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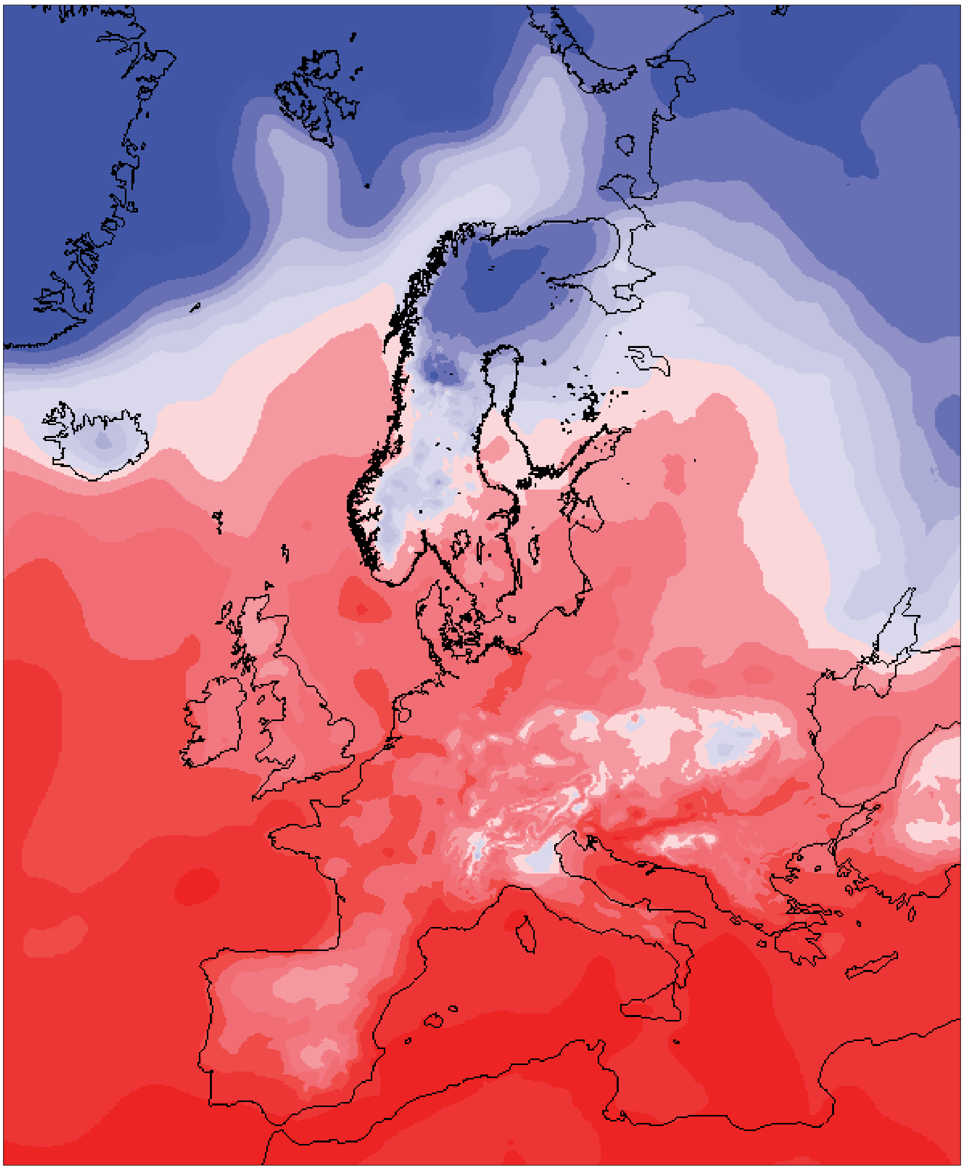

2D meso-scale re-analysis of precipitation, temperature and wind over Europe - ERAMESAN

Time period 1980-2004

Anna Jansson, Christer Persson and Gustav Strandberg

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2D meso-scale re-analysis of precipitation, temperature and wind over Europe - ERAMESAN

Abstract/Sammandrag

The need for long time series of gridded meteorological data with a fine spatial and temporal resolution has increased in recent years. The requirements for this type of gridded meteorological data fields arise from many different areas of the society, in connection to atmospheric environment studies of air quality and deposition and trends in these parameters, regional climate change, wind energy, hydrological studies etc. The aim of the present project is to investigate the possibility of producing historical, high quality and time consistent, meso-scale re-analyses for the whole of Europe regarding precipitation, 2 m temperature and wind for at least 25 years back in time.

The MESAN analysis system (Häggmark et al., 2000) at SMHI was chosen as a basis for the re-analysis and the system was adjusted to cover the whole of Europe. In order to find the most appropriate first guess fields to be used in the MESAN system, a pilot study was performed. ERA-40 data from ECMWF was selected as best possible first guess fields for the re-analysis. The performed re-analysis, which is denoted ERAMESAN, includes gridded data covering all Europe with a time resolution of 6 h and a spatial resolution of 0.1º (11 km) in a rotated latitude longitude coordinate system for the time-period 1980-2004. All analyses are archived in GRIB-format and stored on disc at SMHI. The dataset is also available within the EUMETNET optional programme Showcase EUROGRID.

A partial validation for the years 1998-2000, using a cross validation procedure with independent observations (5.5% of the total amount of stations), shows an improvement in ERAMESAN compared to the ERA-40 data for all studied parameters with regard to root mean square deviation, mean absolute deviation and mean bias deviation for all seasons. The deviations are roughly of the order of 15% smaller compared to what is obtained from ERA-40. The frequency distribution of large precipitation amounts per day and high wind speeds are substantially better described in ERAMESAN compared to ERA-40. However, the tendency to underestimate the frequency of very large precipitation amounts or high wind speeds, compared to observations, can be seen also for ERAMESAN. It is important to be aware of this limitation when using ERAMESAN data for practical applications concerning evaluation of risks for extreme wind speeds or very large precipitation amounts or in e.g. wind energy studies.

Key words/sök-, nyckelord
Meteorology, climate, re-analysis, meso-scale, temperature, precipitation, wind, MESAN, ERA-40, validation, data base, 6h, daily, monthly, annual

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Contents

1 Introduction

The need for long time series of gridded meteorological data with a fine spatial and temporal resolution has increased in recent years. The requirements for these types of gridded meteorological data fields arise from many different areas of the society, in connection to atmospheric environment studies of air quality and deposition and trends in these parameters, regional climate change, wind energy, hydrological studies etc.

Since late 1990-ies SMHI has utilised a system for meso-scale analyses (MESAN) of selected meteorological parameters (Häggmark et al., 2000) in an operational production. MESAN is based on statistical interpolation for each studied meteorological parameter, where observations at each time are used together with a background field, often referred to as the first guess field. The MESAN meso-scale analyses at SMHI have been used in near real-time for weather now-casting in order to obtain information of significantly higher quality compared to the numerical weather prediction (NWP) system, and also as historical meteorological input data to air pollution assessment studies, studies of domestic heating, etc. There are, however, some limitations in using the present available operational MESAN analyses at SMHI for e.g. atmospheric environmental studies. The main drawbacks are: a) the analyses only cover the rather short time period 1998-present, b) the utilized meteorological first guess fields are non-consistent, resulting in non-consistent analyses, for the time period and, c) the analysed area only covers northwest Europe. Thus, the present operational MESAN analysis at SMHI is not sufficient for all needs.

2 Objectives

The present project was initiated mainly due to the needs within SMHI and within Swedish authorities in general for an improved quality of fine resolution gridded meteorological input data on the European scale for atmospheric environment modelling, for evaluation of regional scale climate change models, for wind energy studies and as an input to oceanographic and hydrological modelling.

The objectives of the present project are focused on the formulation and test of a re-analysis method which can be applied in a consistent way for a period of 25-50 years back in time. In order to limit the costs the present project was decided only to include already existing models, systems and input data. The detailed aim is to investigate the possibilities and clarify difficulties of producing historical, high quality, meso-scale re-analyses for the whole of Europe regarding the parameters precipitation, 2 m temperature, 10 m u- and v-component of wind and total wind speed.

The purpose of the present report is to give an overview of the methods applied, present the structure of the produced gridded re-analysis dataset and show some basic validations and limitations of the data. No extensive climatological presentation or evaluation for Europe is included.

3 Calculation method

The MESAN univariate analysis system at SMHI, Chapter 3.1, was chosen as a basis for the re-analysis and was extended to cover the whole of Europe with a horizontal resolution of 11 km.

3.1 MESAN meso-scale analysis system

The MESAN system, developed at SMHI (Häggmark et al., 2000), is a system for operational meso-scale univariate analyses of selected meteorological parameters. The analysed parameters are of general interest for operational weather forecasting and now-casting. MESAN is built on the optimal interpolation (OI) technique (Daley, 1991). In OI the observations are used together with a background field, often referred to as the first guess field. Observations can be ordinary in situ weather observations as well as radar and/or satellite data. In OI the first guess field is modified by observations. The used values of the weights depend on the assumed accuracy of the measurements as well as on the assumed quality of the first guess field.

In the present operational MESAN at SMHI, covering only northwest Europe, the first guess fields for the OI procedure are taken from HIRLAM (Undén et al., 2002) +3 h to +12 h forecasts and adjusted with regard to satellite and radar composites as well as with regard to observations from synop-, metar- and climate stations. Also all observations from automatic stations run by SMHI and the Swedish national road authority are included. Besides, physiografic fields such as fraction of land/water, albedo, roughness length, topography and also precipitation climate associated information are included as input.

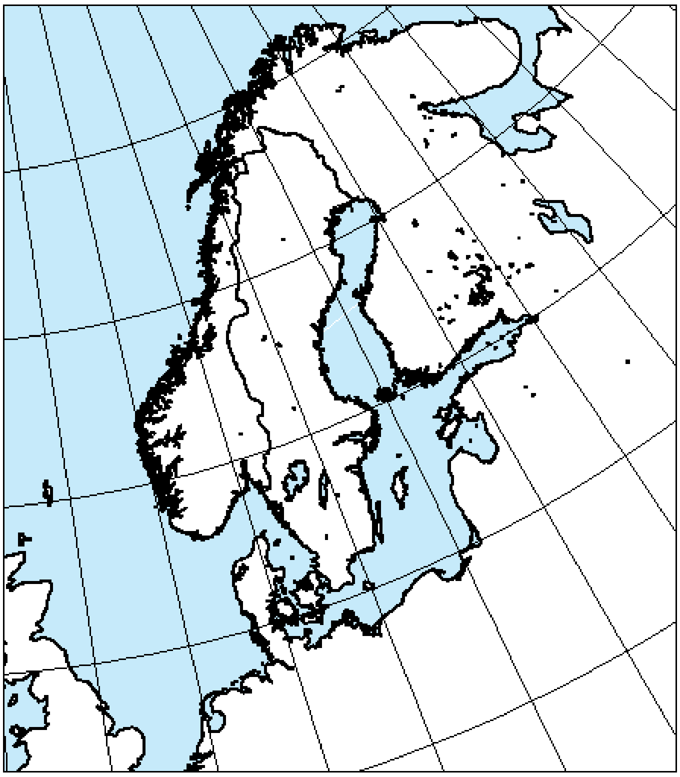

Figure 1. *The operational MESAN area available for this project.*

MESAN has at SMHI been applied for operational analyses of e.g. temperature, precipitation, wind, humidity and clouds since 1998. Analyses, with a spatial resolution of 22 km over northwest Europe (Figure 1), have been run on an hourly basis during several years. In July 2006 the MESAN area was extended a little and the spatial resolution increased to 11 km (Haase et al., 2006). The operational MESAN analyses are used for now-casting and provide gridded input data to models concerning e.g. hydrology, air quality, atmospheric deposition, atmospheric radiation and forest fire risks.

During later years several development projects have been performed concerning implementation of new products from satellites and radar into the MESAN system.

3.2 Alternative first guess fields

In this project we have identified three different convenient possibilities at SMHI for producing meteorological background fields, or first guess fields as they are often called, covering the whole of Europe. These three datasets are already available at SMHI, can easily be obtained or can relatively easy be produced at SMHI.

