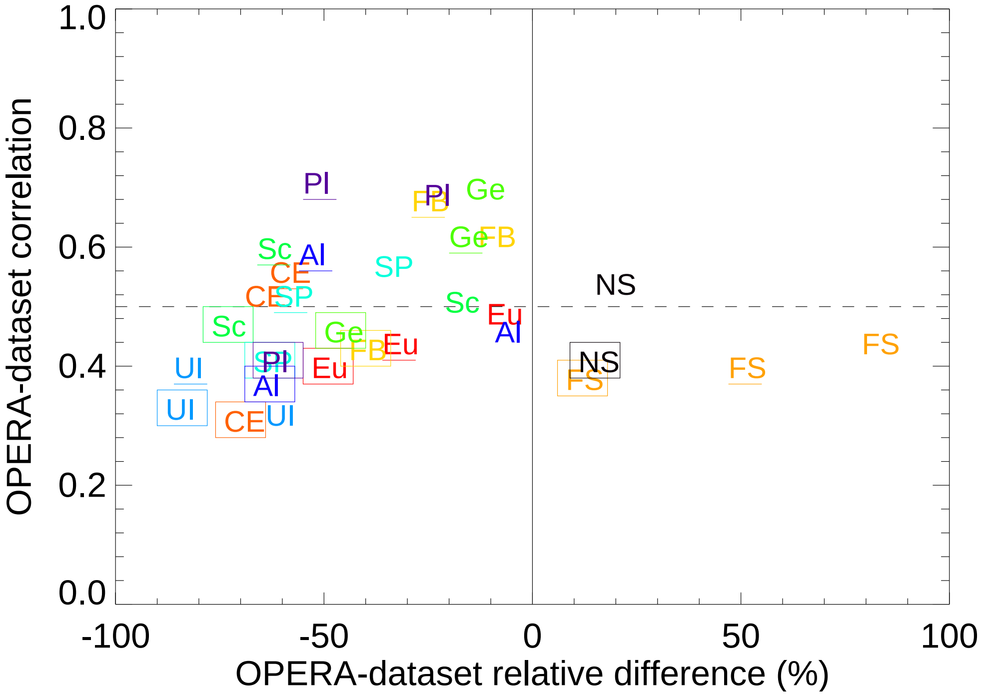


FIGURE 5: Summary plot showing OPERA-dataset mean correlation versus OPERA−dataset mean relative difference (in %) over each subdomain (labels; see Table 2) and with respect to CMORPH (plain labels), SYNOP (underlined labels) and ECMWF (boxed labels).

Region	Statistics	OPERA	CMORPH	OPERA	SYNOP	OPERA	ECMWF
Europe (EU)	Mean	1.21	1.36	1.49	2.32	1.09	2.34
	Diff	**-0.16** *(-12%)*		**-0.83** *(-36%)*		**-1.25** *(-53%)*	
	RMSD	5.40		9.27		6.55	
	Correl	0.44 (0.47)		0.40 (0.42)		0.37 (0.38)	
Alps (Al)	Mean	1.83	2.01	1.96	4.43	1.88	5.60
	Diff	**-0.18** *(-9%)*		**-2.47** *(-56%)*		**-3.73** *(-67%)*	
	RMSD	4.89		8.45		8.44	
	Correl	0.29 (0.44)		0.49 (0.57)		0.28 (0.35)	
CentEuro (CE)	Mean	0.69	2.25	1.05	2.85	0.74	2.89
	Diff	**-1.56** *(-69%)*		**-1.80** *(-63%)*		**-2.15** *(-74%)*	
	RMSD	4.86		6.44		5.27	
	Correl	0.32 (0.50)		0.43 (0.54)		0.22 (0.29)	
France SW (FS)	Mean	4.39	2.45	5.16	3.50	4.42	4.11
	Diff	1.94 *(79%)*		1.65 *(47%)*		0.31 *(8%)*	
	RMSD	8.31		11.29		9.02	
	Correl	0.31 (0.42)		0.32 (0.38)		0.31 (0.36)	
FrBeNeLux (FB)	Mean	1.98	2.27	1.89	2.68	1.97	3.50
	Diff	**-0.29** *(-13%)*		**-0.79** *(-29%)*		**-1.53** *(-44%)*	
	RMSD	3.84		4.72		5.06	
	Correl	0.38 (0.60)		0.55 (0.66)		0.29 (0.41)	
Germany (Ge)	Mean	1.06	1.25	1.37	1.71	1.12	2.26
	Diff	**-0.20** *(-16%)*		**-0.34** *(-20%)*		**-1.14** *(-50%)*	
	RMSD	2.78		4.87		4.31	
	Correl	0.45 (0.68)		0.43 (0.60)		0.30 (0.44)	
Poland (Pl)	Mean	0.75	1.01	0.91	2.02	0.75	2.13
	Diff	**-0.26** *(-26%)*		**-1.11** *(-55%)*		**-1.38** *(-65%)*	
	RMSD	2.31		4.19		3.74	
	Correl	0.44 (0.67)		0.52 (0.69)		0.29 (0.39)	
Scandinavia (Sc)	Mean	0.22	0.28	0.28	0.86	0.26	1.15
	Diff	**-0.06** *(-21%)*		**-0.57** *(-66%)*		**-0.89** *(-77%)*	
	RMSD	1.31		2.82		2.90	
	Correl	0.16 (0.49)		0.40 (0.58)		0.29 (0.45)	
Spain-Port (SP)	Mean	1.09	1.76	1.19	3.17	1.07	3.25
	Diff	**-0.67** *(-38%)*		**-1.98** *(-62%)*		**-2.18** *(-67%)*	
	RMSD	3.85		7.03		6.32	
	Correl	0.34 (0.55)		0.44 (0.50)		0.28 (0.39)	
UK-Ireland (UI)	Mean	0.27	0.72	0.28	1.95	0.26	2.06
	Diff	**-0.46** *(-64%)*		**-1.67** *(-86%)*		**-1.81** *(-88%)*	
	RMSD	2.54		5.29		4.67	
	Correl	0.17 (0.30)		0.32 (0.38)		0.22 (0.31)	
North Sea (NS)	Mean	1.23	1.07	-	-	1.35	1.22
	Diff	0.16 *(15%)*		-		0.13 *(11%)*	
	RMSD	3.01		-		3.90	
	Correl	0.31 (0.52)		-		0.16 (0.39)	

