EURO4M
European Reanalysis and Observations for Monitoring
Grant agreement no. 242093

Deliverable D.2.12 Evaluation of reanalysis surface solar radiation, cloud properties, precipitation and water vapour using CM SAF and W1.2 products

Delivery date: 42
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2. Motivation & Introduction

The two new EURO4M high resolution regional reanalyses (provided by SMHI and the MetOffice) offer unprecedented possibilities for industry, science and politics to get detailed information about climate change over Europe. For the application of these data sets, it is indispensable to know about the strengths and weaknesses of these new data sets. Therefore, it has been intended in EURO4M to conduct a detailed evaluation of the reanalysis data sets with well documented and established reference data sets. Here, satellite-derived climate data sets from the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) and from EURO4M are used for comparison.

This report informs about the evaluation results and is organised as follows: All used data sets are introduced Section 3. Section 4 provides information about the general concept that has been set up to compare the models with the satellite-derived data sets. Afterwards, all results are presented in Chapter 5. The data quality of four essential climate variables is assessed, in particular solar radiation, cloud coverage, precipitation and water vapour. Finally all gained reanalyses evaluation results are summarized and discussed in Section 6 within the scope of EURO4M.
3. Data sets

3.1. Introduction

This section introduces the different data sets that have been used for the evaluation of the EURO4M reanalyses with satellite-derived products from CM SAF and EURO4M.

In Section 3.2 the reanalysis data are presented, first starting with the HIRLAM 3DVAR regional reanalysis provided by SMHI and subsequently with the Met Office 4DVAR data set. Section 3.3 describes the reference data sets of CM SAF (CLARA-A1, ATOVS) and EURO4M (GPCC/HOAPS).

3.2. EURO4M reanalyses

3.2.1. SMHI HIRLAM 3D-VAR dynamical downscaling re-analysis

The HIRLAM 3D-VAR is the new regional reanalysis by the Swedish Meteorological and Hydrological Institute (SMHI) in the scope of EURO4M. This reanalysis is updated every 6 hour with boundaries from ECMWF ERA-Interim and a large scale constraint (Jk) (Dahlgren and Gustafsson, 2012) using vorticity from ERA-Interim. Conventional observations are used in the assimilation scheme: SYNOP, SHIP, BUOY, DRIBU, AIREP, AMDAR, TEMP, PILOT. The large scale constraint ensures that satellite large scale information from the ERA-Interim data assimilation process is introduced implicitly.

![Figure 1: ERA Interim analysis of the 2m temperature](image1)
![Figure 2: HIRLAM 2m temperature using ERA-Interim analysis on the borders and as a large scale constraint](image2)

The HIRLAM-based reanalysis provides 6-hourly information on numerous atmospheric variables with a spatial resolution of 0.2 deg on a rotated grid. The available parameters
include surface information (e.g., temperature, moisture, wind, radiation, precipitation), vertically-integrated quantities (e.g., total cloud coverage, precipitable water), and vertically-resolved data (e.g., profiles of the temperature, wind, humidity, cloud). The available long time series (1989-2010) allow the calculation of local anomalies and temporal changes.

The analysed temperatures agree well with observations where there is good data coverage. The cloudiness agrees well with SYNOP observations.

For validating the SMHI HIRLAM reanalysis data set with CM SAF and EURO4M data the following fields (parameter, GRIB code) have been selected:
- Total Cloud Cover (71, 109)
- Total Precipitation (61, 105)
- Integrated Water Vapour (54, 109)
- Downwelling (global) shortwave radiation (117, 105)

The evaluation of the reanalysis data set considers the monthly means, which have been derived from the 6-hourly data. For the parameters solar radiation and precipitation the 24 h minus 12 h forecasted accumulation have been used. Figures 5 to 8 show the multi-year monthly averages for July of the parameters that are evaluated from the SMHI reanalysis.
Figure 5 - 8: Multi-year average for July of selected HIRLAM EURO4M fields (1990-2002): total cloud cover, total precipitation, integrated water vapour, downwelling (global) shortwave radiation
3.2.2. **Met Office 4D-VAR re-analysis**

The new 4D-VAR high resolution atmospheric reanalysis is operated by the MetOffice (MO) in the scope of EURO4M. This reanalysis is available for 2008 and 2009. Monthly statistics including screen level means and climate indices have been produced.