3.2.1 HIRLAM

The international HIRLAM (High Resolution Limited Area Model) project is a co-operation between several meteorological institutes in Europe. The project develops and maintains a numerical short-range weather forecast system for the participating institutes (Undén et al., 2002).

The operational HIRLAM run at SMHI, which covers the whole of Europe, is performed every 6 h and each new run is based on data assimilation of all available real-time meteorological data and with real-time boundary conditions from ECMWF (European Centre for Medium-Range Weather Forecasts). HIRLAM results regarding analysis (0 h forecast length) and forecast lengths for every +3 h up to +12 h are long time archived. At present the operational HIRLAM version at SMHI covers all Europe has a horizontal grid resolution of 22 km, and a version covering northwest Europe has a horizontal resolution of 11 km. For analysis and short-range weather forecasts HIRLAM is regarded to offer the best quality weather data on the European scale available at SMHI. However, archived HIRLAM data at SMHI only go 6 years back in time. Besides, HIRLAM data for that period is not consistent in time since new model versions with e.g. different horizontal and vertical resolutions have been introduced with 2-3 years intervals. This means that operational HIRLAM data at SMHI is not suitable for long-term re-analysis, but can be used as a source for high quality first-guess fields for a few years back in time. A special re-run of the present version of HIRLAM for decades back in time, including data assimilation, is in principle possible to perform but is far beyond the economic limit of the present project. Thus, the present re-analysis project, going 25 years or more back in time, has to be based on other first guess fields than HIRLAM.

3.2.2 RCA

The RCA model (Rossby Centre regional Atmospheric climate model; Rummukainen et al., 1998 and 2001) at SMHI is originally based on the operational regional weather prediction model HIRLAM but with process formulations and parameterizations adjusted to suit long-term climate simulations. The model is mainly applied for simulations of future climate scenarios, where the RCA model is used for downscaling results from global models.

In the RCA runs for historical data boundary conditions are obtained from ECMWF/ERA-40 (Chapter 3.2.3) or from NCEP/NCAR. An important difference between the RCA runs and HIRLAM is the absence of data assimilation of meteorological observations in RCA. The RCA model is designed for simulations of future climate scenarios, where no observations are available, while data assimilation is an important part of HIRLAM. RCA is run in routine for long periods of time at the Rossby Centre at SMHI and it is possible to use RCA to produce first guess fields for re-analysis calculations back to 1957.

3.2.3 ERA-40

ERA-40 is a comprehensive set of global analyses describing the state of the atmosphere and ocean-wave conditions from September 1957 to August 2002 performed by ECMWF (European Centre for Medium-Range Weather Forecasts; Uppala et al., 2005). The re-analyses are archived in the Meteorological Archive and Retrieval System at ECMWF (MARS; Kållberg et al., 2004), where registered users from the member states can select and retrieve global re-analyses.

The atmospheric model used for ERA-40 is known as IFS CY23r4 which has 60 levels in the vertical, T159 spherical-harmonic representation for basic dynamical fields and a reduced Gaussian grid with approximately 125 km horizontal spacing for surface and other grid point fields. ERA-40 includes four analyses per day (00, 06, 12 and 18 UTC). The forecasts are based on the 00 and 12 UTC analyses and are stored in 3 h interval from 00 to 72 h and in 6 h intervals from 72 to 240 h.

Observations used in the ERA-40 include both observations from the operational ECMWF archive and data supplied to ECMWF by external institutions for use in the re-analysis. The large amount of observations used in ERA-40 originates from the following sources:

1) SYNOP/SHIP, synoptic land and ship observations
2) Radiosonds
3) Pilot balloons
4) Aircraft
5) Buoys
6) Satellite radiances
7) Satellite winds
8) Scatterometer
9) PAOBs (Psuedo Surface Pressure Observations)

ERA-40, with an original spatial resolution of about 125 km, can be interpolated to a higher resolution grid. In the present project the ERA-40 data to be used as first guess fields have been interpolated to a spatial resolution of 44 km, in the same geometry (rotated latitude-longitude, later referred to as rotated lat-lon) as used by HIRLAM at SMHI. ERA-40 data can in this way be obtained for the period 1957-2002. After 2002 data from operational ECMWF runs can be used in a similar way, since the surface analysis formulations in ERA-40 and in the present operational model at ECMWF are very much the same. Data has however a higher spatial resolution in the operational runs after 2002, compared to ERA-40.

4 Evaluation of alternative first guess fields

In order to find the most appropriate first guess fields to be used, covering all Europe and with time consistent data for a period of more than 25 years back in time, a pilot study was performed. Analyses based on the operational MESAN system and first guess fields from SMHI-HIRLAM, available for 2001 and onwards, was considered as best possible and used as key results and “truth”. Such a MESAN set-up was originally designed and extensively cross validated by Häggmark et al. (2000). The pilot study was focused on data for the year 2001.

Comparisons were made between these selected key results and MESAN calculations based on first guess fields from either ERA-40 or RCA. Both ERA-40 and RCA data can be obtained for the time back to 1957.

Thus, the pilot study was used to evaluate which of RCA and ERA-40 would give the best first guess fields for the planned meso-scale re-analysis over Europe. In the pilot study the operational MESAN system at SMHI (Chapter 3.1) was adjusted to 11 km spatial resolution and run for 6 hourly data for year 2001 with three different set-ups, using the three alternative ways of producing the first guess fields as mentioned above (Chapter 3.2). In order to keep labour costs on a low level the pilot study was partly based on an already available MESAN study for wind and temperature. Therefore the pilot study was limited to these two parameters. In all other ways except the choice of first guess fields, the MESAN system was identical for the three alternative set-ups. Also weather observations used for the re-analyses were identical for the three alternatives.

In the pilot study the MESAN system was applied with following characteristics:

System: Operational MESAN, but with 11 km spatial resolution.
Area: Operational MESAN area (Figure 1).
Spatial resolution: 0.1° (11 km), rotated lat-lon coordinates.
Parameters: 2 m temperature and 10 m wind speed (calculated from u- and v-components).
Time period: Year 2001.
Time resolution: 6 h (00, 06, 12 and 18 UTC).
Observations: Identical weather observations have been used in the three alternative cases, based on about 1000 weather stations in northwest Europe.
First guess fields:

- **a) HIRLAM:** Forecast +6 h data applied, rotated lat-lon coordinates, resolution 0.4° (equal to SMHI operational HIRLAM during 2001).
- **b) RCA:** Dynamically downscaled data from ERA-40, data resolution 0.2° with the same geometric projection as HIRLAM. The RCA data was originally produced by the Rossby Centre at SMHI as a part of another project (Magnusson et al., 2004).
- **c) ERA-40**: Original data has a resolution of approximately 125 km (Chapter 3.2.3). Data for this study was retrieved from ECMWF with the same geometrical projection and grid resolution as used in HIRLAM.

The first guess fields in all three alternatives, i.e. the data from HIRLAM, RCA and ERA-40, were interpolated to 0.1° (11 km) spatial resolution within MESAN.

4.1 Results of comparisons

The MESAN results based on first guess fields from HIRLAM were regarded as "truth" and key results without further investigations than referred to above. These key results were compared to MESAN results based on either RCA (comparison denoted "RCA-HIRLAM") or ERA-40 (comparison denoted "ERA40-HIRLAM") as first guess fields.

For the validations included in the present project we have used the following notations. The "error" of an individual value is:

$$\varepsilon = AN - OBS \tag{1}$$

AN refers to the studied analysis and *OBS* refers normally to the observed value. In the present Chapter, describing the pilot study, *OBS* refers to the "truth" obtained from the MESAN system using first guess fields from SMHI-HIRLAM. Having a set of *N* hourly, daily or monthly ε-values different "error" quantities can be calculated. Below the expression "deviation" is used instead of "error" because the observations, or the best possible MESAN analyses, are not perfect references.

In this project three deviation quantities have been used, namely:

The mean bias deviation (MBD):

$$MBD = \left(\sum_{i=1}^{N} \varepsilon \Big/ N \right) \tag{2}$$

the mean absolute deviation (MAD):

$$MAD = \left(\sum_{i=1}^{N} |\varepsilon| \Big/ N \right) \tag{3}$$

and the root mean square deviation (RMSD):

$$RMSD = \sqrt{\left(\sum_{i=1}^{N} \varepsilon^2 \Big/ N \right)} \tag{4}$$

In the pilot project also the mean correlation coefficient (*R*) is applied and calculated for the total number (*N*) of samples of the variables *x* and *y*:

$$R = \frac{\frac{1}{N} \sum_{i=1}^{N} \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{N} \left(x_i - \bar{x}\right)^2 \Big/ N} \sqrt{\sum_{i=1}^{N} \left(y_i - \bar{y}\right)^2 \Big/ N}} \tag{5}$$

where x_i and y_i denote the individual values for *AN* and *OBS* in Eq. 1. *N* equals to the total number of samples for *x* and *y*. The bar notations stand for the mean values of all samples.

These four statistical quantities were calculated for the studied parameters in the RCA-HIRLAM and ERA40-HIRLAM comparisons and are presented in Figures 2 and 3 below. In order to reveal any seasonal variation the results are presented separately for each month of the year.

4.1.1 Temperature

In Figure 2 results from the RCA-HIRLAM and ERA40-HIRLAM comparisons for temperature analyses are shown. MAD- and RMSD-values are lower and R-values

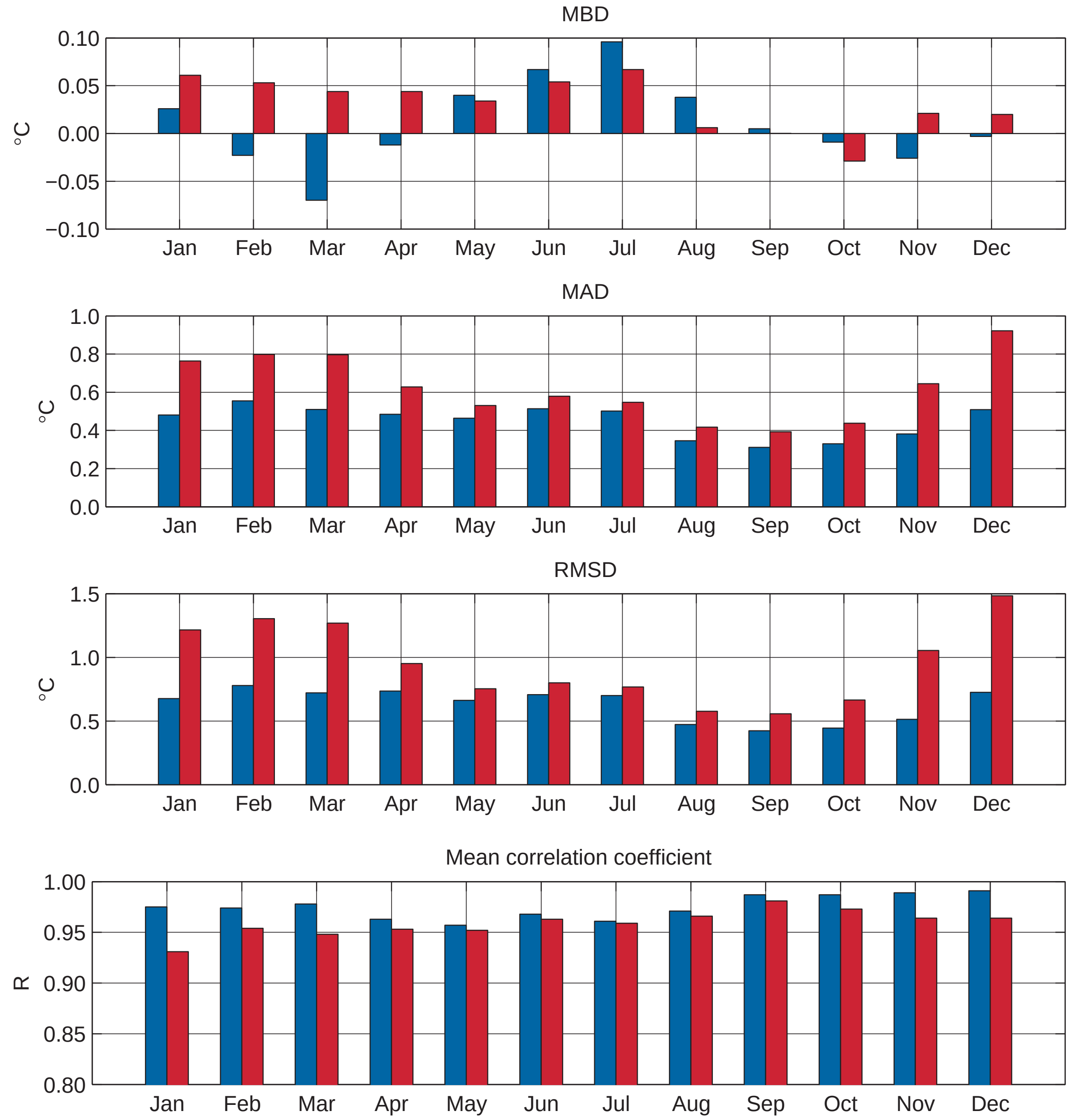

Figure 2. *Deviations calculated for temperature analyses 2001: Histogram for MBD (Eq. 2), MAD (Eq. 3), RMSD (Eq. 4) and mean correlation coefficient R (Eq. 5, y-axis starts above zero) for the comparisons ERA40-HIRLAM (blue bars) and RCA-HIRLAM (red bars).*