TABLE 2: Statistics of OPERA compared with SYNOP, CMORPH and ECMWF model: domain averages of 6h-accumulated precipitation (Mean), OPERA−dataset differences (Diff) and RMS differences (RMSD) and temporal correlations (Correl). Bold font is used for negative mean differences. Mean relative differences (in %) are also indicated in parentheses. All other quantities are in mm day^{-1}, except for correlations. For correlations, each number in parentheses corresponds to the correlation coefficient restricted to 6h time slots with subdomain-averaged precipitation above 0.5 mm day^{-1}.

negative OPERA departures amounting to 63 and 74% of each datasets are found for subdomain ”CentEuro”.

Over region ”UK-Ireland”, OPERA lies dramatically below CMORPH, SYNOP and ECMWF by as much as 64, 86 and 88%, respectively.

Similarly, significant negative departures (about 70% deficit) of OPERA versus SYNOP and ECMWF can be identified over Scandinavia. Here, these lower values in OPERA might be partly explained by the use of a Z-R relationship which is only valid for rain while a significant fraction of the total precipitation falls as snow, as illustrated by the map of snowfall fraction shown in Fig. 6 (as computed from ECMWF 24h operational forecasts). Over Scandinavia, the substantially lower mean precipitation amounts of CMORPH (0.28 mm day^{-1}) compared to SYNOP and ECMWF (resp. 0.86 and 1.15 mm day^{-1}) should be interpreted with caution since precipitation retrievals from PMW instruments are known to be unreliable in snowy situations over land (Joyce *et al.* 2004). One should also note that the CMORPH data coverage is by construction limited to the regions south of 60°N, while SYNOP and ECMWF extend over whole Scandinavia, which should affect statistics.

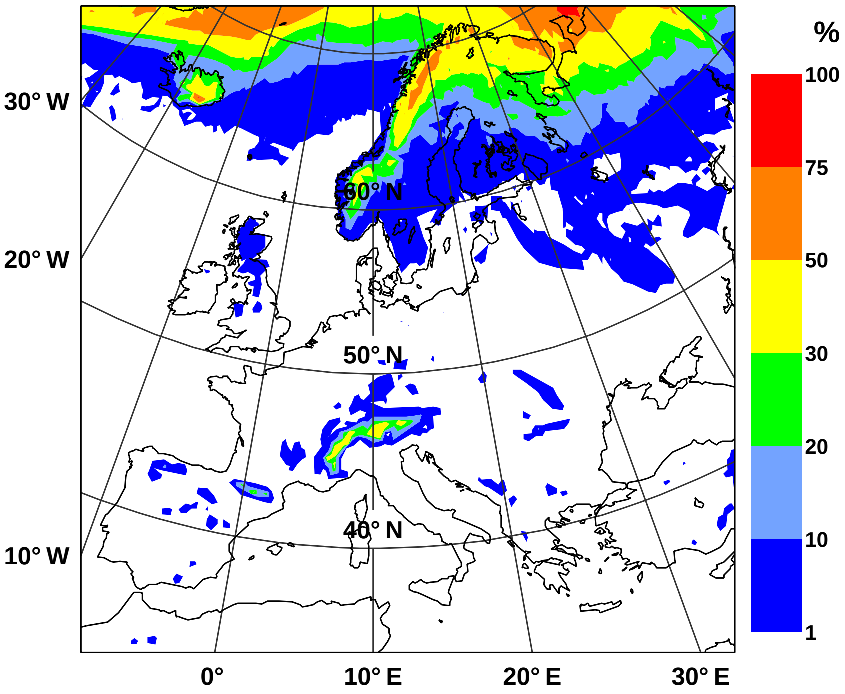


FIGURE 6: Fraction of snowfall in the total precipitation amount as computed from ECMWF model outputs between 10 April and 8 June 2008. Units are in %.

The snow limitation of CMORPH is also likely to apply over the ”Alps” region (only 9% deficit) where snowfall accounts for more than a third of the total precipitation (Fig. 6), while OPERA gives 56% (resp. 67%) less precipitation than SYNOP (resp. ECMWF).

Over ”Germany” and ”FrBeNeLux”, OPERA mean differences with respect to CMORPH and SYNOP are again on the negative side, to a much lesser extent though (between 13 and 29% deficit). On the other hand, compared to ECMWF, the relative deficit in OPERA reaches 44-50% which might indicate that the ECMWF model produces too much precipitation over these two regions over the selected two-month period.

Over the ”North Sea” region, which also encompasses a small portion of the southern Baltic Sea in its definition, Fig. 1 and 3 clearly exhibit positive OPERA departures. Table 2 indicates that on average this excess amounts to 15 and 11% with respect to CMORPH and ECMWF, respectively. This particular signal will be further analyzed in section 4.2.

It is noteworthy that ECMWF mean precipitation amounts shown in Table 2 slightly exceed SYNOP amounts over all regions, but are substantially higher than CMORPH values, even over snow-free areas where CMORPH is expected to be rather accurate. In fact, the rather good agreement between ECMWF and SYNOP should be taken with caution because of the representativeness issue underlined in section 2.3. More confidence should be given to the comparison of ECMWF with CMORPH over snow-free regions since both datasets have similar horizontal resolutions (roughly 25 km). Therefore, the ECMWF model probably overestimates precipitation for forecast ranges shorter than a day.