![Mean surface temperature in September 2008](image1)

![Monthly mean surface temperature at Le Mans](image2)

**Figure 9:** Mean surface temperature in September 2008.  
**Figure 10:** Monthly mean surface temperature at Le Mans

The reanalysis produces analysis fields of variables four times a day with a spatial resolution of 0.11° (12 km) on a rotated grid (pole: lat = 40°N, lon=20°S). The available parameters include monthly means of meteorological variables (e.g. cloud cover, screen level temperature, temperature range and relative humidity, mean sea level pressure, precipitation, 10m wind speed, precipitation on wet days, daily minimum and maximum temperature) and climate indices (e.g. number of frost / summer / icing days, tropical nights, max/min of max/min temperature, maximum 1-day / 5-day precipitation, number of days with precipitation greater than 10 / 20 mm, maximum length of dry/wet spell, number of wet / mostly sunny / mostly, cloudy / windy / calm days, maximum of daily maximum wind gust).

For validating the 4D-VAR reanalysis with CM SAF and EURO4M data the following fields have been selected:

- Total Cloud Cover
- Total Precipitation
- Integrated Water Vapour
- Downwelling (global) shortwave radiation

Figures 11 to 14 show the multi-year monthly averages for July of the parameters that are evaluated from the MetOffice reanalysis.
Figure 11-14: Multi-year averages for July of selected parameters from the MetOffice EURO4M reanalysis (2008-2009): total cloud cover, total precipitation, integrated water vapour, downwelling (global) shortwave radiation.
3.3. References: Satellite-derived data sets of CM SAF and EURO4M

3.3.1. CM SAF: CLARA-A1 data set for radiation and cloud cover

CLARA-A1 (CM SAF cloud, albedo & radiation dataset - AVHRR-based, Edition 1, Karlsson et al., 2013) is a comprehensive satellite-derived climate data set generated and provided by the CM SAF. This report concentrates on the variables surface incoming shortwave radiation and cloud fractional cover that have been used for the evaluation of the EURO4M reanalysis.

The data set provides global coverage from AVHRR satellite observations. The products are available as monthly averages on a regular latitude / longitude grid with a spatial resolution of 0.25° x 0.25° degrees. The temporal coverage ranges from January 1982 to December 2009.

The retrieval of the surface incoming solar radiation is based on a look-up-table method (Mueller et al., 2009). The cloud detection provided by the Nowcasting SAF software (PPS, Polar Platform System) is used to distinguish between cloudy- and clear-sky pixels. For clear-sky pixels, no additional satellite information is required to calculate the surface in coming solar radiation using the Mesoscale Atmospheric Global ‘Irradiance Code (MAGIC, http://gru.magic.sourceforge.net/). For cloudy pixels, look-up tables are used to assign the atmospheric transmissivity to the measured albedo at the top-of-the-atmosphere. The transmissivity can be directly converted to the surface incoming solar radiation. The temporal averaging of the instantaneous retrieval results on the pixel level is conducted following the method of Möser and Raschke (1984). At least 20 instantaneous observations need to be available in each grid box to calculate the daily average; monthly averages are only generated when at least 20 valid daily mean values are available. To ensure a high data quality no data is provided over bright surfaces (i.e., desert, snow).

The overall accuracy of the CM SAF CLARA-A1 SIS data set has been estimated to be 10 W/m² for the monthly mean data and 20 W/m² for the daily averages.

![Figure 15: CLARA-A1 data set: Mult.-year monthly average for July of surface solar incoming radiation from 1990-2002](image)
The parameter cloud fractional cover is available as daily and monthly composites on a regular latitude / longitude grid with a spatial resolution of 0.25° x 0.25° degrees with a temporal coverage from January 1982 to December 2009. The product is derived directly from results of a cloud masking method. The cloud fractional cover is defined as the fraction of cloudy pixels per grid square compared to the total number of analysed pixels in the grid square. Fractional cloud cover is expressed in percent.