higher for ERA40-HIRLAM compared to RCA-HIRLAM for all months of the year. Thus, MESAN analyses for temperature based on ERA-40 first guess fields have the best agreement with the selected key results. The bias, MBD, is small, less than ±0.1 ºC for all months and for both first guess alternatives. The lowest MAD and RMSD values are obtained during late summer and early autumn and the largest deviations during winter. The seasonal variation for RMSD is up to a factor of two when using RCA as first guess.

4.1.2 Wind speed

In Figure 3 results from the RCA-HIRLAM and ERA40-HIRLAM comparisons for wind speed analyses are shown. The general pattern for wind speed analysis is the same as for the temperature analysis. The MAD- and RMSD-values are lower and R-values higher for ERA40-HIRLAM compared to RCA-HIRLAM for all months of the year.

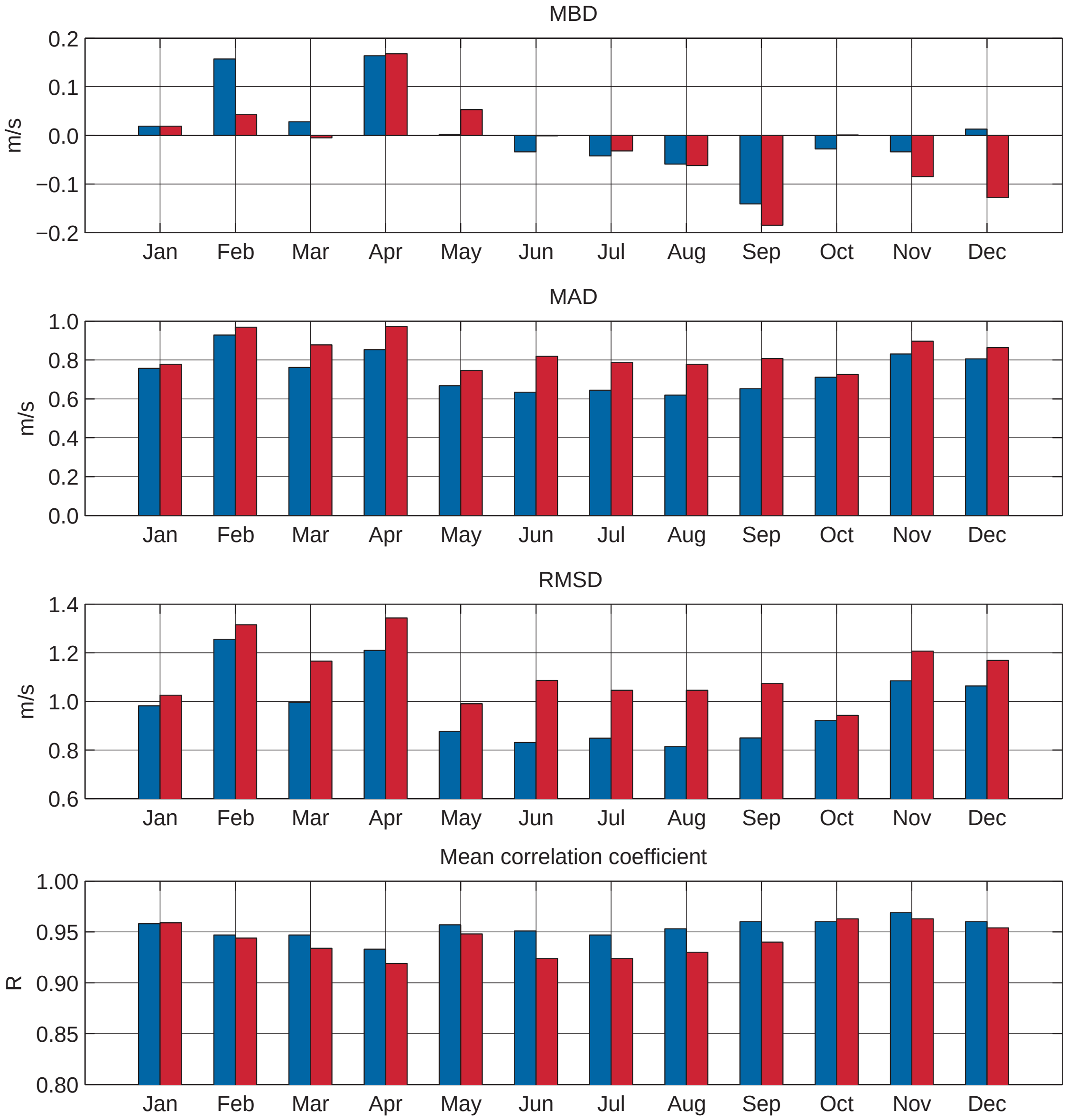

Figure 3. *Deviations calculated for wind speed analyses 2001: Histogram for calculated MBD (Eq. 2), MAD (Eq. 3), RMSD (Eq. 4) and mean correlation coefficient R (Eq. 5, y-axis starts above zero) for the comparisons ERA40-HIRLAM (blue bars) and RCA-HIRLAM (red bars).*

Thus, also for wind speed, MESAN analyses based on ERA-40 first guess fields have the best agreement with the selected key results.

The bias is small also for wind speed, ± 0.15 m/s or less, for almost all months and both alternatives. The smallest deviations for MAD and RMSD are obtained during summer and the largest during winter.

4.1.3 Conclusion

It is quite clear from this pilot study that the MESAN temperature and wind analyses based on ERA-40 first guess fields agree better with the selected key results, compared to when RCA first guess fields are used.

Some case study investigations indicate, not surprising, that the lack of data assimilation in RCA can be crucial in certain situations. The propagation of cyclones within the RCA model area can differ compared to what is obtained in the HIRLAM analyses, where data assimilation is included, and thus reduce the agreement in the RCA-HIRLAM comparison. When increasing the model area from northwest Europe, which is used in our pilot study, to the whole of Europe in the main re-analysis project, this effect might even increase.

There is a risk in statistical analyses when including the same observations in both the first guess fields and the OI-analysis. When applying HIRLAM first guess fields this problem is avoided through the use +6 h forecasts. It is neither a problem for wind fields from ERA-40, since 10 m wind observations over land are not included in the data assimilation (same would be true for precipitation). For 2 m temperature from ERA-40 this could be a problem, but the ERA-40 has a course spatial resolution and includes a full dynamical solution, which reduce the dependence of a single temperature observation.

Since we have no reason to question our choice of key results, our conclusion from the pilot project is that ERA-40 is most suitable to use as first guess fields in our re-analysis project. From the discussion above concerning RCA, it is also plausible to assume that ERA-40 data would be most suitable for the precipitation re-analysis, although that parameter was not included in the pilot study. The long-term re-analysis, based on ERA-40 data and the MESAN system, will below be referred to as ERAMESAN.

5 ERAMESAN analysis system

5.1 MESAN set-up

The MESAN system was applied with following characteristics:

System: Operational MESAN.
Area: All Europe (Figure 4, left). North-West corner at 80.69° N, 61.79° W, North-East corner at 59.92° N, 76.57° E, South-West corner at 33.87° N, 18.69° W and South-East corner at 25.95° N, 23.31° E. 497 grid points in the North-South direction and 413 grid points in East-West direction. The area is 4.3 times larger than the operational MESAN area (Figure 1).
Spatial resolution: 0.1° (11 km), rotated lat-lon coordinates.

Parameters: 2 m temperature, 10 m wind speed based on analyses of u- and v-components, 10 m wind speed based on analyses of total wind speed, 12 h accumulated precipitation and 24 h accumulated precipitation.
Time period: 1980-2004.
Time resolution for temperature and wind: 6 h (00, 06, 12 and 18 UTC).
Time resolution for precipitation: 12 h accumulated values ending at 06 and 18 UTC and 24 h accumulated values ending at 06 UTC.
Observations: About 1900 weather stations in Europe (Figure 4, right).
First guess fields: ERA-40 data. The original analysis has a horizontal resolution of approximately 125 km. For this study data was retrieved from ECMWF with the same geometrical projection as used in HIRLAM and with a horizontal grid resolution of 44 km. First guess fields were then interpolated to 0.1° spatial resolution within the MESAN system.
Physiographic fields: Topography, roughness length, fraction of land, fraction of water etc. were obtained from HIRLAM (horizontal resolution 44 km) and interpolated to 11 km horizontal resolution.

A field describing the standard deviation of precipitation for the ERAMESAN area is needed and was calculated based on 24 h accumulated precipitation from ERA-40 for the time period 1961-1990.

5.2 First guess

The ERA-40 data was retrieved from the MARS system at ECMWF. Data was retrieved in a rotated lat-lon coordinate system (same as HIRLAM) with the South Pole at 30° S and 10° W and with a spatial resolution of 0.4° (44 km). For the period 2002-2004 operational ECMWF model data was used as a replacement for ERA-40, since ERA-40 ends August 2002. This is justified by the fact that the surface analysis formulations in ERA-40 and in the operational model at ECMWF 2002-2004 are roughly the same. The operational model is however run with a higher spatial resolution than ERA-40.

The data was selected from the spherical-harmonic representation in the MARS system and the retrieved parameters were:

- 2 m temperature analyses at 00, 06, 12 and 18 UTC
- 10 m u- and v-component of the wind analyses at 00, 06, 12 and 18 UTC (used for analyses of u- and v-components as well as for total wind speed)
- 6 h and 18 h forecast for convective and stratiform precipitation at 00 and 12 UTC (used for analyses of 12 h and 24 h precipitation).

By subtracting the +6 h forecast from the +18 h forecast at 00 and 12 UTC, 12 h accumulated precipitation values valid at 18 and 06 UTC respectively are obtained. These forecast lengths are regarded as most suitable in order to avoid most of the model spin-up effect which occurs during the first hours of precipitation forecast. In ERA-40 the spin-up effect during the first forecast hours is known to cause an underestimate of precipitation at higher latitudes and an overestimate in tropical regions (Uppala et al., 2005).

5.3 Observations

All weather observations used in the present project were obtained from the archive at SMHI. The geographical distribution of the weather stations used for the re-analysis is given in Figure 4, right. The whole ERAMESAN area is covered but with relatively large differences in station density for different parts of Europe. Swedish observations, and Norwegian observations for a short period, were quality controlled before archived, while all other observations from outside Sweden are without any other quality control than what was performed in real-time and a rudimentary check within the MESAN system. A detailed quality control of observational data was regarded as being beyond the economic limits of the present study. This is however an important limitation and such an effort should be emphasized in later steps towards a high-quality gridded dataset for Europe.