As far as correlations are concerned, values shown in Table 2 and in Fig. 5 are expectedly lower against ECMWF (below 0.5) than against CMORPH and SYNOP observations (up to 0.7) over most subdomains, especially over ”FrBeNeLux”, ”Germany”, ”Poland”. These correlations are of comparable magnitude to those found in Ebert *et al.* (2007), for instance. The weakest correlations of OPERA with respect to CMORPH and SYNOP that are obtained over ”UK-Ireland” confirm that there is a problem in OPERA composites over this region.

The RMSD values given in Table 2 summarize the contributions of bias, correlation and dataset standard deviations. The relative weakness of the correlations generally found between OPERA and the other datasets lead to RMSD values that are comparable to those of the standard deviation of each datasets (not shown).

4.2 Time series

It is also interesting to consider the time series of precipitation over different regions in order to assess how variable in time or systematic the differences that were evidenced in section 4.1 are. As an example, Fig. 7 displays the 60-day long series of OPERA versus CMORPH 6h-accumulated precipitation over ”Europe”, ”France SW”, ”UK-Ireland” and ”North Sea”.

Figure 7a indicates that over whole ”Europe” there is a rather good agreement through time between OPERA and CMORPH precipitation amounts, except around days 29-31 and 39-48 for which OPERA is up to 50% lower than CMORPH. With respect to SYNOP and ECMWF (not shown), the OPERA deficit is more systematic in time and of larger magnitude, especially with respect to ECMWF, which is now thought to over-predict precipitation at short range (see section 4.1). These findings are consistent with those found in Fig. 2-3 and in Table 2.

Figure 7b suggests that the excess of precipitation in OPERA relative to CMORPH over ”France SW” (see section 4) seems to be mainly due to a large overestimation of the events around days 19-22, 35-39 and 53-54. This remark also applies to the comparison with ECMWF and SYNOP data (not shown).

Over region ”UK-Ireland”, the large deficit of OPERA precipitation compared to CMORPH occurs rather systematically over time (Fig. 7c), except during the first three days of the period. This underestimation is particularly obvious for the heavier rain events around days 46-56. This strong signal is even stronger with respect to SYNOP and ECMWF (not shown).

Interestingly, Fig. 7d shows that over ”North Sea”, several periods are characterized by mean 6-hourly precipitation amounts of several mm day^{-1} in OPERA, while no rain is observed in CMORPH. This is clearly the case for days 18, 24-33 (2-11 May 2008), 43-44 and 60. For these periods, no precipitation is simulated by the ECMWF model either (not shown). The corresponding maps of precipitation averaged over the period 2-11 May 2008 from OPERA and CMORPH (Fig. 8) show that OPERA rainfall occurs exclusively over sea in the ”North Sea” region, while CMORPH (and ECMWF, not shown) are completely precipitation free. As a clue to the reason for these large discrepancies, Fig. 9 displays a map of averaged mean-sea-level pressure