The CFC product is calculated using the NWC SAF PPS (Polar Platform System) cloud mask algorithm (http://NWD_SA F.inm.es/). The algorithm is based on a multi-spectral thresholding technique applied to every pixel of the satellite scene. It has been evaluated against two independent observation datasets; global synoptical cloud observations in the period 1982-2009 and cloud observations from the CALIPSO-CALIOP instrument in the period 2006-2009.

Globally averaged results showed some overestimation in comparison with synoptical observations (+3.6%) while a significant underestimation (-10%) was seen when comparing with CALIPSO-CALIOP. The difference in results reflect mainly the higher sensitivity to cloud detection in the CALIPSO-CALIOP dataset but there are also aspects related to data availability to consider (e.g. synoptical observations are mainly available over land in densely populated areas). Consistency checks were also made with datasets from PATMOS-x, MODIS and ISCCP. Here, overall results pointed at a general negative deviation between 0-15 percentage points.

Figure 16: CLARA-A1 data set: Multi-year monthly- average for July of cloud fractional cover from 1990-2002
3.3.2. **EURO4M: Integrated HOAPS / GPCC data set for precipitation**

The integrated global HOAPS / GPCC data set of precipitation is a combination of satellite-based precipitation estimates over ocean and rain-gauge station data over land surfaces providing a global overview of monthly precipitation. The product is available for monthly means in a spatial resolution of 0.5° degrees on a regular longitude / latitude grid from 1987 to 2008.

This dataset is based on the precipitation datasets by HOAPS (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data) and GPCC (Global Precipitation Climatology Centre). While HOAPS provides precipitation only over ice-free oceans, GPCC offers precipitation data only over land. The quality of the integrated EURO4M dataset relies on the quality of HOAPS (Version 3.2) and GPCC (Full Data Reanalysis Version 6) data. In coastal areas, where the source datasets are brought together a data gap is filled with help of spatial interpolation. Hence coastal precipitation uncertainty is increased.

**Figure 17**: HOAPS/GPCC precipitation (1989-2005) in mm/d.

**Figure 18**: Time series of averaged precipitation of HOAPS/GPCC, GPCP, ERA-Interim and TRMM Version 6, in the area ±50° latitude.

HOAPS is based on measurements by the SSM/I satellite sensors onboard the DMSP satellite series. Inter-sensor calibrated, homogenized microwave measurements are used to generate precipitation data over oceans, in exploiting the direct interactions between precipitation-sized particles and microwave radiation. A neural network based retrieval scheme, trained with SSM/I brightness temperatures and dedicated ECMWF (European Centre for Medium-Range Weather Forecasts) model data, is applied to detect precipitation. A detailed description of the HOAPS dataset can be found in Andersson et al., 2010. The HOAPS processing is now done within the framework of CM SAF.

Over land, the Global Precipitation Climatology Centre (GPCC) generates a precipitation analysis, based on quality-controlled rain-gauge measurements (Becker et al., 2013). The dataset used in the combined EURO4M precipitation product is the GPCC Full Data Reanalysis Version 6, which uses all available rain-gauge stations the provide the complete time series over at least 10 years.

It can be constituted that GPCC is the precipitation reference over land, but data quality is reduced in data-poor regions of the world (see Fig.7).
Figure 19: Rain-gauge stations included in the GPCC Full Data Reanalysis (taken from Schneider et al., 2013)

The focus of the validation activities of this combined product was ocean regions. Using precipitation measurements at tropical atoll stations the mean absolute bias of the monthly mean surface precipitation was found to be about 2 mm/d, corresponding to about 30% (Pfeifroth et al., 2013). The bias was determined to be is -0.6 mm/d (-9%).