About 1900 weather stations in Europe (not identical stations for all parameters) were used for each of the temperature, precipitation and wind analyses. In Sweden the precipitation station network for the analysis is substantially denser than for the rest of Europe, since also a large number of small Swedish stations, not included in the international data exchange, were obtained. The GPCC (Global Precipitation Climatology Centre) quality controlled precipitation observations have not been utilized since only monthly accumulated values were available.

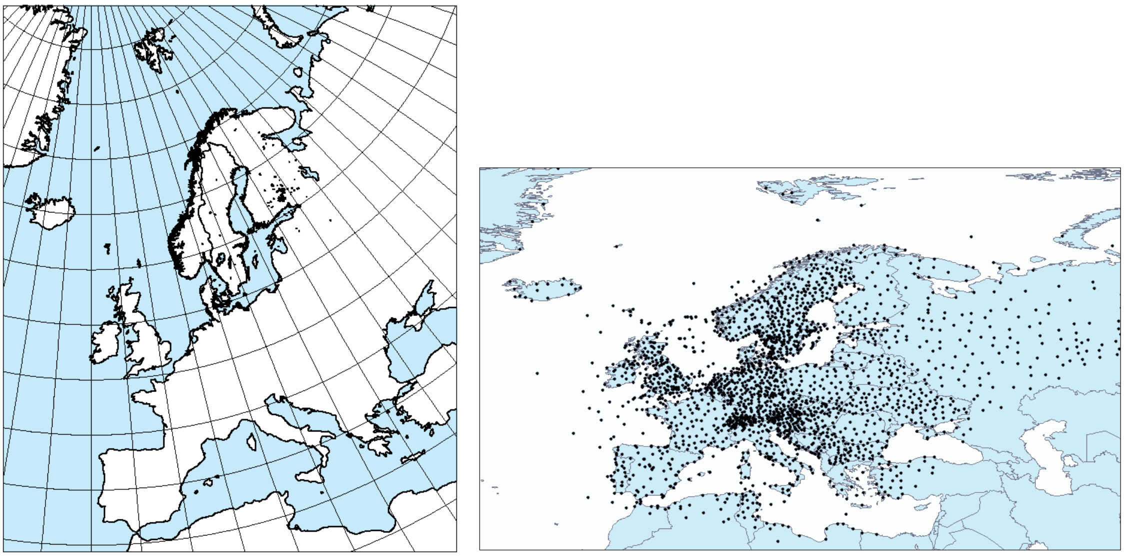

Figure 4. *Left: ERAMESAN area; Right: Temperature observations available at 18 UTC January 1st, 2004 which roughly indicates the station network used for the analysis.*

6 ERAMESAN results

The present project is only a first attempt to perform a high-quality, high-resolution re-analysis over Europe, further steps have to follow. Therefore just some few examples of results are presented and no more extensive climatological evaluation is given. Future practical use of the ERAMESAN dataset has to reveal further details.

6.1 Examples of results for temperature

The mean temperature over Europe for the 10-year period 1980-1989 is in fairly good agreement with the mean temperature for the whole normal period 1961-1990 which, based on ERA-40 data, is shown in Figure 5. This makes it possible to use the ERAMESAN mean temperature 1980-1989 (Figure 6, left) as a rough normal year reference in order to investigate the yearly deviations from normal temperature for 1990 and onwards over Europe.

In Figure 6, right, the temperature difference between ERAMESAN and ERA-40 for the time-period 1980-1989 is indicated. The most pronounced differences are caused by the difference in resolution of topography. The higher spatial resolution in the ERAMESAN topography compared to ERA-40 results in a more detailed description with e.g. higher temperatures over low-land areas which are surrounding larger mountains, compared to what is obtained from ERA-40. However, unfortunately also the present ERAMESAN topography is relatively coarse (interpolated from 0.4° spatial resolution) and the current structure functions in the MESAN system are blunt and neither fully optimized for mountainous areas.

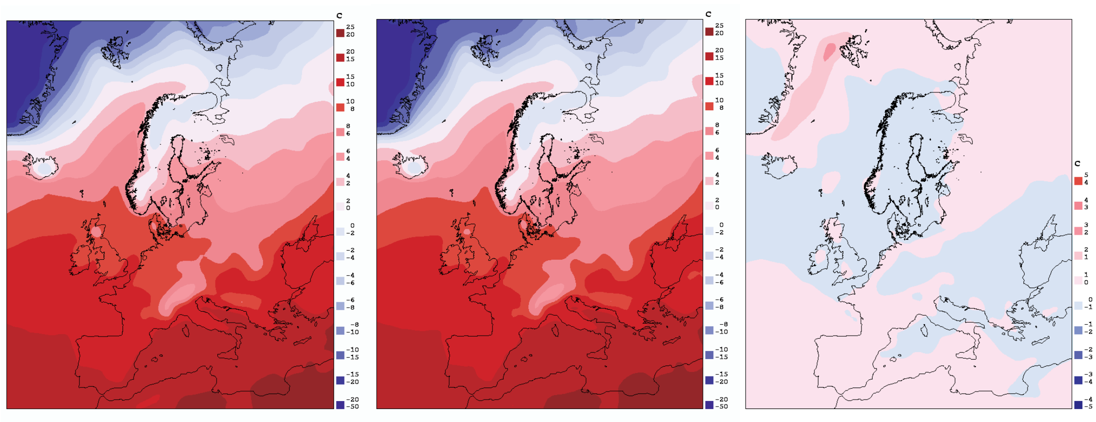

Figure 5. *Mean temperature (ºC) from ERA-40. Left: Period 1961-1990. Middle: Period 1980-1989. Right: Difference between the mean temperature for the period 1980-1989 and the period 1961-1990 (1980-1989 minus 1961-1990).*

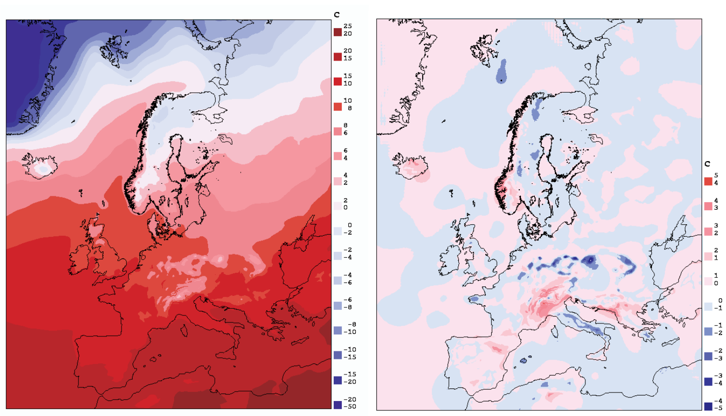

Figure 6. *Left: Annual mean temperature (ºC) from ERAMESAN for the period 1980-1989, which is used as a reference period for the difference plots in Figures 7 and 8. Right: The difference in annual mean temperature (ºC) 1980-1989, ERAMESAN minus ERA-40.*

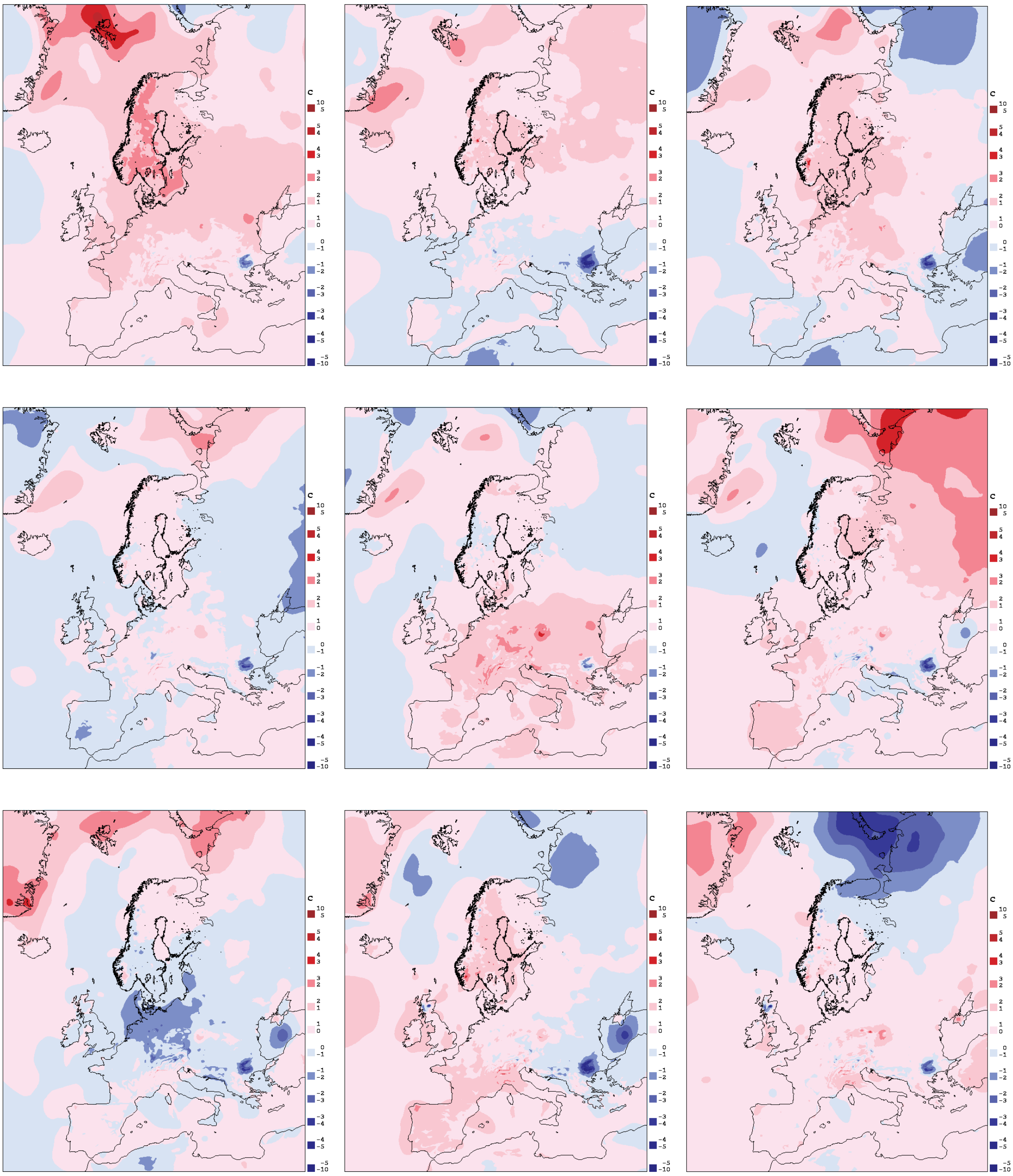

Figure 7. *Difference between annual mean temperature for each specific year and the mean temperature for the selected reference period 1980-1989. All data refer to ERAMESAN. Top row from left to right: 1990, 1991, 1992. Middle row from left to right: 1993, 1994, 1995. Bottom row from left to right: 1996, 1997, 1998.*

