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Uncertainties in **E**nsembles of **R**egional **R**e-**A**nalyses

Deliverable D2.7

HARMONIE reanalysis report of results and dataset

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Name of author/contributors:	Martin Ridal, Esbjörn Olsson, Per Unden, Klaus Zimmermann, Alexandra Ohlsson
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1. Introduction

Within the European Union funded project European Reanalysis and Observations for Monitoring (EURO4M), the work started to answer the need for regions re-analyses with a high resolution compared to what the global RA can provide. EURO4M delivered RA products at an intermediately high-resolution (22 km) but also with a downscaling to higher resolutions.

UERRA has increased the resolution even further to address some limitations of EURO4M but also focus on the uncertainties in the re-analyses. The time period of the RA in UERRA is also much longer than in EURO4M. In order to assess the uncertainties in the RA, Advanced Ensemble Data Assimilation was used for a long time period. High-resolution deterministic RA and other gridded datasets are also included in the evaluation of the uncertainties.

Within the framework of UERRA a regional re-analysis has been made using the HARMONIE (HIRLAM ALADIN Regional/Mesoscale Operational NWP In Europe) system. HARMONIE is a complete system for numerical weather prediction. It is developed in the HIRLAM (Hi-Resolution Limited Area Model)-consortium and builds upon the code of the models ALADIN (Aire Limitée Adaptation Dynamique Développement International), AROME (Applications of Research to Operations at MEsoscale) and ALARO (ALADIN and AROME combined model) developed in collaboration of Météo France and the consortia ALADIN and HIRLAM. The description of the model setup is very similar to that of deliverable D2.5 (Ridal et. al. 2016a) in which two versions of model physics were used to create a mini ensemble over five years. The experiments also served as a preparation for the long re-analysis to avoid as many mistakes, errors and bugs in the long run as possible.

The HARMONIE-RA was run from 1961-2015 with a horizontal resolution of 11 km and the ALADIN physics scheme. Both upper air as well as surface data assimilation was included. To introduce large scale information from the global reanalyses a large scale constraint has been added to the cost function. A report with the first, preliminary, results has already been delivered to UERRA as deliverable 2.6 (Ridal et. al 2016b).

In this report, the modelling system, the data assimilation methods, and the production scheme are explained in Section 2. Section 3 describes what is archived in the MARS archive. In Section 4, examples of results from the long regional reanalysis are presented as observation monitoring, verification against observations and comparison with the global reanalysis ERA-Interim is presented. The report is concluded in Section 5.

2. Model setup

The 55 year reanalysis run was performed using the HARMONIE system cycle 38h1.1. HARMONIE is basically a script framework that allows for different physics packages, surface schemes or data assimilation schemes. In the long UERRA run several changes in the script system were made, compared to the reference version of HARMONIE, to speed up the code. The main achievement was to separate the analysis and forecast steps. In the UERRA runs the new analysis is started as soon as the first guess is available, i.e. the 6 hour forecast. The remaining forecast hours is run in parallel to the next analysis. This saves a lot of time in a reanalysis but is of no use for operational forecasts. The ALADIN synoptic scale physics scheme was used together with a three dimensional variational data assimilation (3D-Var) scheme including only conventional observations and an OI assimilation scheme for the surface observations. This is described in more detail below.

The re-analysis was run at the ECMWF facilities in several streams (time periods) with four months overlap between the streams to allow spinup of the slowly varying soil parameters. One year of re-analyses took about one month to produce and created around 22 Tb of output data.

Data assimilation

Observations are introduced into the model through data assimilation, both in the upper air and in the surface scheme. The assimilation scheme used for the upper air analyses is a 3D-Var assimilation scheme which creates an analysis by minimising a cost function (e.g. Gustafsson et al. 2001, Lindskog et al. 2001 or Brousseau et al. 2008):

$$J(x) = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}\big(y - H(x)\big)^T R^{-1}\big(y - H(x)\big)$$

where *x* is the model state vector (containing the control variables vorticity, divergence, temperature, specific humidity and surface pressure), x_b is the first guess or background, in our case a 6-hour forecast. *y* represents the observations while *H* is the observation operator, *B* is a matrix that describes the errors of x_b and *R* is a matrix that describes the errors of the observations *y*. It is assumed that the observation errors are spatially uncorrelated and thus, R is represented as a diagonal matrix. The background error matrix on the other hand, describes both spatial correlations and balances between variables. It uses a multivariate formulation based on the forecast errors of the control variables and horizontal spatial homogeneity and isotropy are assumed (Berre 2000). The background error correlations are calculated only once and do not take into account any time dependence (Brousseau et al. 2012) or any heterogeneous information in space (Montmerle and Berre 2010).

The observations included are the so-called conventional observations which include synoptic stations, ships, drifting buoys, aircraft observations and radio soundings. No remote sensing data is used for these experiments.

Blending, or large scale mixing, refers to the methodology of introducing the large scale features of the host model into the initial condition of a regional model. In the HARMONIE re-analysis, large scales from the available ERA re-analyses are mixed in via a Jk-term in the 3D-Var minimisation. This means that the large scale mix will be added as an extra constraint in the 3D-Var (Guidard and Fischer, 2008; Dahlgren, 2012).

The surface observations are assimilated using an optimal interpolation (OI) method using CANARI (Code for the Analysis Necessary for ARPEGE for its Rejects and its Initialization) and SURFEX (surface externalisée).

CANARI (Taillefer, 2002) is a part of the IFS/ARPEGE (Integrated Forecast System/Action de Recherche Petite Echelle Grande Echelle) (Bubnová et al. 1995; ALADIN International Team 1997) source code and were developed to provide both surface and upper air ARPEGE/ALADIN analysis based on the optimum interpolation (OI) method. Together with SURFEX however, it is only used for the horizontal interpolation (Seity et al 2011).