Figure 20: Multi-year monthly average July surface precipitation from 1990-2002
3.3.3. CM SAF: ATOVS integrated water vapour data set

The CM SAF ATOVS data set provides global water vapour and temperature products as well as error information (for the daily mean products), extra-daily standard deviation (for monthly products) and the number of observations. The products are available as daily and monthly means on a cylindrical equal area projection of 90 km x 90 km. The temporal coverage of the data set ranges from January 1999 to December 2011.

The water vapour and temperature retrieval is done with the IAPP (International ATOVS Processing Package) software version 3.0. ERA-Interim reanalysis is used as a priori input data to IAPP. The parameter profiles are retrieved on 42 pressure levels. A quality control is applied to the IAPP outputs and afterwards the profiles are sampled, integrated and arranged. Finally, a Kriging routine (Lindau and Schröder, 2010) is applied to obtain the daily and monthly means.

![Figure 21: ATOVS based Integrated Water Vapor, Mean (1999-2011).](image)

The products have been compared to the GUAN (GCOS Upper-Air Network) radiosondes and to AIRS (Atmospheric InfraRed Sounder) data. The validation against the GUAN radiosondes shows that most of the data exhibit a bias within the +- 0.5 K range.

![Figure 22: ATOVS data set: multi-year monthly averaged water vapour for July from 1999-2002](image)
This chapter describes the general methods that were used to evaluate the two EURO4M reanalyses with the satellite-derived reference data sets from CM SAF and EURO4M.

To identify the strengths and the weaknesses of the reanalyses and assess regional differences and climate variability, the data records should be compared under identical conditions if possible.

As most of the data sets cover different spatial regions, they are first cut to cover the same region, i.e., the EURO4M focus region: 20°W – 40°E, 30°N - 75°N. Since all data sets are available on different spatial grids, they have been converted to a common regular lon-/lat-grid. To minimize errors that occur in the remapping a conservative remapping method was chosen. The selected spatial resolution was determined by the lowest resolution data set.

Only monthly means of the parameters from the reanalyses data sets have been used for this evaluation.

For each climate variable under investigation one common file was generated that contains all monthly mean values from the reanalysis and the reference data set together with the corresponding differences (for each grid box) for the entire study period. This file is used to assess the quality of the reanalysis data sets in reproducing the climatological means derived from the reference data sets. To evaluate the quality of the reanalyses data set in the description of anomalies, the multi-year monthly means were subtracted from the data of the corresponding months of the individual years.

For the evaluation the climate data operators (cdo) were used. cdo is an open-source collection of command line operators to analyse gridded data and supports the use of shell scripts. For the graphics and standardized figures R, an open source GNU program for statistical computing and graphics, has been used. R provides a wide variety of statistical and graphical techniques and is well known for its strengths in generating scientific projections.
5. Results

5.1. Introduction

The following sections present the results of the comparison of the SMHI (3DVAR) and MetOffice (4DVAR) EURO4M reanalyses with the reference data sets of CM SAF / EURO4M. The compared parameters are presented in respective subsections. In each of the sections first the evaluation results of HIRLAM and secondly of the MetOffice reanalysis are described. For all subsections figures of monthly means, differences of monthly means and annual cycle variability are presented.

5.2. Parameters

In the following the evaluation results of the parameters solar radiation (5.2.1), cloud cover (5.2.2), precipitation (5.2.3) and water vapour (5.3.4) are described. For evaluating the 3DVAR HIRLAM reanalysis with CM SAF data sets the parameters solar radiation, cloud cover and precipitation were investigated from 1990 to 2002 (i.e, 13 years). The comparison of the parameter water vapour covers the 4 year from 1999 to 2002.

For the evaluation of the 4DVAR MetOffice reanalysis with the CM SAF data from 2008 and 2009 were used. The evaluation for precipitation was possibly only for 2008.
5.2.1. Solar radiation

5.2.1.1. SMHI Reanalysis


In figures 23 & 24 the average solar radiation for July of the years 1990-2002 for the reference and the reanalysis data set is displayed. Both, CLARA-A1 and the 3DVAR HIRLAM reanalysis, show an increase in solar radiation from northwest to southeast. The lowest surface solar radiation can be found over the northern Atlantic, the highest over land below 45°N in the Mediterranean region.