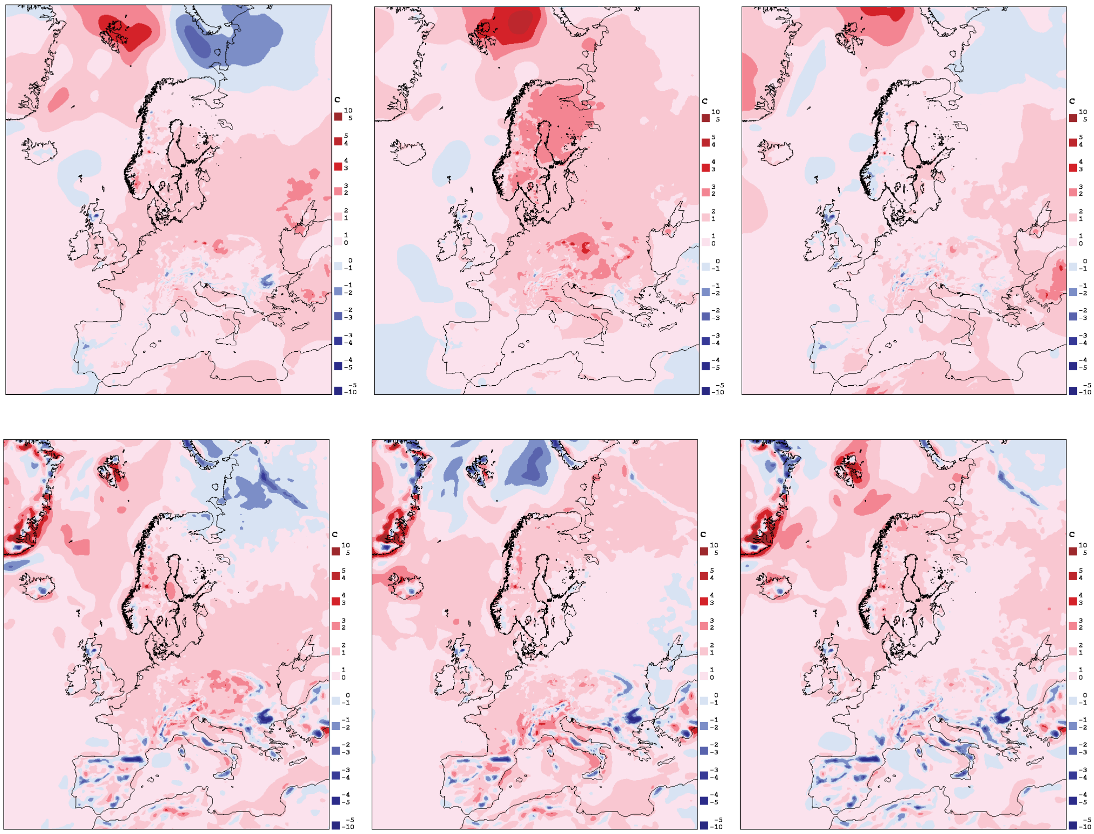

Figure 8. *Difference between annual mean temperature for each specific year and the mean temperature for the selected reference period 1980-1989. All data refer to ERAMESAN. Top row from left to right: 1999, 2000, 2001. Bottom row from left to right: 2002, 2003, 2004.*

Data from 1990 and later is of specific interest since 1990 is often used as a reference year in connection to environmental studies and in connection to emissions of greenhouse gases and the Kyoto protocol. An important part of these emissions are related to heating of buildings and thus related to temperature. Figures 7 and 8 indicate that during the 15-year period 1990-2004 all years except one, 1996, had a mean temperature above normal for most of Europe. Further details can of course be studied by means of the available dataset.

The effect of an increased resolution in the applied first guess fields, compared to what was used for the reference period, can easily be seen in Figure 8. For the years 2002-2004 results from the ECMWF operational runs, with higher spatial resolution, were used as first guess since no complete year of data from ERA-40 is available after end of 2001. The small scale deviations in temperature compared to the reference period are mainly caused by the difference in resolution of the topography.

6.2 Examples of results for precipitation

Presentations for precipitation, in the same way as for temperature (Chapter 6.1), can be seen in Figures 9-12. Also for precipitation the period 1980-1989 is selected as a reference period and compared to each of the years 1990-2004. For precipitation no such clear pattern in differences, compared to the reference period, can be seen as for temperature.

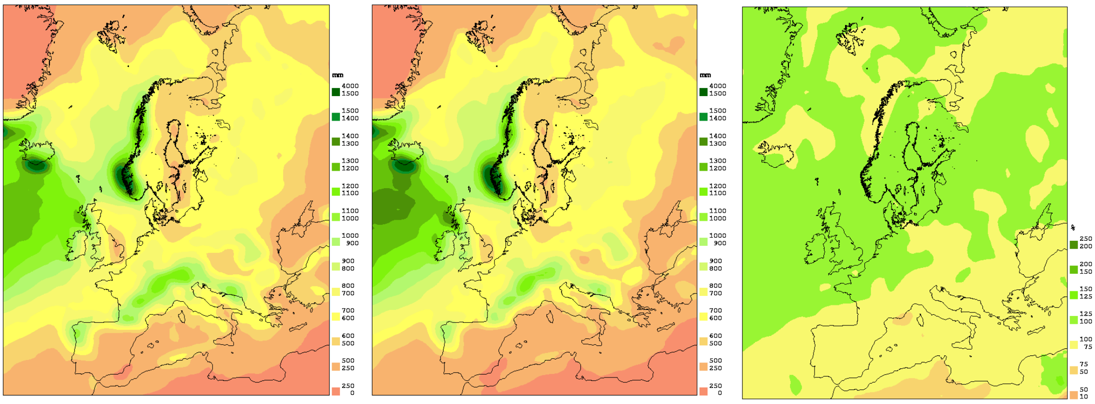

***Figure 9**. Mean annual precipitation (mm) from ERA-40. Left: Period 1961-1990. Middle: Period 1980-1989. Right: Ratio in %, annual mean precipitation for period 1980-1989 divided by period 1961-1990.*

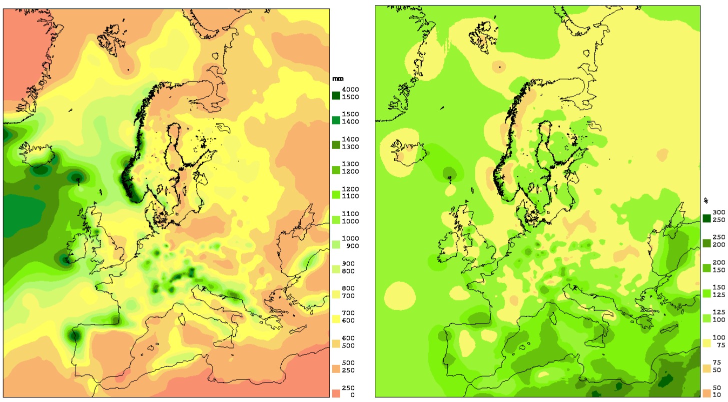

***Figure 10.** Left: Annual mean precipitation (mm) from ERAMESAN for the period 1980-1989, which is used as a reference period for the ratio plots in Figures 11 and 12. Right: Ratio in %, ERAMESAN divided by ERA-40, for annual mean precipitation for the period 1980-1989.*

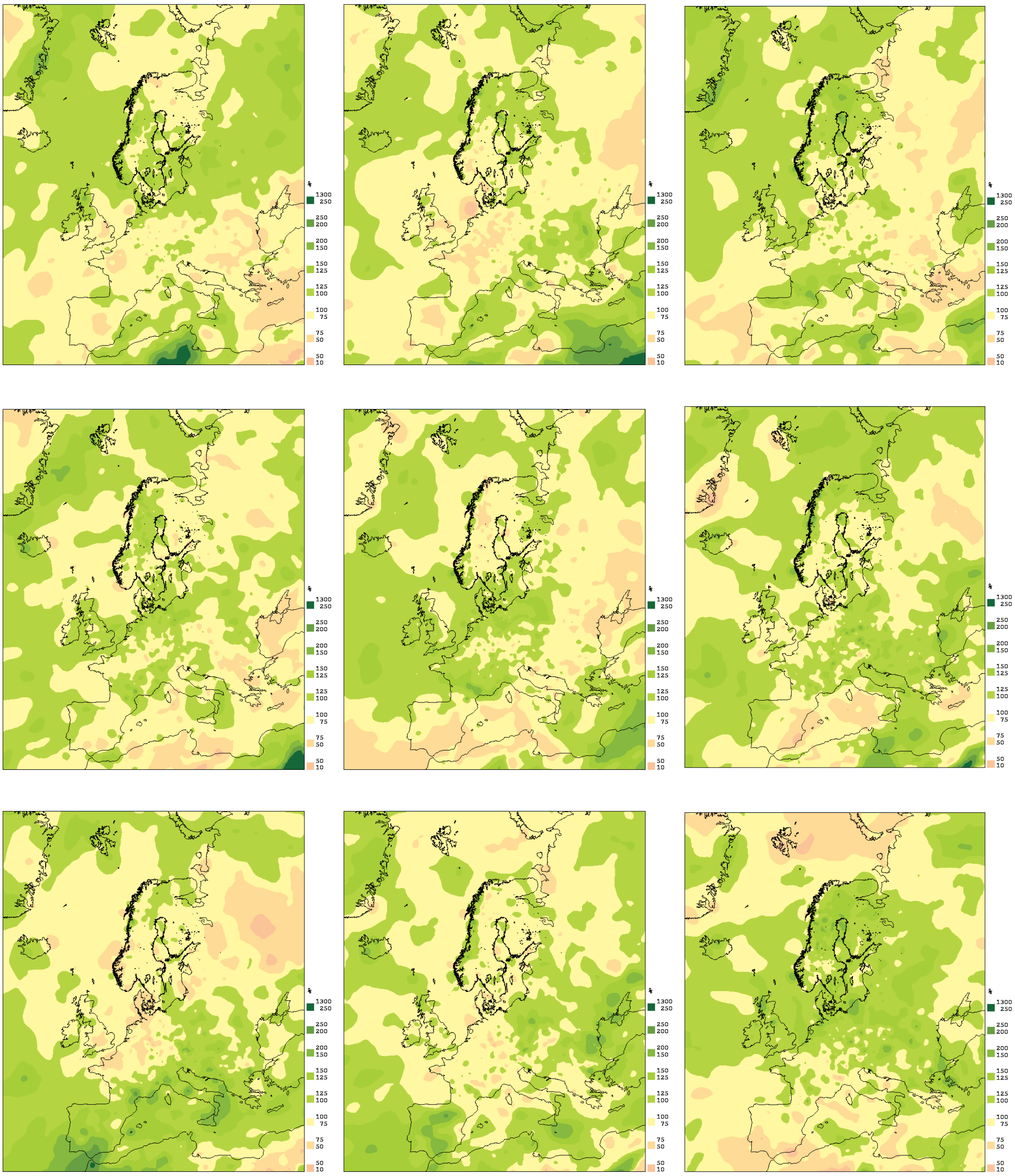

Figure 11. *Ratios (%) between annual precipitation for each year and the annual mean precipitation for the selected reference period 1980-1989 (specific year/1980-1989). Top row from left to right: 1990, 1991, 1992. Middle row from left to right: 1993, 1994, 1995. Bottom row from left to right: 1996, 1997, 1998.*

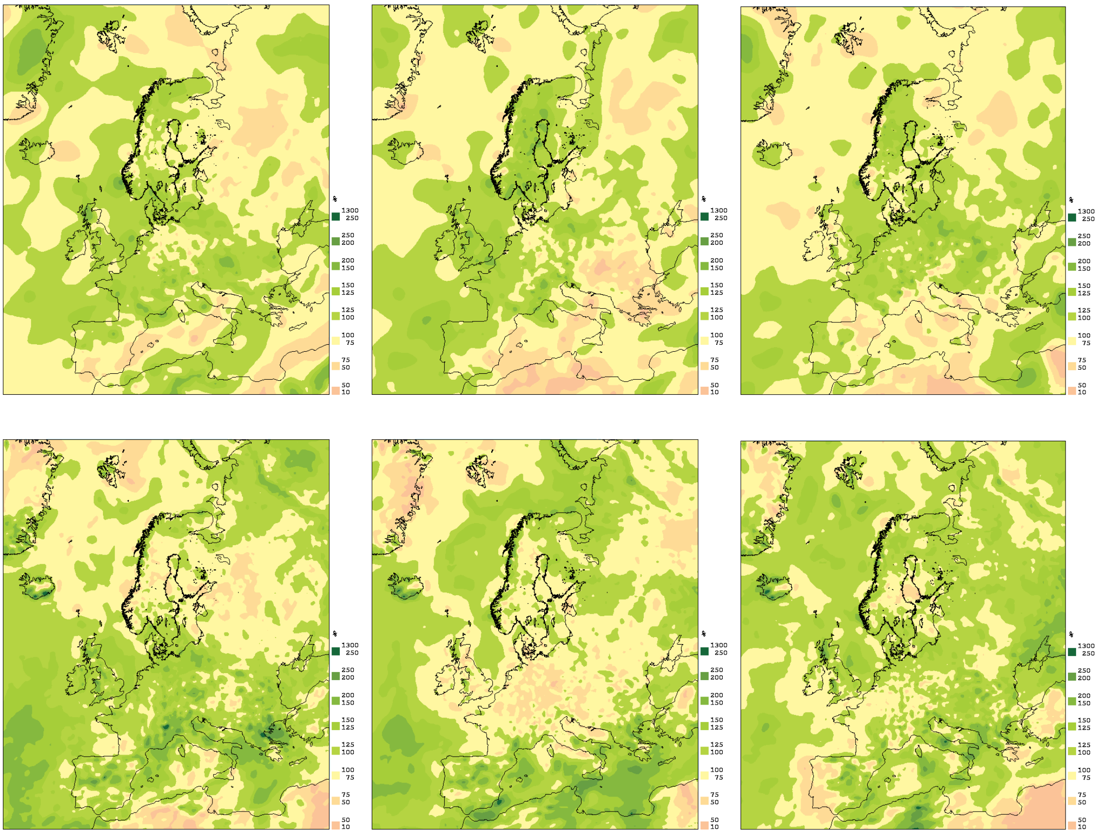

Figure 12. *Ratios (%) between annual precipitation for each year and the annual mean precipitation for the selected reference period 1980-1989 (specific year/1980-1989). Top row from left to right: 1999, 2000, 2001. Bottom row from left to right: 2002, 2003, 2004.*