With SURFEX the surface analysis is performed in two steps. First CANARI finds the analysis increments in each grid point based on observations minus first guess. In the next step a consistent update of the SURFEX surface fields is made based on analysis increments interpolated to all grid points by CANARI.

SURFEX has 4 tiles; nature, sea, inland waters (lakes and rivers) and town. The Interactions between Soil, Biosphere, and Atmosphere (ISBA) parameterization (Noilhan and Planton, 1989) is by default used at nature points updating temperature, water and ice in 3 layers (surface, soil and deep soil) and the properties of a single layer of snow. Only surface temperature is updated at sea and lake surfaces.

In the UERRA-RA, only synoptic observations are used to analyse 2 meter temperature (T2m), 2 meter relative humidity (RH2m) and Snow Water Equivalent (SWE).

The ALADIN setup

The basis for the ALADIN setup is the limited area model (LAM) version of the ARPEGE-IFS (Bubnová et al. 1995; ALADIN International Team 1997). It comprises a non-hydrostatic spectral dynamical core with semi-implicit time stepping and semi-Lagrangian advection. In the horizontal resolution used in UERRA, 11km, the model is applied using the hydrostatic assumption.

In ALADIN the radiative transfer in the atmosphere (gaseous, clouds, ozone, and aerosols) with the surface is described using the RRTM scheme (Rapid Radiative Transfer Model) for longwave radiation (Mlawer et al., 1997) and the six-band Fouquart–Morcrette scheme for shortwave radiation (Fouquart and Bonnel, 1980; Morcrette, 1991). Several phenomena linked to the subgrid orography, such as gravity waves, their reflection and trapping, as well as upstream blocking, are taken into account (Catry et al., 2008). The transport in the atmospheric boundary layer is represented with a diffusion scheme based on prognostic turbulent kinetic energy (Cuxart et al., 2000) using the Bougeault and Lacarrère (1989) mixing length, and on a mass-flux shallow convection scheme using a CAPE closure (Bechtold et al., 2001). Deep convection is represented with a mass-flux scheme based on a moisture convergence closure (Bougeault, 1985). A statistical cloud scheme (Smith, 1990; Bouteloup et al., 2005) is used for the representation of stratiform clouds. Microphysical processes linked to resolved precipitation such as auto-conversion, collection, evaporation, sublimation, melting and sedimentation are explicitly represented (Lopez, 2002).

ALADIN is coupled to the externalized version of the Méso-NH surface scheme, called Externalized Surface (SURFEX). Here each grid box is split into four tiles: land, towns, sea, and inland waters (lakes and rivers). The Interactions between Soil, Biosphere, and Atmosphere (ISBA) parameterization (Noilhan and Planton 1989) with two vertical layers inside the ground is activated over land tile. The Town Energy Budget (TEB) scheme used for urban tiles (Masson 2000) simulates urban microclimate features, such as urban heat islands. Sea tiles use the Exchange Coefficients from Unified Multicampaigns Estimates (ECUME) parameterization (Belamari and Pirani 2007). It is a bulk iterative parameterization developed in order to obtain an optimized parameterization covering a wide range of atmospheric and oceanic conditions. Based on the Liu–Katsaros–Businger algorithm (Liu et al. 1979), ECUME includes an estimation of neutral transfer coefficients at 10 m from a multicampaign calibration derived from 5 flux measurement campaigns. Concerning inland waters, the classic Charnock's (Charnock 1955) formulation is used. Output fluxes are weight averaged inside each grid box according to the fraction occupied by each respective tile, before being provided to the atmospheric model. Physiographic data are initialized due to the ECOCLIMAP database (Masson et al. 2003) at 1-km resolution.

3. Archiving

Output data from the HARMONIE-ALADIN re-analysis is stored in the MARS archive at ECMWF. For the analyses all model levels are archived while the forecast are stored on given pressure and height levels to reduce the data amount. In total about 350 Tb of data are stored for the HARMONIE-ALADIN re-analysis.

Analysis

The analysed fields of specific humidity, temperature and the u and v components of the wind are stored from each analysis time, i.e. 00, 06, 12 and 18 UTC, for all model levels.

For the surface a number of parameters are archived such as surface pressure, relative humidity, different types of fluxes, wind information as well as a few soil parameters. A full list of what is stored is available through the UERRA home page in the annex of deliverable D4.2: Data plan: INSIPRE compliant data dissemination plan and hand over to CLIPC

Forecasts

The forecasts are stored every hour up to 6 hours and thereafter every third hour up to 30 hours lead time, i.e. T+1,2,3,4,5,6,9,12,15,18,21,24,27,30 started from the analyses at 00 UTC and 12 UTC.

The forecasts are stored on both pressure levels and height levels. For pressure levels the stored parameters are cloud cover, cloud water and ice content, geopotential height, relative humidity, temperature and the u and v wind components. The pressure levels are given in Table 1.

Pressure levels [hPa]
1000
975
950
925
900
875
850
825
800
750
700
600
500

400
300
250
200
150
100
70
50
30
20
10

Table 1. Pressure levels in the UERRA HARMONIE-ALADIN MARS archive

It was agreed to store lower tropospheric, near-ground, output on height levels in addition to pressure levels. Height levels are provided on fixed geometric height above model topography. It is a user friendly format, and the main user communities interested in this output may be the wind energy sector and forestry. It was decided that wind is provided as wind speed and wind direction on height levels because it is envisaged that the user community interested in height levels is more interested in these parameters instead of the separate components. For the height levels the fields archived are apart from the wind information also the same cloud information as for the model levels, relative humidity, pressure and temperature. The height levels are given in Table 2.

Level above ground[m]
15
30
50
75
100
150
200
250
300
400
500

Table 2. Height levels in the UERRA HARMONIE-ALADIN MARS archive

As for the analyses there are a large number of surface parameters and essential climate variables (ECVs) archived for the forecasts. More details are available in the annex of deliverable D4.2: Data plan: INSIPRE compliant data dissemination plan and hand over to CLIPC, available from the UERRA home page.