Figure 25 shows the difference between the CM SAF and HIRLAM data sets. It can be seen that the reanalysis generally tends to underestimate the surface solar radiation over the ocean and to overestimate the solar radiation over land. Particularly strongly overestimated areas are mountainous regions such as the Alps and the Romanian Carpathians. In addition, the
overestimation increases as the climate becomes more continental. The underestimation over the ocean near the coast is smaller and steadily decreases with increasing distance from land. An exception is reflected off the south coast of Ireland. Here the model significantly underestimates the solar radiation despite the nearby land. HIRLAM compares well on inland water areas, such as the Mediterranean and the Baltic. However, the Black Sea is slightly overestimated.

The annual course of the differences shows strong annual fluctuations (Figure 26). While the differences are small during the winter, substantial differences are present during the summer months with the largest differences occurring in May and June. It is noticeable that there are significantly more positive outliers than negative ones.


Figures 27-29 show the anomaly of the solar surface radiation for July 2001 compared to the multi-year mean solar radiation for July. Large regional scale positive / negative anomalies can be seen over Eastern / Northern Europe for July 2001. The HIRLAM reanalysis reproduces well the spatial distribution of the anomaly, but tends to intensify both positive and negative anomalies. It appears regardless of whether the anomaly occurs over the ocean
or land. Regions where the anomalies in July 2001 are overestimated are, for instance, the Atlantic Ocean north of Iceland, the Baltic Sea, over west Russia and across the border to Finland. The HIRLAM reanalysis underestimates the anomaly over the ocean at the Norwegian Sea, north of Scotland and west of Spain and France. Over land the anomalies are underestimated in Central France, in the North of Germany and Greece.

The anomalies between CLARA-A1 and the HIRLAM reanalysis are highly correlated with a correlation coefficient of 0.815 and a mean absolute bias of only 7.8 W/m² (Figure 30).

5.2.1.2. Met Office Reanalysis


The mean solar surface radiation of CM SAF and the 4DVAR MetOffice Reanalysis in July (based on 2008 and 2009) is shown in figures 31 and 32. Both data sets show that the radiation is mainly continuously increasing from north to south. Minimum values appear over the Norwegian Sea, Scotland, northwest Russia and Germany. Regions with very high radiation budgets are Spain, the Mashreq and Maghreb regions and the Mediterranean.

Figures 33 & 34: Monthly July differences and annual course of differences of Solar Surface Radiation from 2008-2009 by CLARA-A1 and MetOffice
As Figure 33 shows, the reanalysis tends to overestimate the surface solar radiation mainly over land. Regions with too high surface radiation are in particular mountainous regions, like the Scottish Highland, the Alps, the Romanian Carpathians, the Atlas Mountains in Morocco and the Turkish mountain chains. The model underestimates the surface radiation almost exclusively over water. Especially low values occur off the Moroccan coast and over the Mediterranean. Over the course of a year, the differences are much higher in summer than in winter (figure 34).

Comparing the anomalies derived from only the two years (2008 and 2009) of CLARA-A1 and the 4DVAR reanalysis, both data sets show a similar structure, as displayed in figures 35 to 37. In July 2008 a strong positive anomaly occurs over Scandinavia, while negative values are reached over Slovakia and surrounding countries and over the ocean north Ireland. All in all, there are hardly any nameable differences between both data sets, but a very slight underestimation in the reanalysis over some parts of the Atlantic ocean.
5.2.2. Cloud cover

5.2.2.1. SMHI Reanalysis

Figures 38 & 39: Monthly July means of cloud cover from 1990-2002 by CLARA-A1 and HIRLAM

Figures 38 & 39 show the multi-annual (1990 to 2002) average cloud coverage for July from the CM SAF CLARA-A1 data set and the SMHI 3DVAR reanalysis.