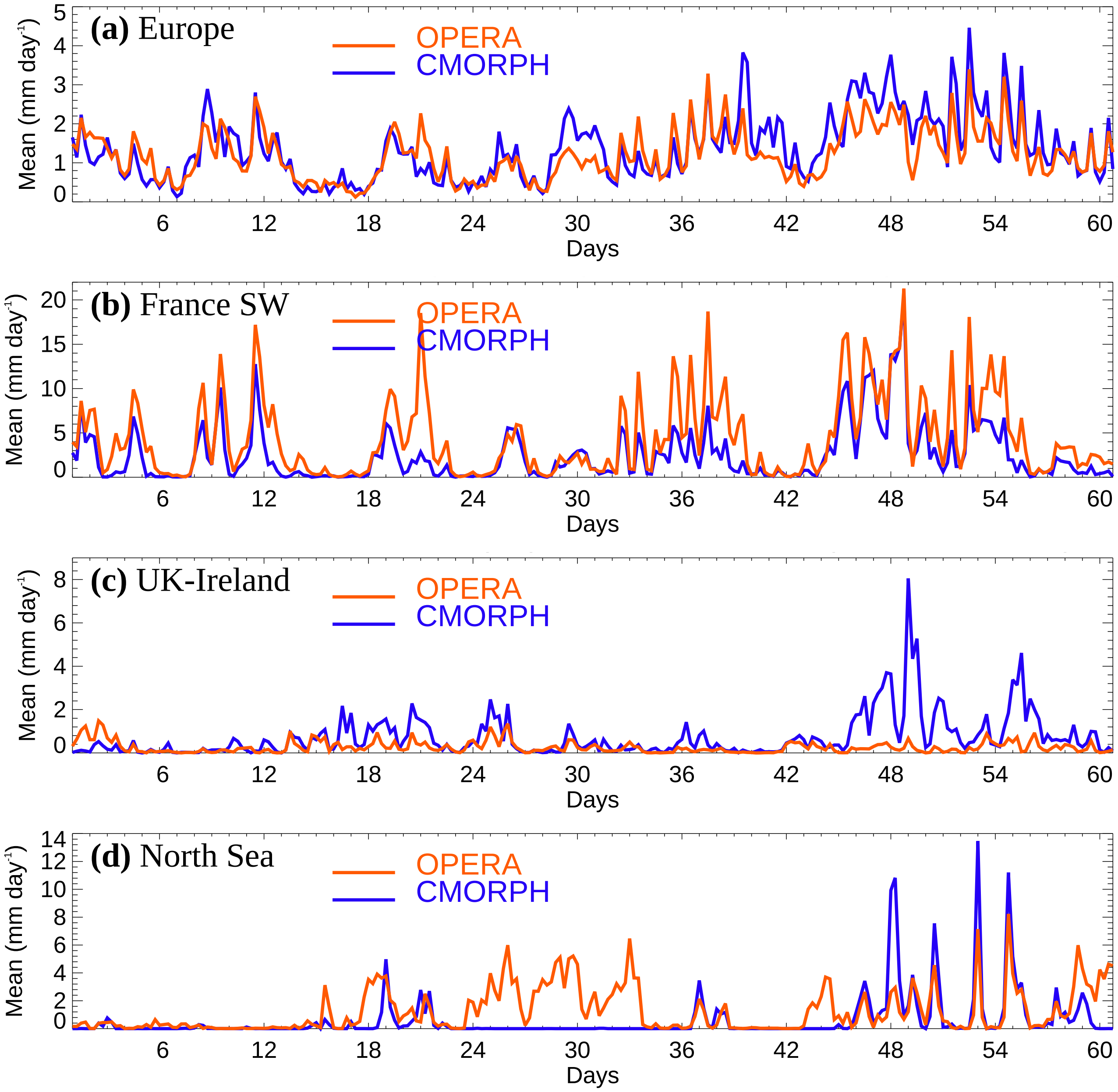


FIGURE 7: Time series of 6h-accumulated precipitation from OPERA (orange curve) and CMORPH (blue curve) over the selected 60-day period (10 April-8 June 2008) and over regions (a) "Europe", (b) "France SW", (c) "UK-Ireland" and (d) "North Sea". See Fig. 4 for the definition of subdomains. Precipitation is in mm day^{-1}.

over Europe for the period 2-11 May 2008, from ECMWF operational analyses. The "North Sea" region is clearly affected by a persistent anticyclone (about 1025 hPa) stretching from Denmark to the southwest of Norway. In such conditions that combine atmospheric stability and still cold sea surface temperatures (about 8°C), radar observations are likely to be affected by anomalous propagation (Turton 1988). To support this explanation, ducting occurrence have been diagnosed from vertical gradients of atmospheric refractivity using ECMWF model analyses at 0000, 0600, 1200 and 1800 UTC, as previously done by Lopez (2008) to build his 5-year 40-km resolution climatology of ducting. And indeed, Fig. 10, which displays the resulting frequencies of ducting occurrences over Europe for the period 2-11 May 2008, clearly exhibits large values (above 70%) over the North Sea. An additional check on Meteosat imagery (not shown) confirms the absence of precipitating clouds over the North Sea during the entire period. Anomalous propagation is therefore the most likely explanation for the spurious but substantial precipitation amounts found in OPERA in spring stable conditions over the North Sea.

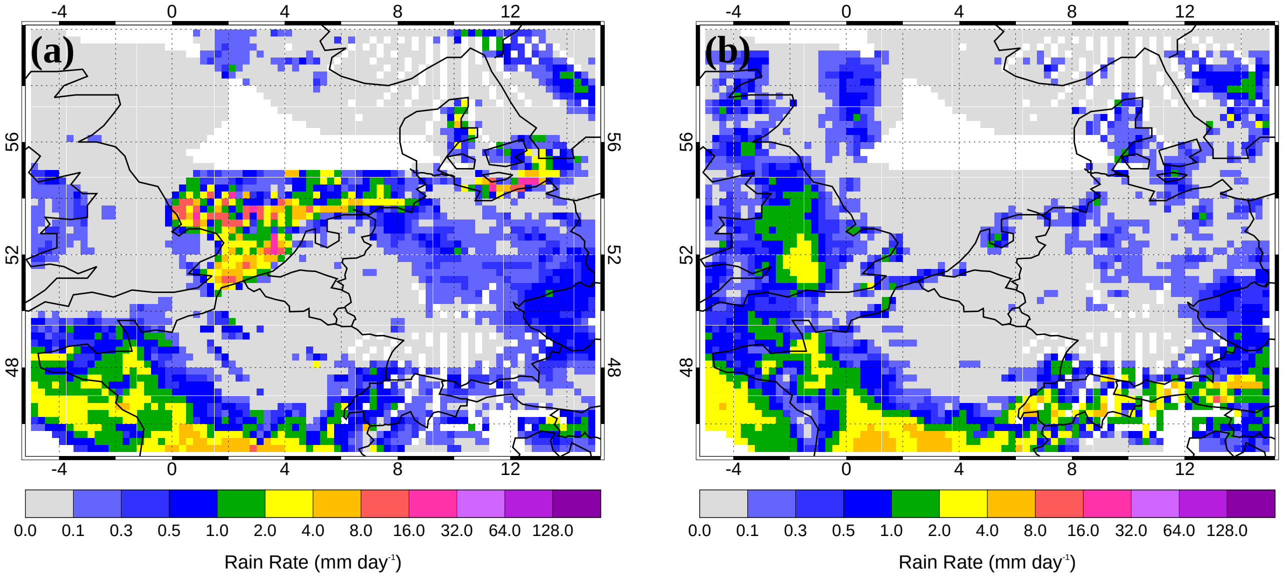


FIGURE 8: Average precipitation (in mm day^{-1}) from (a) OPERA and (b) CMORPH over the period 2-11 May 2008. White regions correspond to missing data.

4.3 Precipitation skill scores

As a complement to the previous statistics, precipitation skill scores have been computed for each geographical subdomain. Here the intention is to assess how OPERA performs relative to the three other datasets, but again it is not assumed that the latter are necessarily better. However, consistent signals with respect to CMORPH, SYNOP and ECMWF could point towards some deficiencies in the OPERA data.