4. Results

The long reanalysis was run from January 1961 to December 2015. For the upper air data assimilation only the so called conventional observations are included. This means observations from SYNOP stations, ships, drifting buoys, aircraft observations and temperature soundings. For the surface assimilation temperature and relative humidity at two meters as well as snow water equivalent, all from SYNOP stations are included. In the observation monitoring shown here only the upper air observations are shown.

Observation monitoring

Observation monitoring is a useful tool to check that the data assimilation is working as expected. In an operational environment it is also used to monitor the incoming observations in order to discover if any observation type is partly or totally missing.

An observation monitoring system has been partly developed within UERRA. Figure 1 shows the total number of observations used together with the amount of observations from each observation type. Shown are the monthly averages from 1961 to 2015.

As expected the number of observations increases during the re-analysis period. Aircraft observations are not available until 1980 and after that it is constantly increasing, especially at high altitude, i.e. cruising level (not shown). In the 1980s and 1990s all of the aircraft observations were reported manually as AIREP (AIRcraft REPorts) but later more and more are automatic AMDAR (Aircraft Meteorological DAta Relay). The latter together with the increase in air traffic is noticeable not only in the number of observations but also in the distribution of the observations both horizontally and vertically.

One observation type that is actually decreasing in number during the last 10-15 years is the radio soundings. There is an increase from 1961 to 1980’s but after that the number of radio sounding launch sites decrease slightly. The reason is probably that it is a rather expensive observation type and the number of remote sensing observation, e.g. satellite and radar, increase, which also provides a 3D view of the atmosphere.

There are a few features in Figure 1 that need further investigation. It can also be seen that during 2015 the number of aircraft observations reduces dramatically, almost to zero. This is due to a change in the BUFR templates in the aircraft reports from December 2014. This has now been taken into account and the last year will be re-run in order to have a complete data set with all available observations.

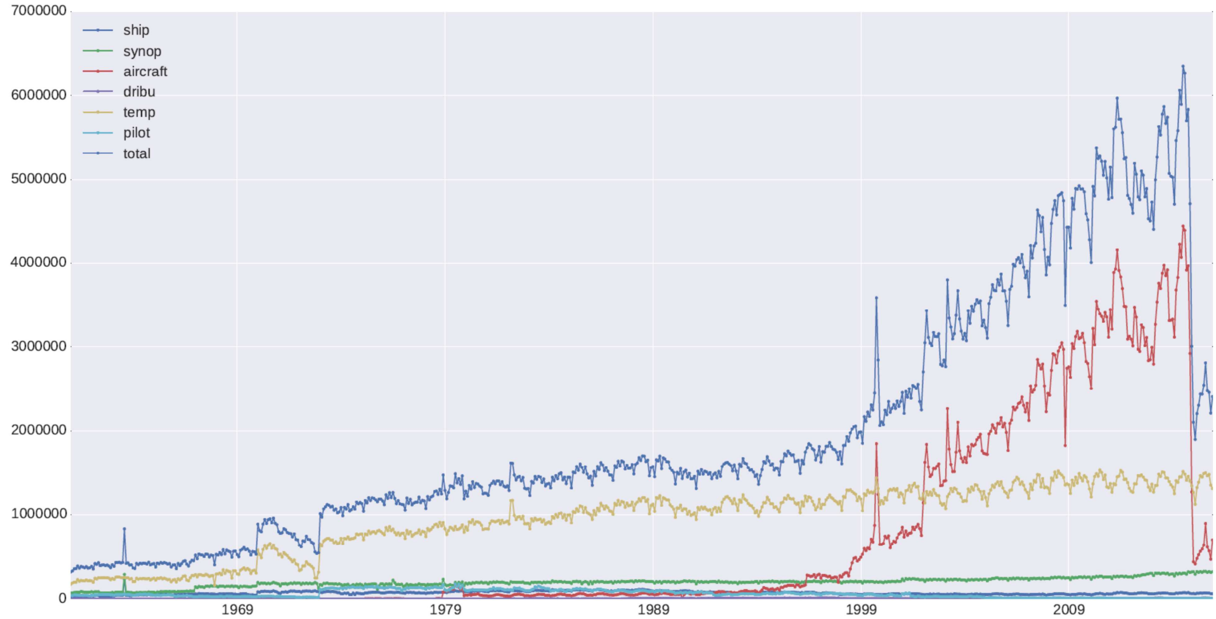

Figure 1. Monthly mean of number of observations used in the upper air analysis from 1961 to 2015. Both the total number of observations (blue) as well as the different observation types are shown.

Another example of the importance of observation monitoring is to check if the assimilation is working properly. This can be done by comparing the first guess (background) and analysis departure, i.e. how much the observations differ from the first guess and from the resulting analysis. If everything is working well the analysis departure should be smaller than the first guess departure. This means that the model has adjusted to the observations. How big this adjustment is will depend on both the background and the observation error. Examples are shown in Figure 2and Figure 3 that show the first guess departure and the analysis departure respectively for the temperature at two meter level (T2m). It shows that the average (blue) is centred around zero, which is good, and means that there is no strong bias in the model or observations. It is also obvious that the analysis departure Figure 3 is smaller than the first guess departure (Figure 2) as expected.