The EURO4M reanalysis reproduces well the spatial distribution of the cloud coverage with high cloudiness in the North Western region of the domain and the low cloud coverage in the Southern part, i.e., the Mediterranean region. Also some regional features, e.g., the reduced cloud coverage over the Baltic Sea and the Eastern Mediterranean compared to the bordering land as well as the effect of Madeira on the cloud coverage, are well reproduced by the reanalysis.

Figures 40 & 41: Monthly July differences and annual course of differences of cloud cover from 1990-2002 between CLARA-A1 and HIRLAM
In general the reanalysis tends to underestimate the cloud coverage compared to the CLARA-A1 data as can also be seen in figure 40. The biggest underestimation is found in the Mediterranean region over land with differences of up to 50%. On overestimation of the cloud coverage can be seen in the South Western part of the domain where the reanalysis overestimates the cloud coverage over the Atlantic west of the Iberian Peninsular.

The annual variability of the difference between the EURO4M reanalysis and the CM SAF data can be seen in figure 41. While the difference is mainly small (i.e., below 5%) for most pixels and constant throughout the year, some outliers with deviations (overestimation in winter, underestimation in summer) of up to 60% exist.

The spatial distribution of the cloud coverage anomaly for July 2001 is well reproduced by the SMHI reanalysis, while the extent of the negative anomalies in the Eastern part of the domain is slightly underestimated (figures 42 to 44). The scatter plot in figure 45 shows the good correlation between the anomalies provided by HIRLAM and CLARA-A1.
5.2.2.2. MetOffice Reanalysis

Figures 46 & 47: Monthly July means of cloud cover from 2008-2009 by CLARA-A1 and MetOffice

Figures 46 and 47 show the average cloudiness in July, calculated from the years 2008 and 2009 from the reference data CLARA-A1 and the 4DVAR MetOffice reanalysis data set.

The reanalysis and the CLARA A1 data sets both show a northwest-southeast decreasing cloudiness structure. Even locally occurring differences are reproduced realistically in the reanalysis. For example, the low cloud cover is realistically reproduced on the eastern half of the Mediterranean, on the Straits of Gibraltar and on islands such as Madeira, Corsica, Sardinia and the Balearic Islands as well as the high clouds over the Central German Uplands and the Alps.

Figures 48 & 49: Monthly July differences and annual course of differences of cloud cover from 2008-2009 by CLARA-A1 and MetOffice

There is a significant underestimation of the cloud cover in the reanalysis data set in the southern part of the study area, and a slight overestimation in the north. This is shown in figure 48. Particularly, strong underestimations are over the southern and eastern coastal regions bordering the Mediterranean and southern Spain. The model overestimates over Iceland, the German Alps and large areas of the Baltic Sea. In general, most differences are
found over land areas; the cloud coverage over water is well reproduced by the reanalysis data set, except the Baltic Sea, where there is an overestimation of the cloud coverage by the reanalysis.

The average annual cycle of the differences between the two data sets is rather constant throughout the year with fewer positive outliers during the summer (Figure 49).

Figures 50 and 51 show the anomalies of the cloud coverage for July 2008 based on the CLARA-A1 and the 4DVAR reanalysis data sets. There is only a small negative anomaly in cloud coverage in Scandinavia in this month, which is well reproduced in the reanalysis data set, even though the spatial extent is underestimated (figure 52).
5.2.3. Precipitation

5.2.3.1. SMHI Reanalysis

Figures 53 & 54: Monthly July means of precipitation from 1990-2002 by EURO4M and HIRLAM

The mean precipitation in July (1990 to 2002) of the EURO4M data set and the 3DVAR SMHI reanalysis is presented in figures 53 and 54. Below 40°N hardly any precipitation is detected in both data sets. North of 40°N significantly more rainfall is displayed over land than over water bodies. Particular high precipitation amounts can be found over mountainous regions, e.g. the Alps, the High Tatra and the Norwegian coast. Local maxima are also found at the south coast of Iceland and the west coasts of Scotland and Ireland.