Four scores are used here: frequency bias (FB), probability of detection (POD), equitable threat score (ETS) and false alarm rate (FAR), which are defined in Appendix 2. Figure 11-13 display the scores of OPERA 6h-accumulated precipitation against CMORPH, SYNOP and ECMWF, respectively, computed over the two-month period for each region of Fig. 4 and as functions of various precipitation thresholds. Note that FB is plotted using a decimal logarithmic scale, so that the zero line corresponds to $FB = 1$. It is also worth underlining that scores for the right ends of each curve should be considered with some caution since they

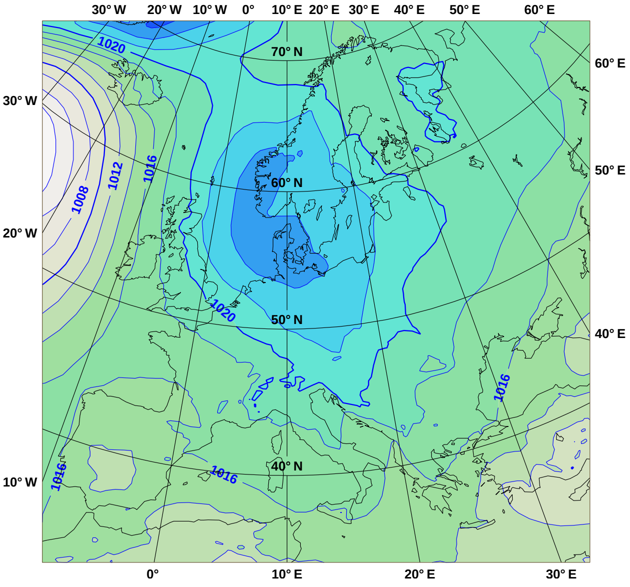


FIGURE 9: Average mean-sea-level pressure (in hPa) from ECMWF model analyses at 0000 and 1200 UTC over the period 2-11 May 2008.

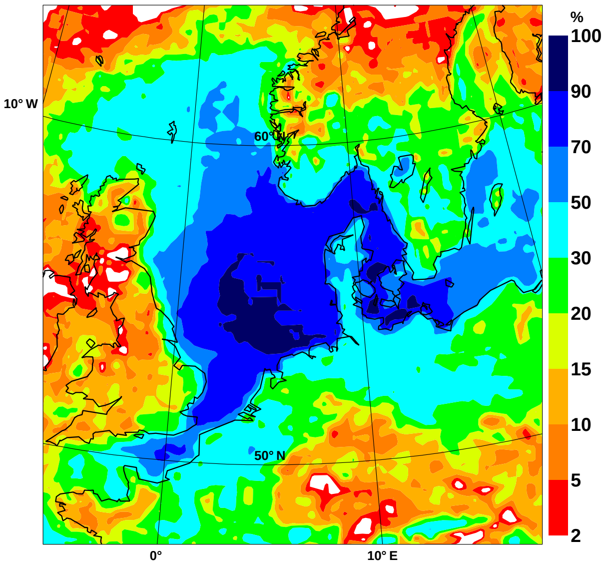


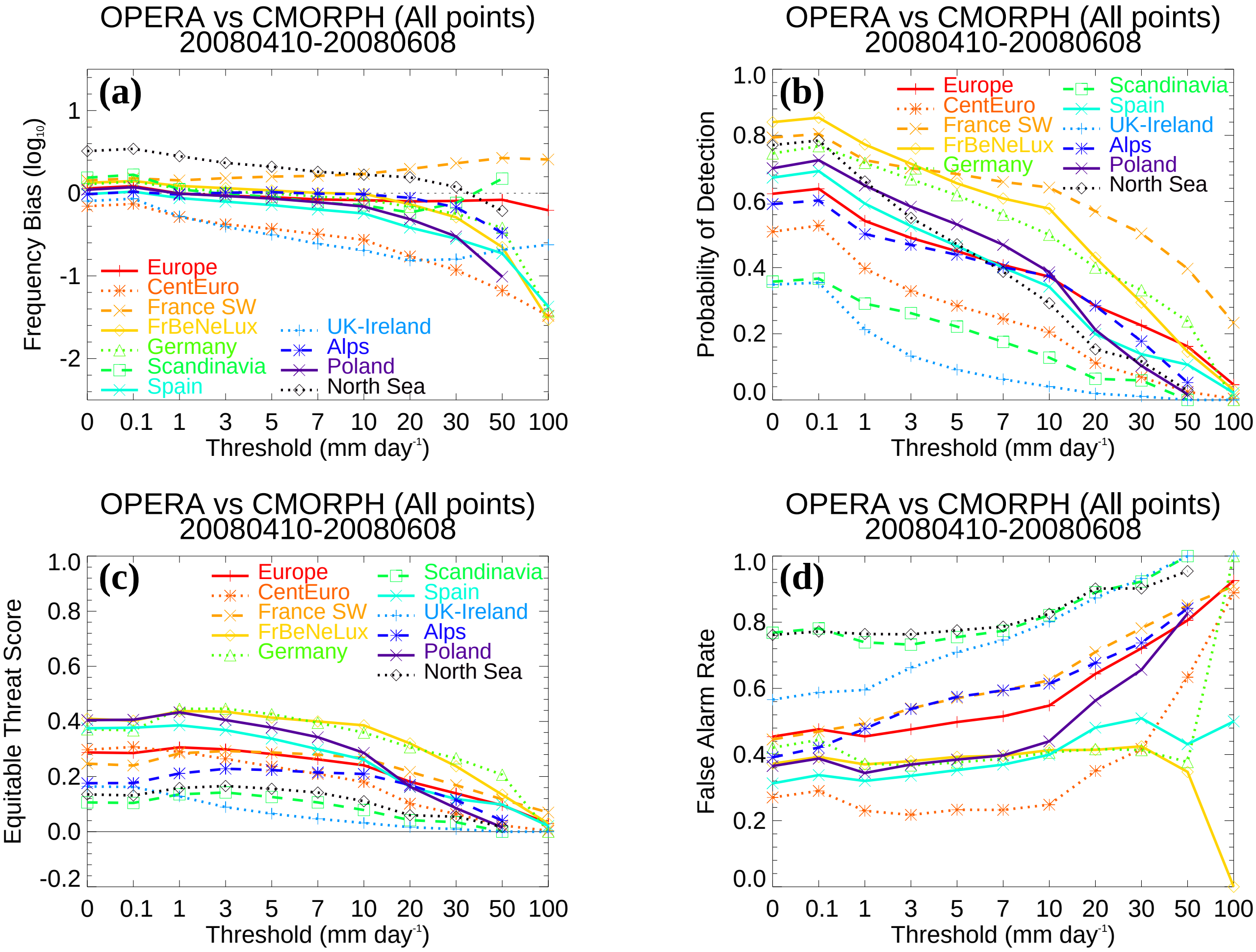
FIGURE 10: Ducting frequency of occurrence (in %) as diagnosed from ECMWF model analyses at 0000, 0600, 1200 and 1800 UTC over the period 2-11 May 2008.