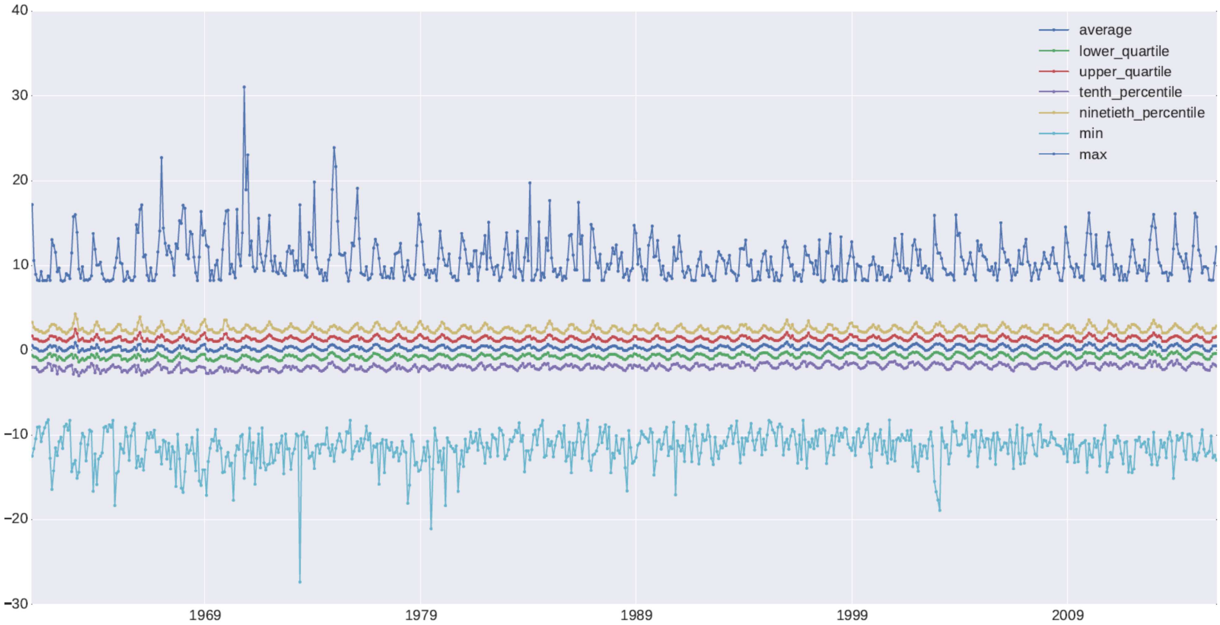

Figure 2. The first guess departure of T2m (degrees C) from observations. Monthly mean is shown (blue) together with the upper and lower quartiles, 10th and 90th percentiles and the max- and min departures.

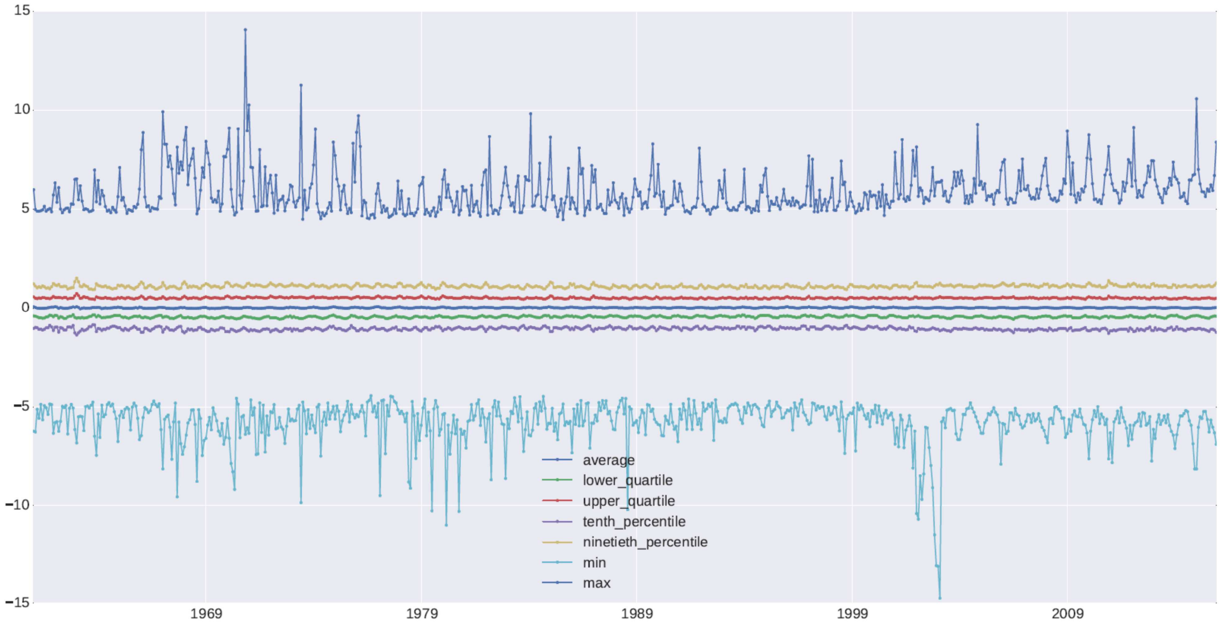

Figure 3. The analysis departure for T2m (degrees C) from observations. Monthly mean is shown (blue) together with the upper and lower quartiles, 10th and 90th percentiles and the max- and min departures.

Climatology

A dataset like the HARMONIE-ALADIN re-analysis can be very useful in studying if and how various types of climatological variables and measures have changed during the last 55 years. Examples of such measures can be the amount of heat waves in Europe or the frequency and intensity of storms or other extreme events. Here we present an example of the T2m for July. Figure 4 shows the mean value of T2m for January from 1961-1980 in the left panel and 1981-2014 in the right panel.