Figures 55 & 56: Monthly July differences and annual course of differences of precipitation from 1990-2002 by EURO4M and HIRLAM

In general the precipitation in July is overestimated in the SMHI reanalysis, in particular in mountainous regions, such as the Norwegian coast and the Alps, where the largest overestimations occur. The precipitation is well reproduced in the Mediterranean and Eastern Scandinavia (i.e., Sweden, Finland), where only a slight underestimation is found (figure 55).
The annual cycle of the differences between EURO4M and HIRLAM shows slightly larger differences during the winter than during spring and summer months as shown in figure 56.

The spatial distribution of the precipitation anomaly in July 2001 is very well reproduced by the SMHI HIRLAM reanalysis compared to the EURO4M data set (figures 57 and 58). Large positive anomalies are present in both data sets over northern Scandinavia, Eastern Europe and parts of France. Differences between the anomalies of these two data sets appear scattered throughout the domain as shown in figure 59. The high quality of the precipitation anomaly in the HIRLAM reanalysis data set is manifested in the low bias and the high correlation compared to the EURO4M data set shown in figure 60.
5.2.3.2. MetOffice Reanalysis


Figures 61 and 62 show the mean precipitation from the EURO4M data set and the MetOffice 4D VAR reanalysis from July 2008. Since only data from one year (2008) was used for this evaluation, more spatial structure is visible in this comparison compared to the evaluation of the SMHI reanalysis. In both data sets the largest precipitation values are present over land in mountainous regions. Low values can be found south of 45°N, particularly over water and the south and east bordering countries of the Mediterranean.

Figures 63 & 64: Monthly July differences and annual course of differences of precipitation in 2008 by EURO4M and MetOffice

The surface precipitation in July 2008 is overestimated over wide areas over the ocean, in particular north of 40°N. Especially over the Celtic Sea, the North Sea and the Black Sea differences up to 5 mm/d are reached. Even over large rivers, like the Dnieper in Ukraine, the reanalysis overestimates the precipitation. Over land the reanalysis data tends to underestimate the precipitation in the Eastern part, while it tends to overestimate the precipitation on land areas around the Mediterranean Sea. The overall accuracy of the reanalysis data is higher over land than over water (figure 63).
The annual cycle of the differences between the MetOffice reanalysis and the EURO4M data set show that the largest differences occur in autumn. The reanalysis data set is closest to the observations in the summer months (Figure 64).

5.2.4. Water vapour

5.2.4.1. SMHI Reanalysis


As shown in figures 65 and 66 the spatial distribution of the integrated water vapour content from the HIRLAM reanalysis closely matches the CM SAF reference data set. The water vapor content in July has low values in the north and rises steadily towards south. Maxima are located in the Atlantic Ocean at about 45°N 20°W and in the Mediterranean Sea north of the Balearic Islands. Over land the water vapor increases towards the East. Maximum values are found over eastern Hungary, Moldova, Ukraine, the adjacent part of Russia, as well as on the eastern Black Sea. The Alps, Spain and Turkey are among the more dry areas in both data sets.
Figures 67 & 68: Monthly July differences and annual course of differences of water vapour from 1999-2002 by ATOVS and HIRLAM

The reanalysis data set tends to underestimate the integrated water vapor over land and to overestimate the water vapor over sea south of 50°N. In particular in mountainous regions the reanalysis data set underestimates the reference data, e.g. Alps and Pyrenees. It is worth mentioning that the HIRLAM reanalysis overestimates the water vapor south of the Alps and along the northeastern Mediterranean coast (figure 67). The monthly comparison of the mean differences between the HIRLAM reanalysis and the CM SAF reference data set shows a clear annual cycle with largest / smallers differences in summer / winter (figure 68).