6.3 ERAMESAN dataset

The present ERAMESAN dataset, which covers the time period 1980-2004 contains re-analyses over Europe for:

- 2 m temperature at 00, 06, 12 and 18 UTC
- u- and v-component of the 10 m wind at 00, 06, 12 and 18 UTC
- wind speed at 10 m based on analyses of total wind speed at 00, 06, 12 and 18 UTC
- 12 h accumulated precipitation ending at 06 and 18 UTC (no corrections for e.g. wind losses or evaporation)
- 24 h accumulated precipitation ending at 06 UTC (no corrections for e.g. wind losses or evaporation).

The spatial resolution is 0.1° (11 km) in a rotated lat-lon coordinate grid with the south-pole at 30° S, 10° W.

Data is stored as GRIB-files (valid 00, 06, 12 and 18 UTC) on disc at SMHI. The ERAMESAN data is also included as a demonstration dataset in the EUMETNET (network of about 25 European National Meteorological Services) optional programme “Showcase EUROGRID” (www.e-grid.eu). The purpose of Showcase EUROGRID, which takes part 2007-2008, is to illustrate how gridded data over Europe can be used for products and services from modern meteorological services. SMHI is Responsible Member for Showcase EUROGRID.

7 Partial validation

7.1 Method

We have performed a partial validation using a limited cross validation procedure. Two subsets of stations were selected, which each represented approximately 2.7% of the total amount of stations. These stations (about 51 per dataset) were randomly chosen and evenly spread over the whole ERAMESAN area. The observations from these stations were excluded from the observations used as input to an ERAMESAN validation analysis. These independent stations were instead used to validate the specific ERAMESAN validation analysis by comparing the observations from the independent stations with the analysis for the same time and location. Thus, for the time being we have limited the validation study to include only a set of altogether 101 independent stations corresponding to approximately 5.5% of all stations. This procedure could of course be extended to include all stations, which however was beyond the economic frame of the present study. We have also limited the validation study to the time period 1998-2000 and results are only presented as a sum for the whole ERAMESAN area. As a comparison a validation based on the same observations was performed for the original ERA-40 re-analyses which were used as first guess fields.

It is anticipated that further validation will be possible to perform at a later stage. The Showcase EUROGRID project might also offer possibilities for comparisons of ERAMESAN to other gridded data-sets over Europe or parts of Europe.

7.2 Results of validation

7.2.1 Temperature

For temperature, hourly values at 00, 06, 12 and 18 UTC together with daily (24 h) and monthly mean values are validated against the independent set of observations. Daily and monthly mean temperatures are calculated as mean value of hourly (00, 06, 12, 18 UTC) values. All comparisons between analyses and observations are made for identical samples in time. Lack of individual samples in time is however not considered in the daily and monthly values. All validations are given as ERAMESAN or ERA-40 re-analyses minus observations. In Figure 13 calculated MBD (Eq. 2), MAD (Eq. 3) and RMSD (Eq. 4) values are presented from our validation of ERAMESAN (blue bars) referring to the validation time period 1998-2000. Corresponding values for the validation of the original ERA-40 data are presented as red bars. In Figure 14 this information is separated into each month of the year in order to reveal possible seasonal variations. All results show a better agreement between the ERAMESAN analyses and the independent observations compared to ERA-40 versus observations. The mean deviations are roughly 15% smaller for ERAMESAN compared to ERA-40.

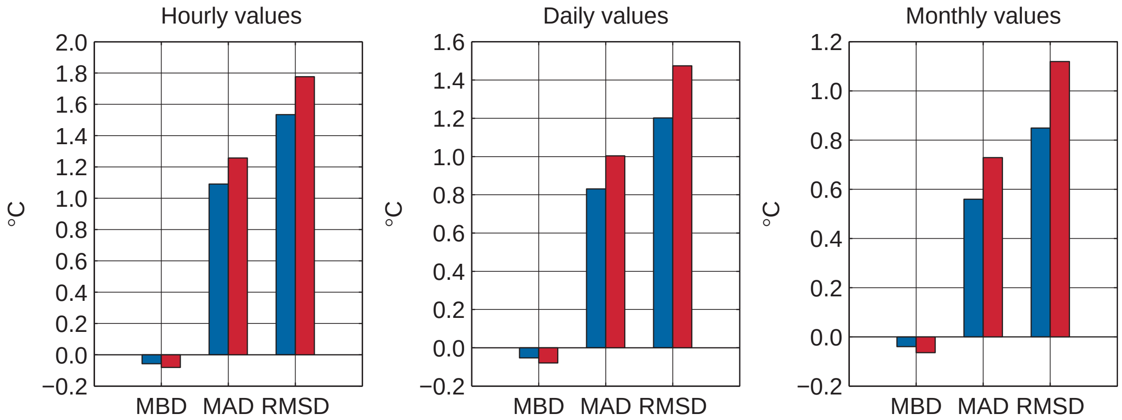

Figure 13. *Validation of temperature analyses for the selected time period 1998-2000, based on all independent stations. Histograms (ºC) are given for MBD (Eq. 2), MAD (Eq. 3) and RMSD (Eq. 4) for comparisons between 'ERAMESAN minus observations' (blue bars) and 'ERA-40 minus observations' (red bars). Left: Temperatures every 6 h (00, 06, 12 and 18 UTC). Middle: Daily mean temperatures. Right: Monthly mean temperatures.*

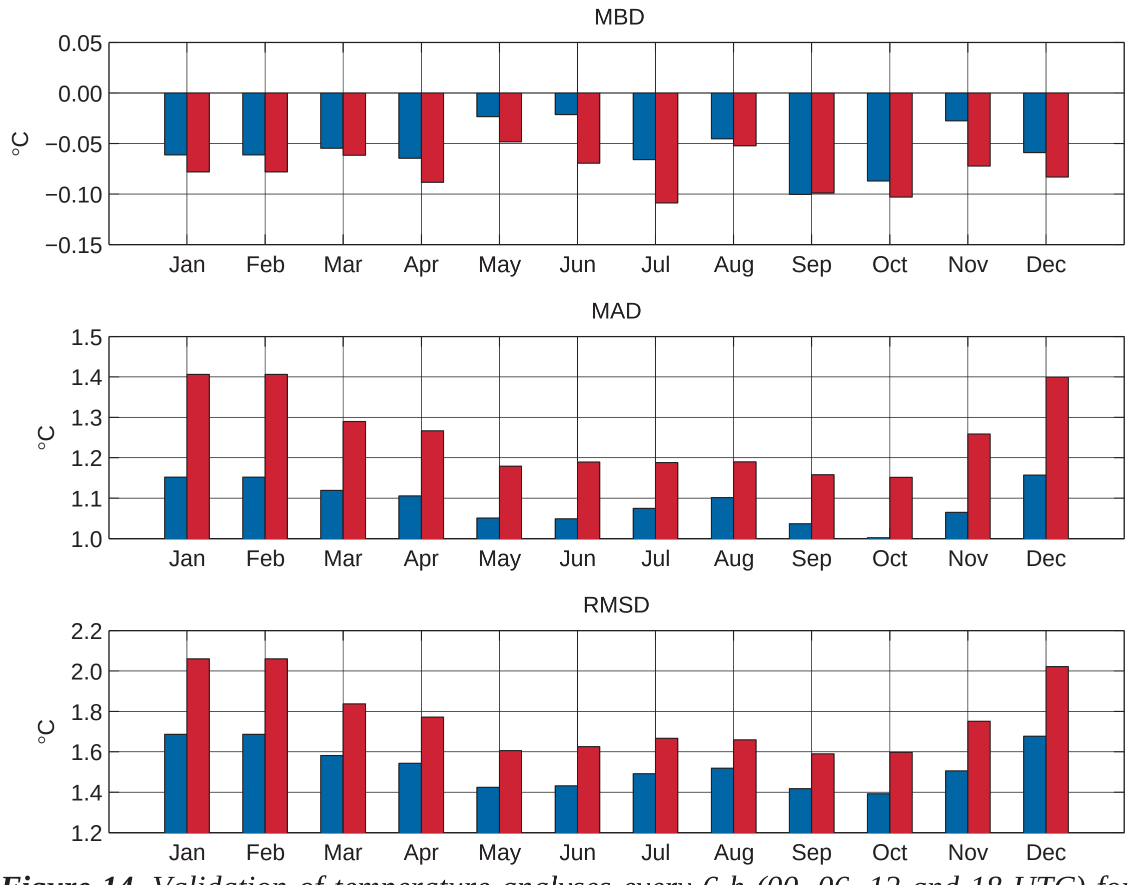

Figure 14. *Validation of temperature analyses every 6 h (00, 06, 12 and 18 UTC) for the time period 1998-2000, separated into each month of the year. Histograms (ºC) for MBD (Eq. 2), MAD (Eq. 3, y-axis starts above zero) and RMSD (Eq. 4, y-axis starts above zero) are given for comparisons between 'ERAMESAN minus observations' (blue bars) and 'ERA-40 minus observations' (red bars).*

There is a small bias, MBD, in both ERAMESAN and ERA-40 for all months of the year with analyses being a little bit colder than observations. But the magnitude is small and smaller for ERAMESAN compared to ERA-40 for all months. MAD is larger than MBD, and a more straight forward parameter to analyse, since both positive and negative deviations are reflected. Also for MAD, for all months, the smallest values are found for ERAMESAN (about 15% lower for ERAMESAN compared to ERA-40) and lower values appear during summer compared to winter. RMSD values, separated into each month of the year, vary between 1.4-1.7 ºC for the ERAMESAN analysis and between 1.6-2.1 ºC for the ERA-40 dataset. Also in this case the lowest values occur during the summer half-year and the deviations for ERAMESAN are about 15% smaller compared to ERA-40.

7.2.2 Precipitation

Daily (24 h) and monthly values of precipitation are validated against the independent set of observations. All comparisons between analyses and observations are made for identical samples in time. Lack of individual samples in time is however not considered in the monthly values. For daily accumulated precipitation the ERA-40 values correspond to two 12 h first guess fields for ERAMESAN. All calculated deviations refer to ERAMESAN or ERA-40 analyses minus observations. MBD (Eq. 2), MAD (Eq. 3) and RMSD (Eq. 4) values for ERAMESAN as well as for ERA-40 are illustrated in Figure 15. Both MAD and RMSD show a better agreement between ERAMESAN and independent observations compared to ERA-40 versus observations, while for MBD the opposite occurs. However, in Figure 16 we can see that ERA-40 actually has larger absolute values of MBD for most months of the year compared to ERAMESAN, but negative values in summer/autumn and positive in winter/spring. For ERAMESAN small positive MBD values (about 0.1 mm/day) are found for most months.

Some weak seasonal variations in the different deviation measures can be seen in Figure 16, with larger deviations in autumn and smaller in spring. The agreement between the ERAMESAN analysis and the observations is almost always better compared to the ERA-40 re-analysis. The deviations are, as a mean, about 15% smaller for ERAMESAN compared to the ERA-40 re-analysis.