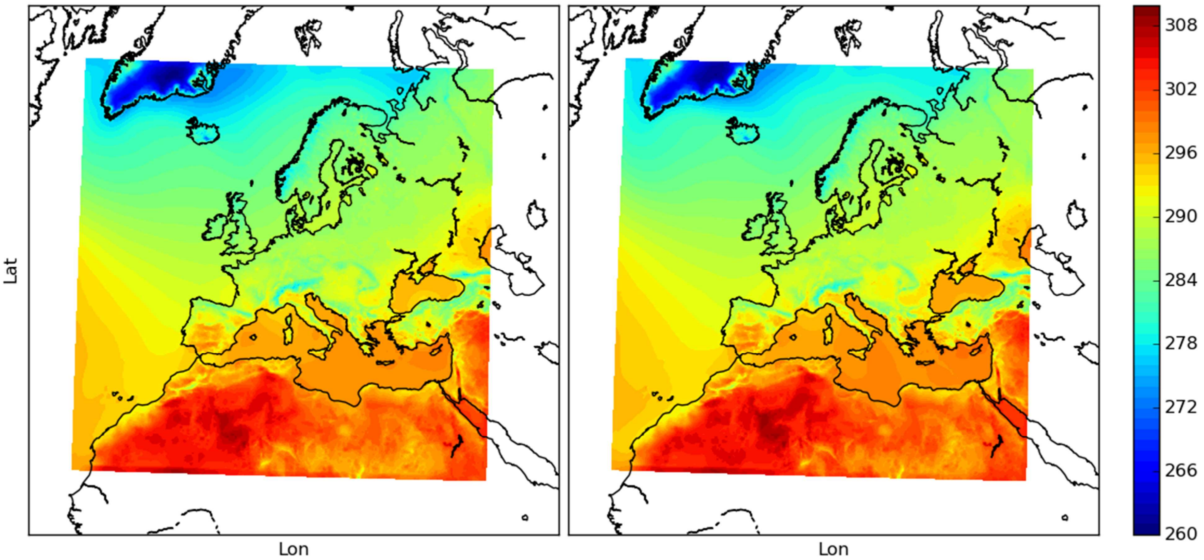

Figure 4. Mean values of two meter temperature for July during the periods 1961-1980 (left) and 1981-2014 (right). Unit on the color bar is degrees Kelvin.

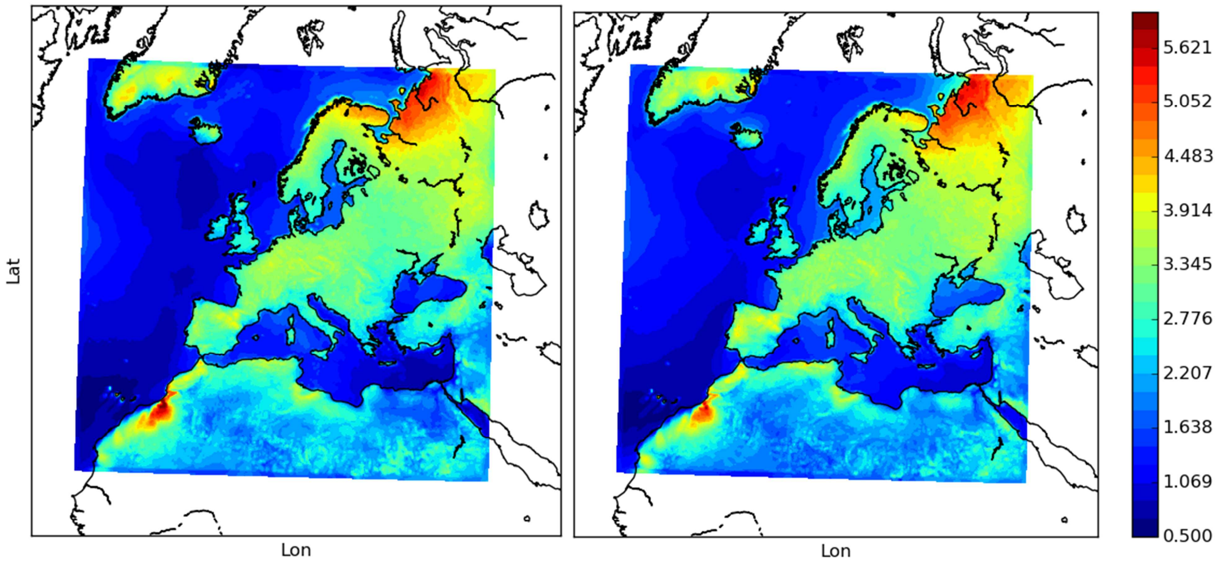

Figure 5. Standard deviation for the mean values presented in Figure 4. Unit on the color bar is degrees Kelvin.

Comparing the mean values for T2m from UERRA with the corresponding mean values from ERA40 and ERA-Interim, presented in Figure 6 shows that they are very similar. The difference in resolution is obvious, especially in areas of steep topography. The standard deviations (Figure 7) are also very similar but more pronounced for the UERRA re-analysis.