Figures 69 & 70: Anomalies of water vapour in July 2001 by ATOVS and HIRLAM

Figures 71 & 72: Difference and correlation of the anomalies of water vapour in July 2001 by ATOVS and HIRLAM

A very good agreement between the two data sets is shown in the comparison of the anomalies for July 2001 both in the spatial distribution, as well as in absolute terms (figures 69 to 71). The differences are scattered distributed in the reference domain, likely caused by the coarser resolution of the ATOVS data set. The mean bias of the anomalies is close to zero and the correlation very high (figure 72).
5.2.4.2. MetOffice Reanalysis

Figures 73 & 74: Monthly July means of water vapour from 2008-2009 by ATOVS and MetOffice

Figures 73 and 74 show the water vapor content on the EURO4M region (mean of July 2008 and 2009). The CM SAF reference data set and the MetOffice reanalysis data set show dry air North of 60°N with local minima over Iceland and Norway. Also the Iberian Peninsula and the Eastern Mediterranean region incl. Turkey are comparably dry. The highest amount of water vapor is found in the eastern part of the Black Sea.

Figures 75 & 76: Monthly July differences and annual course of differences of water vapour from 2008-2009 by ATOVS and MetOffice

The difference values in figure 75 show that the reanalysis data set underestimates the water vapor content over land, but almost exclusively overestimates over water surfaces. Particularly strong is the underestimation over mountainous regions, such as the Norwegian coast, the Alps, the Pyrenees and the Tatra Mountains. There is a slight overestimation of the water vapor at the southern side of the Alps in northern Italy. Over the sea the reanalysis data set tends to overestimate the water vapor, e.g., in the eastern Mediterranean and off the coast of Spain, Morocco and Iceland.
The annual comparison of the differences between ATOVS and 4DVAR reanalysis reflects a distinct annual cycle. During the summer months of May to September, the records differ more than between October and March. It is likely that this is due to the higher variability of exposure in summer (figure 76).

Anomalies July 2008:

**Figures 77 & 78:** Anomalies of water vapour in July 2008 by ATOVS and MetOffice

**Figure 79:** Differences of anomalies of water vapour in July 2008 by ATOVS and MetOffice

The anomalies for July 2008 are well reproduced by the reanalysis data set (figures 77 and 78). While positive anomalies occur above the northwestern Atlantic Ocean, the Mediterranean Sea off the south coast of Spain and the south of Italy and in parts of Russia, negative anomalies are seen over the Baltic states, as well as the Southeastern continental area (figure 79).
6. Summary

The evaluation of the two regional reanalysis developed within EURO4M shows that both data sets well describe the atmospheric conditions and are useful tools for climate monitoring and analysis.

The SMHI HIRLAM reanalysis tends to overestimate the surface solar radiation over land and to underestimate the solar radiation over the ocean. Particular large overestimations were found in mountainous regions. Also the MetOffice 4D-VAR reanalysis data set overestimates the surface solar radiation over land and mountainous regions and underestimates over the ocean.

The spatial distribution of the differences in the integrated water vapor is very similar, but with opposite signs, to those found for the surface solar radiation, meaning an underestimation of the water vapor over land and a tendency to overestimate the water vapor over sea.

The cloud coverage in the HIRLAM reanalysis data set in the Mediterranean region tends to be underestimated consistent with the overestimation found in the surface solar radiation. The MetOffice reanalysis data set tends to underestimate the cloud coverage, but to a lesser extent than the SMHI reanalysis data set.

An overestimation of the surface precipitation is found in the HIRLAM reanalysis data set over the eastern part of the domain and the Northern Atlantic. Particular high differences are found over the Alpine regions and along the Norwegian Coastline. The MetOffice reanalysis data set overestimates precipitation over the sea and shows some regions of underestimation over land. It should be noted that for the assessment of the precipitation in the MetOffice reanalysis data set only data from 2008 could be used.

In all cases the EURO4M regional reanalyses are able to accurately capture monthly anomalies, despite some limitations of the reanalysis data sets in the absolute accuracy of certain parameters, e.g., the surface solar radiation. For all analysed parameters, the anomalies are represented very well.

Based on our assessment we conclude that the new EURO4M regional reanalysis data sets provided by SMHI and MetOffice are well suited for climate monitoring and analysis. In particular the good representation of the monthly anomalies will allow detailed assessments of extreme climate events.
7. References