correspond to the weakly populated tail of the precipitation distribution over a given subdomain. In other respects, all scores are naturally expected to degrade as precipitation threshold increases.

Over most regions, $log(FB)$ (panel (a) in Fig. 11-13) is negative for thresholds higher than 3 mm day^{-1}, which indicates that OPERA underestimates the occurrence of larger precipitation amounts compared to CMORPH, SYNOP and ECMWF. In opposition, OPERA tends to over-represent precipitation amounts lower than 3 mm day^{-1} ($log(FB)$ positive). Positive values of $log(FB)$ for thresholds above 3 mm day^{-1} are only found over regions ”France SW” and ”North Sea”. This result is in agreement with the excess of precipitation found on average in OPERA over ”France SW” in Table 2. Over ”North Sea”, the fact that OPERA gives more frequent precipitation than CMORPH and MODEL for most thresholds is consistent with the occurrence of spurious rainfall that was attributed to anomalous propagation in section 4.2. As far as ”UK-Ireland” is concerned, $log(FB)$ is significantly below zero, which suggests a systematic under-detection of precipitation events in OPERA compared to the other datasets. To a lesser extent, this is also true of subdomains ”Scandinavia” (only relative to SYNOP and MODEL) and ”CentEuro”.

The rather poor performance of OPERA above the three latter regions is also visible in terms of POD and ETS (panels (b) and (c) of Fig. 11-13, respectively). Region ”UK-Ireland” usually exhibits the lowest values for both parameters, with POD below 0.5 and ETS below 0.3. The potential issue of poor snowfall representation in OPERA already suggested in section 4.1 translates into low values of FB, POD and ETS over ”Scandinavia”. On the contrary, POD reaches its highest values for ”France SW”, ”FrBeNeLux” and ”Germany”, above 0.8 for small precipitation thresholds and still around 0.5 for 10 mm day^{-1}. In terms of ETS, the best overall performance with respect to CMORPH and SYNOP is obtained over ”FrBeNeLux”, ”Germany” and ”Poland” (up to 0.52). Against ECMWF, ETS reaches lower values (0.34 at best), which is understandable since OPERA should be in better agreement overall with other observational datasets (CMORPH and SYNOP) than with forecast model outputs. This latter point also explains why POD values in Fig. 13 are generally lower than those in Fig. 11-12. Again, ETS curves evidence the weakness of OPERA over ”North Sea”.

Finally, ”FAR” curves (panel (d) in Fig. 12-13) against SYNOP and ECMWF remain below 0.6 over all subdomains (except ”North Sea” due to spurious OPERA rainfall) for thresholds below 10 mm day^{-1} and degrades substantially beyond. It should be noted that low values of *FAR* can result either from a systematic under-estimation of precipitation in OPERA or from systematic spatial misplacements of precipitating events, and vice versa. Overall, the lowest *FAR* versus SYNOP and ECMWF are found over the region ”Alps”, which can be partly explained by the systematic deficit of OPERA (Table 2). On the other hand, *FAR* plots with respect to CMORPH look rather different. False alarm rates are particularly high over ”North Sea” (anomalous propagation), ”UK-Ireland” (see section 5 for an explanation), and ”Scandinavia” (due to CMORPH probable under-detection of snowfall).



OPERA vs CMORPH (All points) 20080410-20080608

FIGURE 11: Skill scores of OPERA versus CMORPH between 10 April and 8 June 2008 over the subdomains of Fig. 4 (see color coded legend) and as functions of various precipitation thresholds (x-axis). Frequency bias, probability of detection, equitable threat score and false alarm rate are shown in panels (a), (b), (c) and (d), respectively. All scores are unitless.