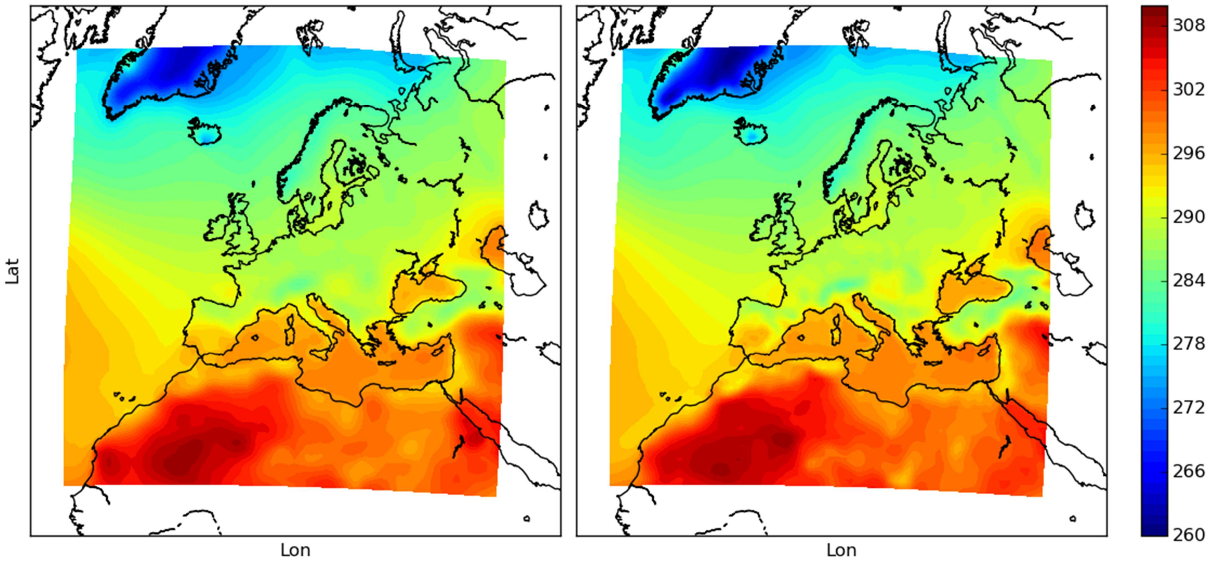

Figure 6. Mean values of two meter temperature for July from ERA40 1961-1980 (left) and ERA-Interim 1981-2014 (right). Unit on the color bar is degrees Kelvin.

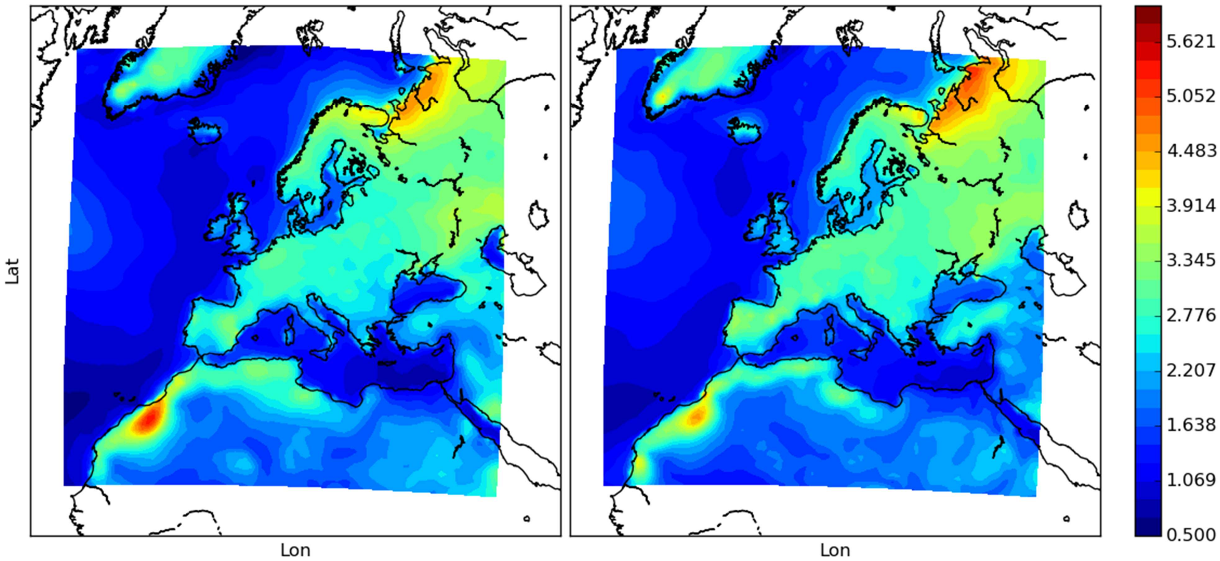

Figure 7. Standard deviation of the mean values presented in Figure 6. Unit on the color bar is degrees Kelvin.

The temperature for the two periods presented in Figure 6 looks very similar. If the difference between the two are plotted however (later period minus early period), as shown in Figure 8, the difference is made clear. There is a clear increase in the mean temperature visible in almost the entire domain. Note that the two periods have different boundaries, ERA40 for the early period and ERA-Interim for the later, so there is not a totally clean comparison. More thorough investigations of this will be performed to see if there is an actual trend in the temperature as well as investigate possible trends for other parameters.

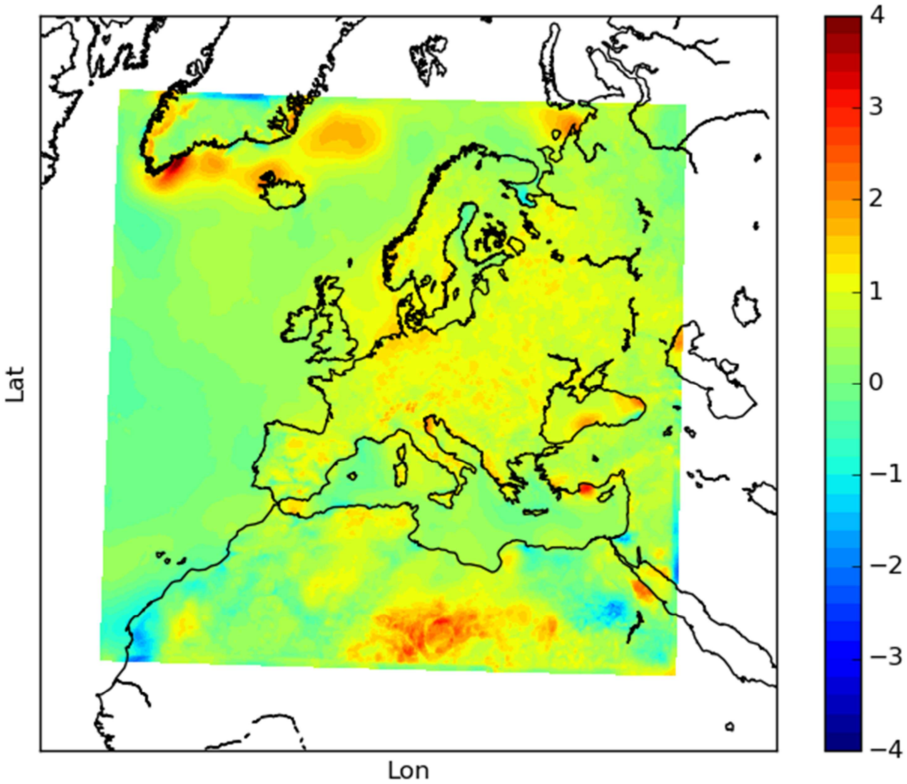

Figure 8. The difference, in degrees Kelvin, between the right and left panels in Figure 4.