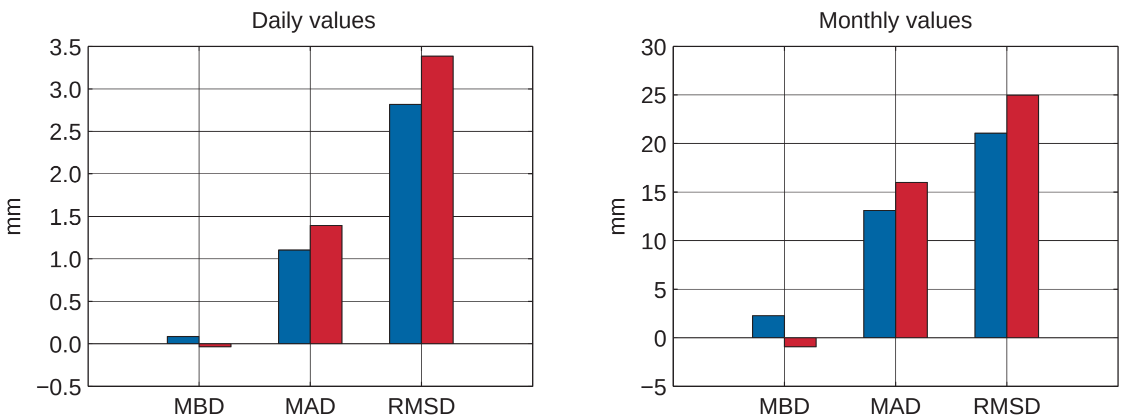

Figure 15. *Validation of precipitation based on data for the selected time period 1998-2000. Histograms for MBD (Eq. 2), MAD (Eq. 3) and RMSD (Eq. 4) are given for comparisons between 'ERAMESAN minus observations' (blue bars) and 'ERA-40 minus observations' (red bars). Left: Daily accumulated precipitation (mm/24h). Right: Monthly accumulated precipitation (mm/month).*

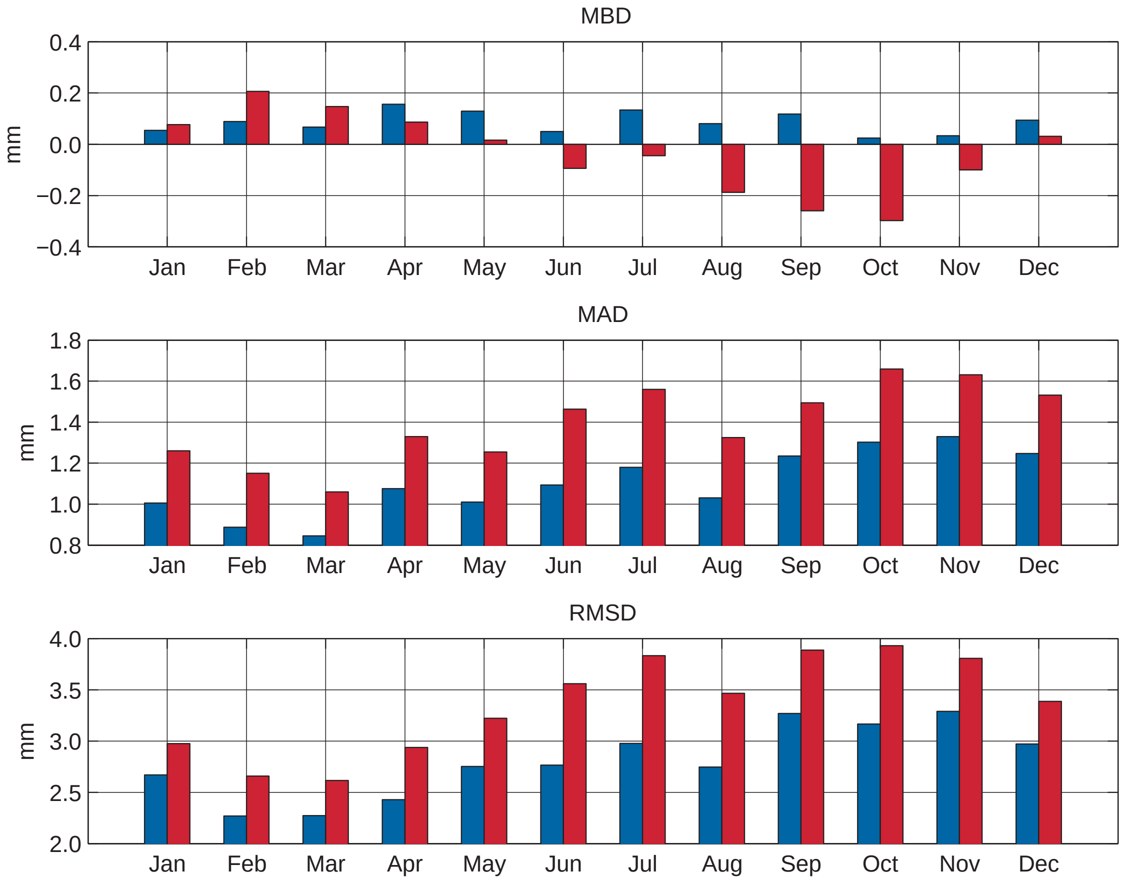

Figure 16. *Validation of daily (24h) accumulated precipitation analyses for the time period 1998-2000 and separated into each month of the year. Histograms (mm/24h) for MBD (Eq. 2), MAD (Eq. 3, y-axis starts above zero) and RMSD (Eq. 4, y-axis starts above zero) are given for comparisons between 'ERAMESAN minus observations' (blue bars) and 'ERA-40 minus observations' (red bars).*

In Figure 17 frequency distributions of different daily (24 h) precipitation amounts during 1998-2000 are shown regarding observations, ERAMESAN and ERA-40. It is important to note that the frequencies of daily accumulated precipitation amounts larger than 25 mm/day are smaller for both ERAMESAN and ERA-40 compared to observations. The ERAMESAN frequency of daily precipitation larger than 25 mm/day is however almost twice as large, and thus substantially better, than the corresponding value for ERA-40. The tendency to underestimate the frequency of large daily precipitation amounts is well known from NWP-modelling and statistical interpolation.

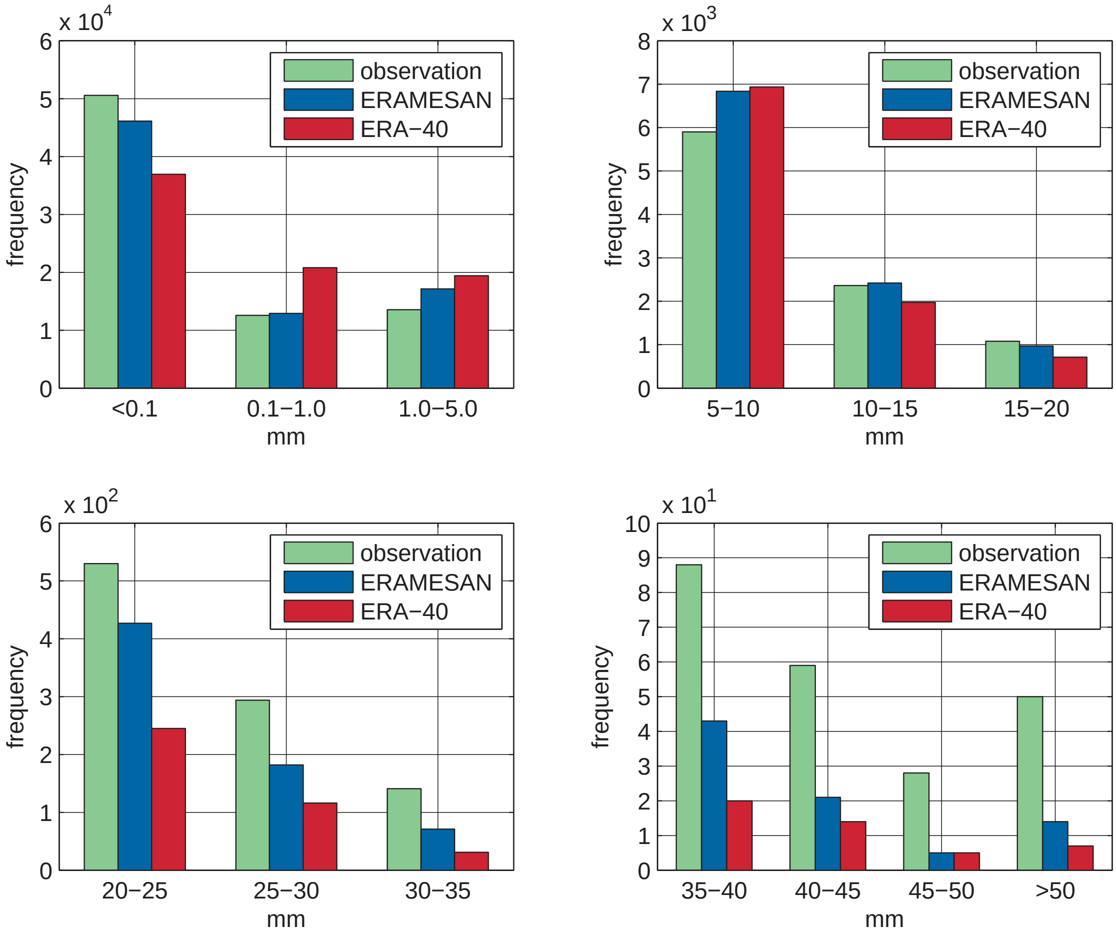

Figure 17. *Frequency distribution of daily (24h) accumulated precipitation amounts during 1998-2000. Green bars correspond to observed precipitation, blue bars to ERAMESAN and red bars to precipitation from ERA-40. Top left: Precipitation amounts 0.1 to 5 mm/24h. Top right: Precipitation amounts 5 to 20 mm/24h. Bottom left: Precipitation amounts 20 to 35 mm/24h. Bottom right: Precipitation amounts larger than 35 mm/24h.*

7.2.3 Wind

Wind analyses every 6 h (10 minutes mean wind) have been made for total wind speed as well as for u- and v-components separately. The validation results presented below only refer to analyses based on total wind speed. Similar results, but with slightly larger deviations for ERAMESAN, were obtained when based on u- and v-components which is plausible. Wind speed is in many applications of interest regardless of wind direction, which motivates a separate analysis of total wind speed. All calculated wind speed deviations refer to ERAMESAN or ERA-40 analyses minus observations. MBD (Eq. 2), MAD (Eq. 3) and RMSD (Eq. 4) values separated into each month of the year are illustrated in Figure 18. Seasonal variations of the deviations can be seen, with larger deviations in winter and smaller in summer. The agreements between observations and ERAMESAN are in most cases better than for comparisons made to the ERA-40 re-analysis.

All Swedish wind observations were quality controlled before archived, while all other observations are without any other quality control than a very rudimentary check within the MESAN system. The validation study for wind made this limitation very obvious.

Wind is a parameter which can vary substantially on a relatively small scale, and quality checks which only refer to large scale first guess fields are not sufficient. A detailed quality control of observational data was however regarded as being beyond the economic limits of the present study. An improved quality check should no doubt be emphasized in future initiatives towards a high-quality gridded dataset for Europe.