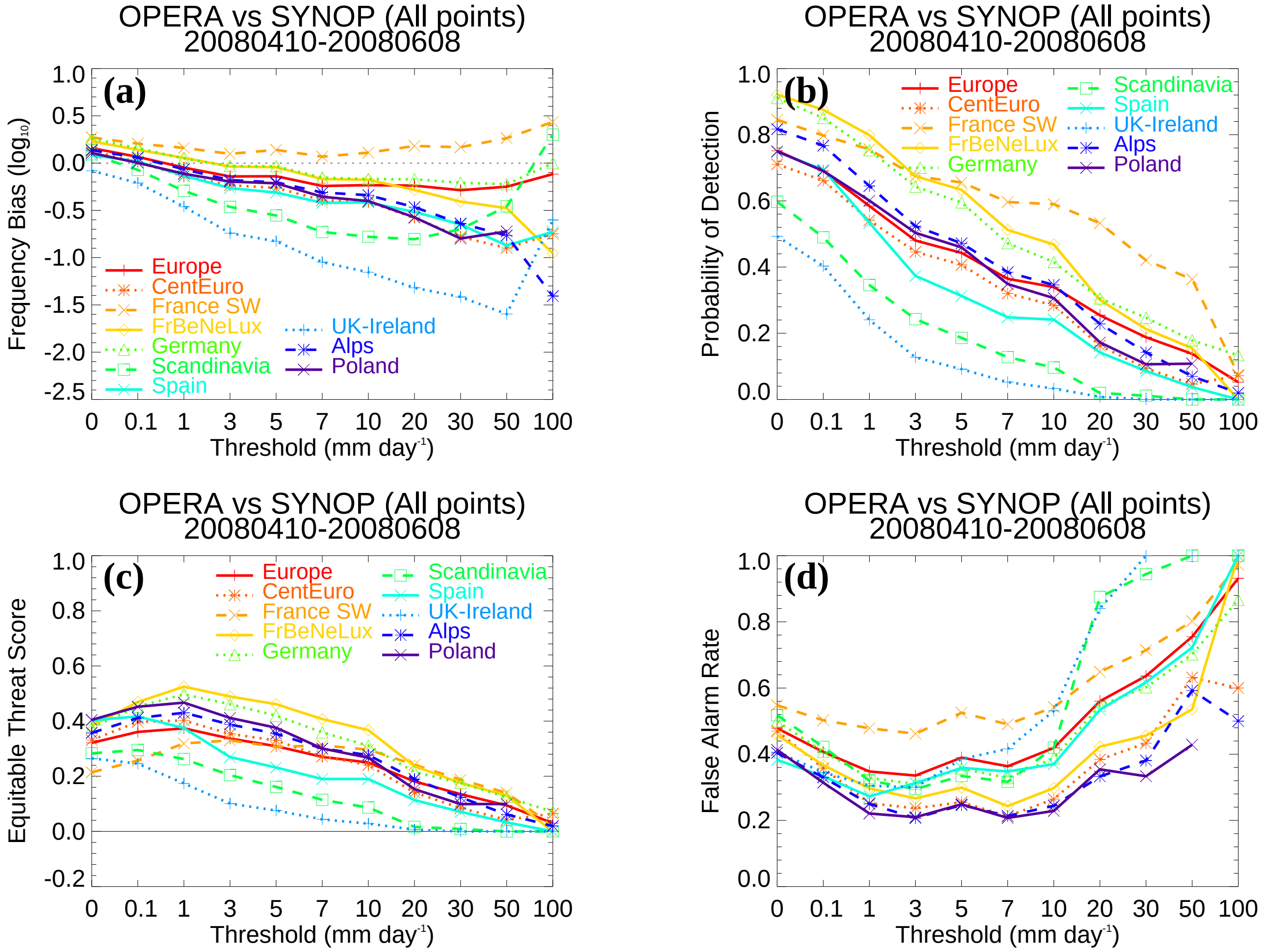


FIGURE 12: Same as in Fig. 11, but versus SYNOP.