For precipitation there are larger differences between UERRA compared to ERA-Interim. In the left panel of Figure 9 UERRA the mean precipitation for July for the period 1981-2014 is presented. There are rather large amounts of precipitation on mountainous areas. In the right panel the mean precipitation for the same month and period for ERA-Interim is presented with less precipitation than for UERRA. The areas with the most precipitation are the same but the amounts are very different. Looking at the standard deviation for the same periods, shown in Figure 10, it is clear that the variability is much larger for UERRA in the whole domain. What the reason for this is and which is more correct need to be studied further but it is known from another study, presented in UERRA deliverable 3.6 (Niermann et. al 2017) that UERRA produces exaggerated precipitation amounts in the Alpine region. It has also been seen that the ALADIN scheme in general, produces too much precipitation.

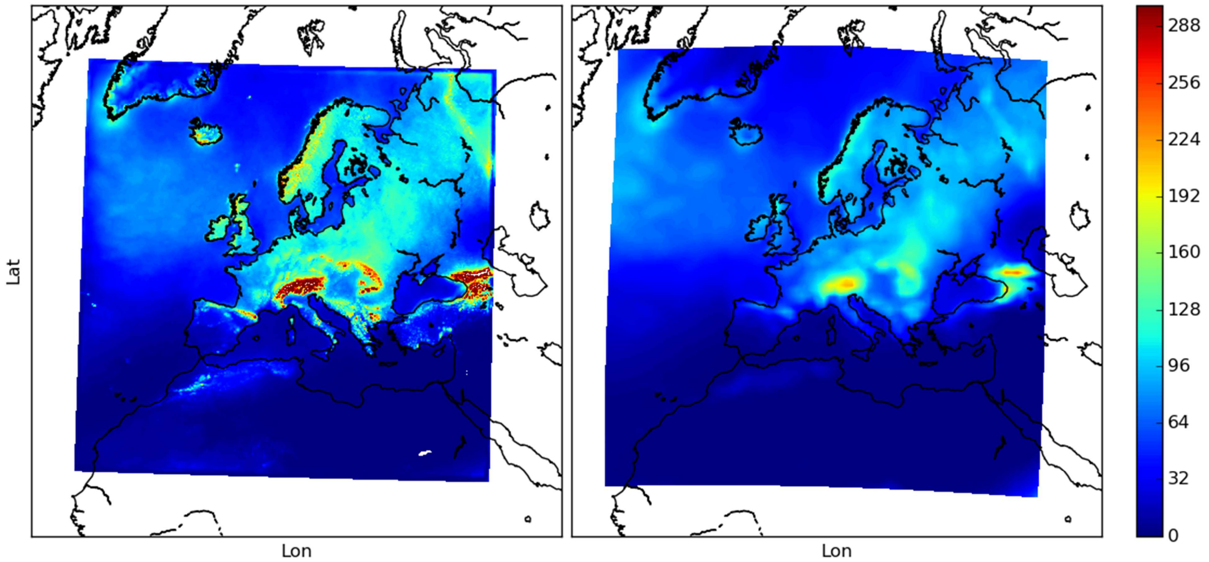

Figure 9. Mean value of total precipitation (mm) for July for the period 1981 to 2014 for UERRA HARMONIE-ALADIN (left) and ERA-Interim (right).

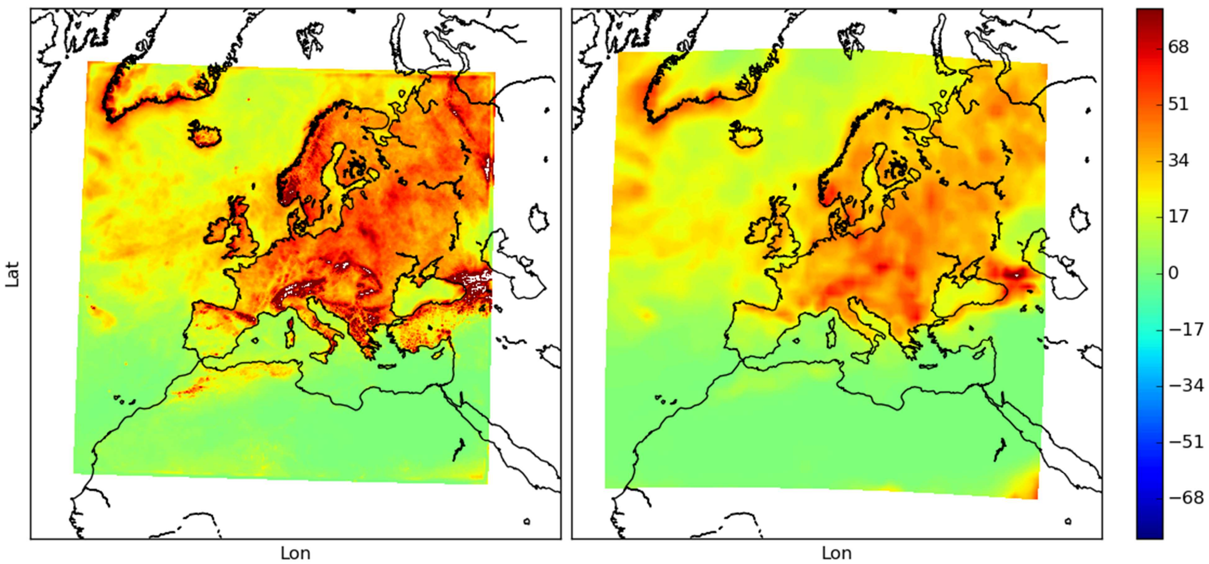

Figure 10. Standard deviation for the mean values presented in Figure 9.