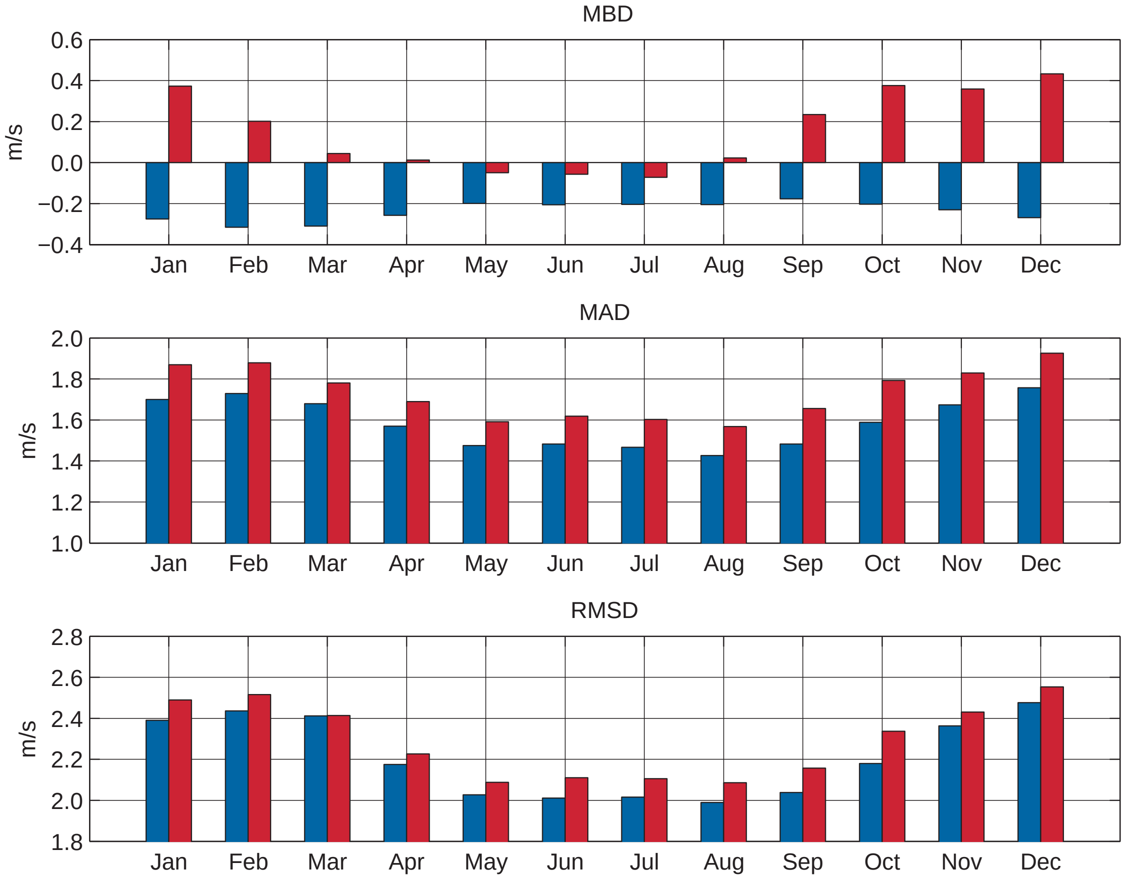

Figure 18. *Validation of wind speed (m/s) regardless of direction every 6 h (00, 06, 12 and 18 UTC) based on data for the selected time period 1998-2000 and separated into each month of the year. Histograms for MBD (Eq. 2), MAD (Eq. 3, y-axis starts above zero) and RMSD (Eq. 4, y-axis starts above zero) are given for 'ERAMESAN minus observations' (blue bars) and 'ERA-40 minus observations' (red bars).*

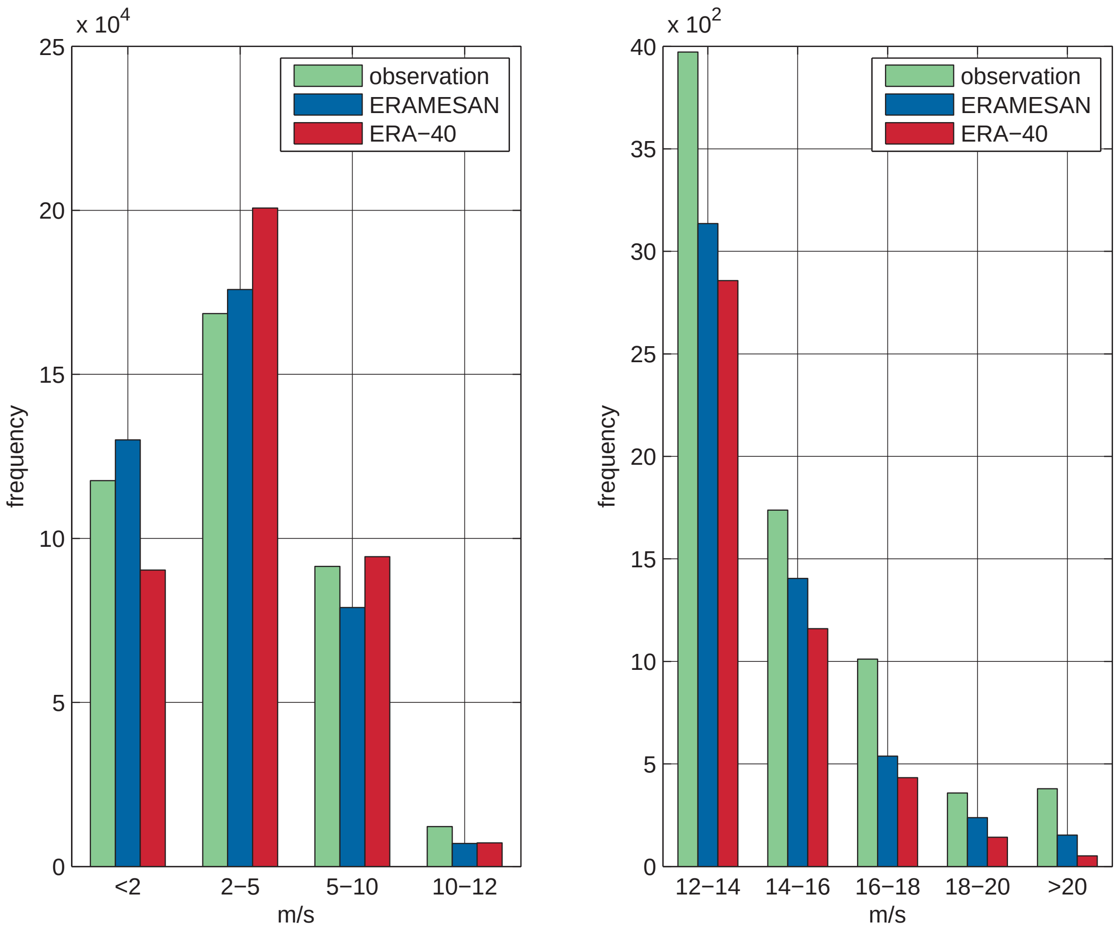

Figure 19. *Frequency distribution of wind speed from observations (green bars), ERAMESAN (blue bars) and ERA-40 (red bars) during the period 1998-2000. ERAMESAN values are based on analysis of total wind speed. Left: Wind speeds below and equal 12 m/s. Right: Wind speeds above 12 m/s.*

The frequency distribution of different wind speeds are in general better described in ERAMESAN compared to ERA-40. However, the tendency to underestimate the frequency of very high wind speeds, compared to observations, and to overestimate the frequency of small values can be seen also for ERAMESAN. This is a well known problem from NWP-modelling and statistical interpolation and is only partly solved by using ERAMESAN instead of ERA-40. This is an important aspect to be aware of when using ERAMESAN data, without any corrections, for evaluation of risks for extreme wind speeds. Also e.g. wind energy studies can suffer considerably from this underestimation of high wind speeds since the wind energy is proportional to the third power of the wind speed. The cut-off for wind turbines at very high wind speeds reduces the influence but, no doubt, the problem has to be carefully considered before using ERAMESAN or similar gridded wind speed data without any correction.

8 Conclusions

The present ERAMESAN study, which is a first test of the possibility to use the MESAN system for a high-resolution re-analyses over the whole of Europe, has shown to give improvements compared to ERA-40 and experiences of value for future development. Future practical use of the produced ERAMESAN dataset is anticipated to give further details.

A partial evaluation of the analysed parameters for the years 1998-2000, using a limited cross validation procedure with independent observations (two subsets representing altogether 5.5% of the total amount of stations), shows an improvement in ERAMESAN compared to ERA-40 data for all studied parameters with regard to root mean square deviation (RMSD), mean absolute deviation (MAD) and mean bias deviation (MBD) for all seasons. The deviations are roughly of the order of 15% smaller compared to what is obtained for ERA-40. It is however obvious that the present dataset includes a relatively poor description of the topographical effects. Unfortunately, in the present study, only a coarse 44 km spatial resolution topography was applied and interpolated. Further improvements can, no doubt, be obtained if higher resolution topography and detailed predictor functions depending on e.g. topography and distance to sea are included. Also an improved quality control of observational data, compared to the rudimentary quality check in the present study due to economic limits, is desirable for a future initiative.

The partial cross validation shows clearly that the frequency distribution of large daily precipitation amounts and frequencies of different wind speeds are better described in ERAMESAN compared to ERA-40. However, the tendency to underestimate the frequency of very large precipitation amounts or high wind speeds, compared to observations, can be seen also for the ERAMESAN dataset. This is a well known problem in NWP-modelling and statistical interpolation and is only partly solved by using ERAMESAN instead of ERA-40. It is important to be aware of this limitation when using ERAMESAN data, without any corrections, for practical applications concerning evaluation of risks for extreme wind speeds or very large precipitation amounts, in wind energy studies etc. This clearly demonstrates the need for future improved re-analyses, which is shortly discussed in next Chapter.

Being aware of the limitations of the results in the present ERAMESAN study as indicated above, still it is of interest to apply the data for different environmental and climate studies. The present ERAMESAN dataset is available on disc at SMHI as well as within the EUMETNET-project "Showcase EUROGRID". Data from 1990 and onwards is of specific interest since 1990 is often used as a reference year in connection to environmental studies and in connection to emissions of greenhouse gases and the Kyoto protocol. Data shows e.g. that during the 15-year period 1990-2004 all years except one, 1996, had a mean temperature for Europe above normal. Details in time and area regarding temperature, precipitation and wind for different parts of Europe can be studied by means of the dataset.

9 Looking forward

The objective for the ongoing EUMETNET programme "Showcase EUROGRID" is to promote a future full-scale EUROGRID to become a European central resource for climate and historical meteorological and environmental data, where a high-quality and high-resolution gridded meteorological dataset for Europe is one important part. The present ERAMESAN study is just a first tentative step towards such a dataset for Europe. Based on experience from the present ERAMESAN study we see a future substantially more ambitious initiative as highly desirable. Such a second step could be a study including the following building blocks:

- A dynamic 3-Dimensional (3D) re-analysis including 3D/4D-variational data assimilation (e.g. using HIRLAM 3D-Var or 4D-Var) with boundary conditions taken from ERA-40/ERA-Interim. Model area should be the whole of Europe, horizontal resolution around 10 km and time resolution 3 h. Such a high-resolution dynamic re-analysis should be performed in close cooperation with ECMWF and as far as possible be based on the infrastructure of ECMWF.

This first step should be followed by:

- 2-Dimensional (2D) analysis based on an improved ERAMESAN analysis technique using Optimum Interpolation, where the current structure functions are further developed including scaling based on predictors such as topography, distance from sea, etc. 2D results from the dynamic re-analysis, step 1 above, shall here be used as first guess. Horisontal resolution for the 2D analysis is assumed to be between 1 km and 10 km (depending on parameter) and time resolution 3 h.

- For specific needs, e.g. for describing frequencies of extreme values when no consistency in time or between weather elements is necessary, a statistical down-scaling can be used.

Such an approach should give a consistent analysis, going from large scale to smaller scales. The suggested dynamic downscaling including data assimilation will produce a 3D dataset with 10 km horizontal resolution which can be used as a 3D input e.g. to off-line Atmospheric Chemistry and Air Quality models such as the EMEP model, models used in GEMS/MACC, etc. A substantially improved ERAMESAN technique should produce a 2D dataset, which can be used for many applications, e.g. related to Climate Change, flooding, draught etc. A final statistical down-scaling can be specifically valuable for describing extremes. A large number of parameters should be included at all three levels. A re-analysis time period from present and about 50 years back in time is desirable and should fulfil many requirements.

The use of observational data, not trans-nationally exchanged in routine, should be included in the 2D analysis. That is an important but not straightforward procedure. Quality control and consistency of observational data is critical. The full accomplishment of such an undertaking as indicated above requires substantial resources.

Acknowledgements

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