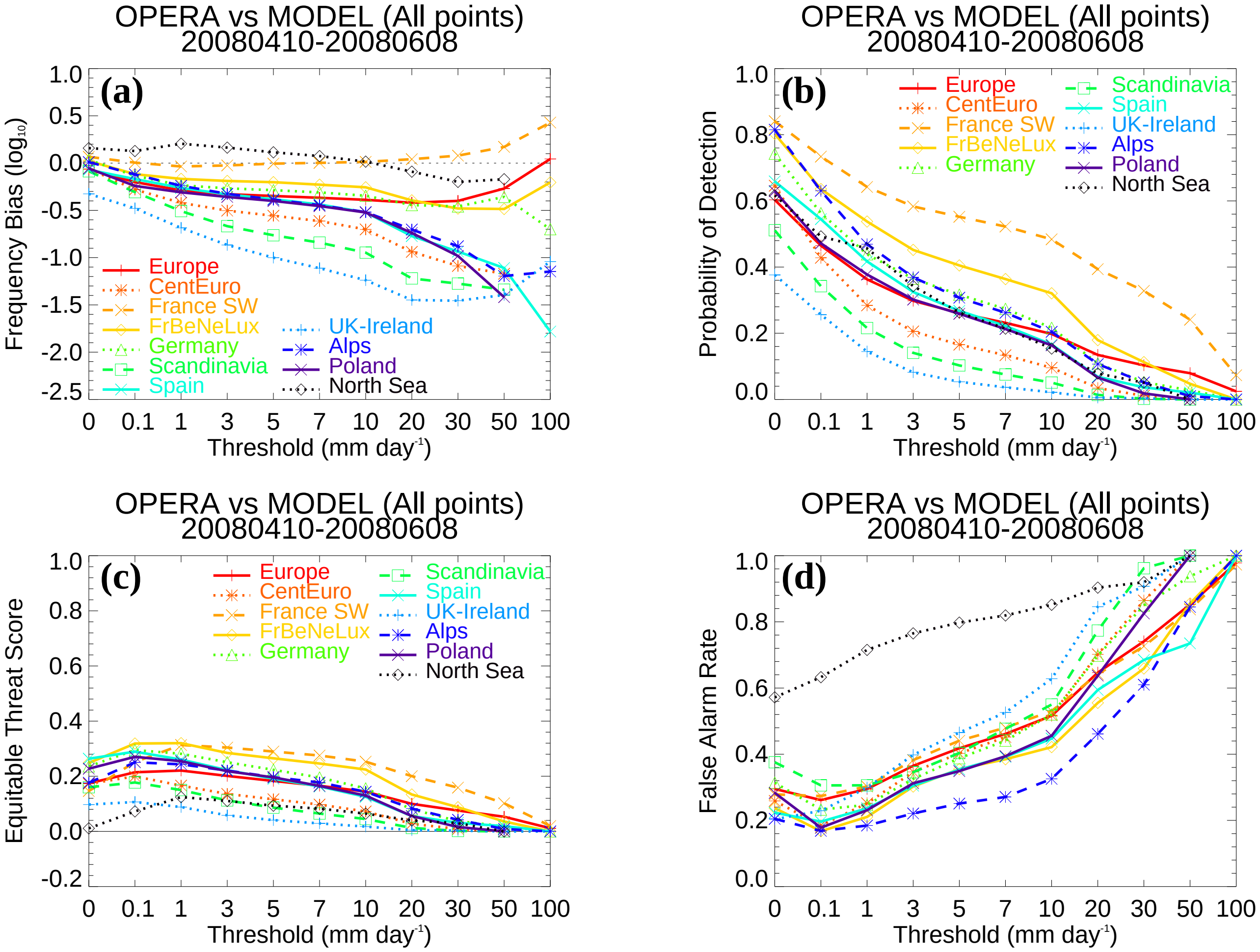


FIGURE 13: Same as in Fig. 11, but versus ECMWF.

5 Conclusions

The preliminary comparison of OPERA precipitation composites over Europe to CMORPH satellite-based, SYNOP rain gauge and ECMWF model output data over two months has permitted the identification of systematic and significant differences that seem to be geographically dependent. Throughout the selected two-month period in spring, the best overall agreement is found over Germany, Belgium and the Netherlands, with an average relative deficit below 25% and a mean correlation above 0.6 with respect to CMORPH and SYNOP, which is reasonably good. Most other regions exhibit larger negative mean relative departures and usually lower correlations of OPERA compared to the three other datasets. In particular, OPERA seems to be in strong deficit over the UK throughout the period studied. The only two regions where OPERA shows significantly more precipitation than the other datasets are the southwestern three-quarters of France and to a lesser extent the North Sea. In other respects, OPERA correlations with ECMWF model outputs are always lower than with CMORPH and SYNOP, which can be explained by the larger uncertainties in precipitation forecasts, in particular in terms of timing of rainy events. The best skill scores are encountered over France, Germany, Belgium and the Netherlands, the poorest over Scandinavia and the UK.

The reasons for some of the most striking differences between OPERA and the other datasets are now understood. The rather poor agreement of OPERA with the other datasets over Scandinavia can be explained by the occurrence of snowy events that are known to degrade the accuracy of measurements from PMW satellite instruments, rain gauges and radars.

The presence of clearly spurious but substantial rain amounts in OPERA over the North Sea is attributed to the anomalous propagation of radar signals in anticyclonic conditions over cold sea surface temperatures. Maybe geostationary satellite imagery or the diagnostic of ducting probability from model outputs (e.g. Lopez 2008) could help to eliminate such anomalous precipitation patterns from the composites.

Similarly, the systematic and strong underestimation found over the UK has been recently clarified by Marion Mittermaier (Met Office), after the completion of the present study. She obtained results totally consistent with those presented in section 4, by comparing OPERA with five NWP models (personal communication). After an investigation with the OPERA Pilot Data Hub team, she could reveal that a technical problem had led to a contamination of UK data when Slovak radar data started to be merged into the European composite earlier this year. This error was corrected on 19 June 2008 and the OPERA precipitation estimates over the UK are now almost unbiased with respect to CMORPH and SYNOP and threat scores are much improved (not shown).

This clearly demonstrates the importance of properly and continuously monitoring OPERA data against various independent sources of information, regardless of whether these are observations or model outputs. As illustrated in this study, consistent and systematic OPERA−dataset departures are likely to indicate the presence of a problem in the radar composites.

Understanding other differences that were found here will probably require further work and some feedback from the OPERA community. Monitoring OPERA data over longer periods of time might allow to stratify the statistics according to precipitation type (e.g. convective or stratiform, rain or snow).

The OPERA team has undertaken the titanic task of merging radar observations from 29 European countries into good quality precipitation composites that should be as homogeneous as possible. Reaching this goal would be a great achievement, with lots of potential applications. In view of present results, improving the accuracy of OPERA precipitation amounts should be a priority since it will determine whether these data can be effectively used for the purposes of quantitative model validation or even radar data assimilation. It is hoped that the quality of OPERA data will be further enhanced in the near future, through a more homogeneous processing of single radar site observations only, for instance. At least, this is the plan for the fully operational version of the OPERA data hub which is expected around 2010.

Acknowledgements

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APPENDIX 1

List of satellite acronyms:

AMSR-E	Advanced Microwave Scanning Radiometer for EOS (on board AQUA satellite)
AMSU	Advanced Microwave Sounding Unit (on board NOAA satellites)
DMSP	Defense Meteorological Satellite Program (USA)
EOS	Earth Observing System (USA)
GMS	Geostationary Meteorological Satellite (Japan)
GOES	Geostationary Operational Environmental Satellite (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
SSM/I	Special Sensor Microwave Imager (on board DMSP satellites)
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission (USA, Japan)

APPENDIX 2

Precipitation scores used in this study are the Frequency Bias (FB), the Probability Of Detection (POD) the Equitable Threat Score (ETS) and the False Alarm Rate (FAR). They are defined as follows

$$\begin{aligned} FB &= \frac{H+F}{H+M} \\ POD &= \frac{H}{H+M} \\ ETS &= \frac{H-H_e}{H+M+F-H_e} \\ FAR &= \frac{F}{H+F} \end{aligned}$$

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

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

where N is the sample size. On a practical point of view, scores are deemed to be good when FB is close to unity (i.e. log(FB) close to zero), POD and ETS tend to 1 and FAR is the lowest possible.

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