Verification

The HARMONIE verification system WebgraF has been used to verify the forecasts for the 55-year period. Due to the amount of data, the number of parameters that were verified had to be reduced. For the surface, wind speed at 10 meters altitude, temperature and dew point at 2 meters, mean sea level pressure, cloud cover and 12 hour accumulated precipitation have been verified. For upper air: temperature, wind speed and relative humidity. The data is seasonally divided in three month periods during the year as winter (DJF), spring (MAM), summer (JJA) and fall (SON). The forecasts are verified against the same observations that were used for the initial analysis. Below a few examples are shown for the summer and winter periods. The full verification can be made available upon request.

The first set of figures, Figure 11 a-f, show verification for T2m for the summer season for the second year in each decade from 1962 (a) to 2012 (f). Included in the same figures are the corresponding verifications for ERA40 (1962 and 1972) or ERA-Interim (1982, 1992, 2002 and 2012). The HARMONIE-ALADIN re-analysis performs better when it comes to standard deviation but the bias is similar.

The second example, Figure 12 a-f, shows the same thing as Figure 11 but for the winter season. The results are very similar except that there is a cold bias in the HARMONIE-ALADIN re-analysis. There is also a warm bias in the ERA40 re-analysis that is not present in ERA-Interim.

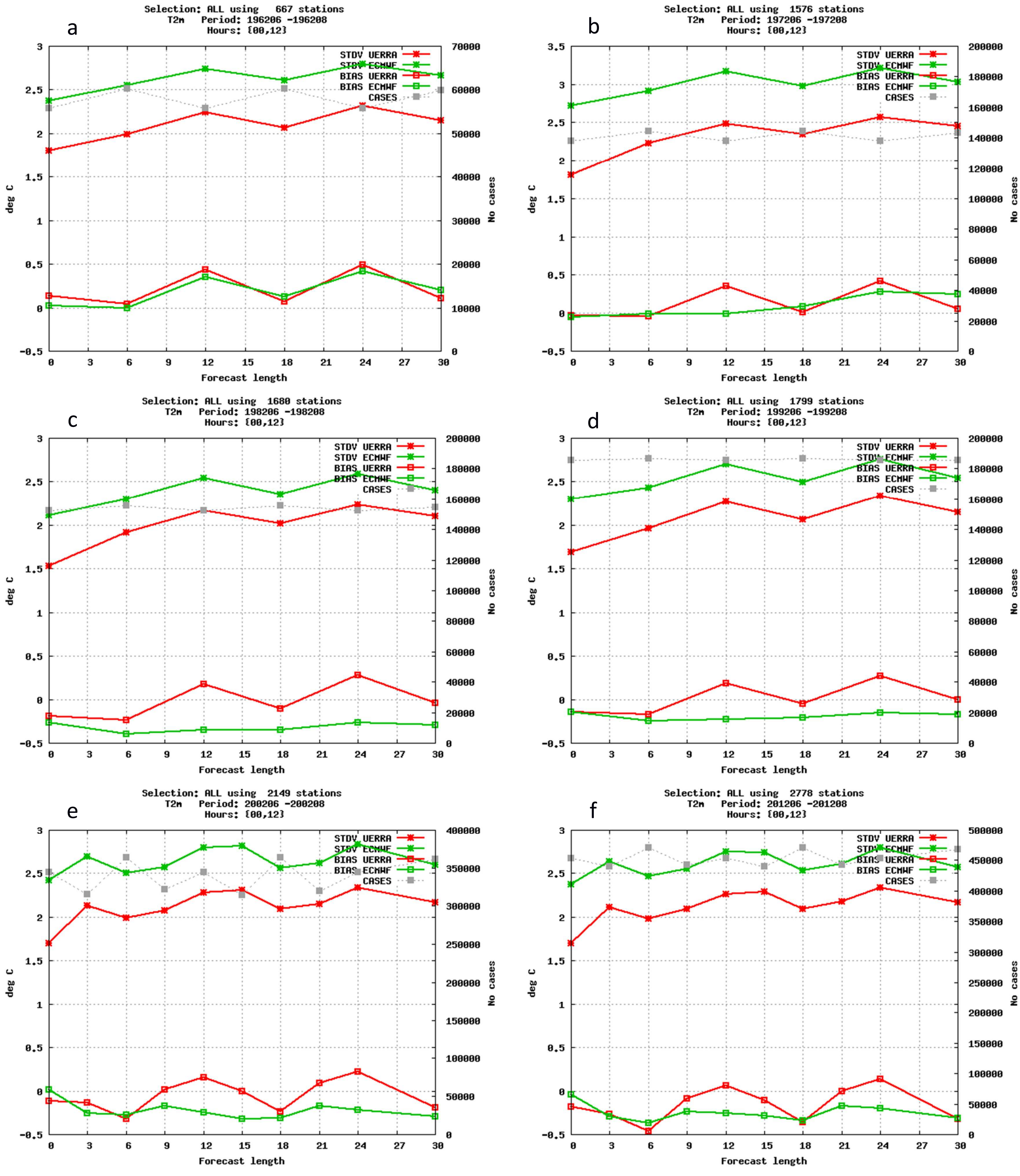

Figure 11. Verification of 2 meter temperature for HARMONIE-ALADIN and ERA40 (1962 and 1972) and ERA-Iterim (1982 to 2012) for June, July, August 1962 (a), 1972 (b), 1982 (c), 1992 (d), 2002 (e) and 2012 (f). Units on the left y-axes are degrees C while the right y-axes show the number of verified cases.

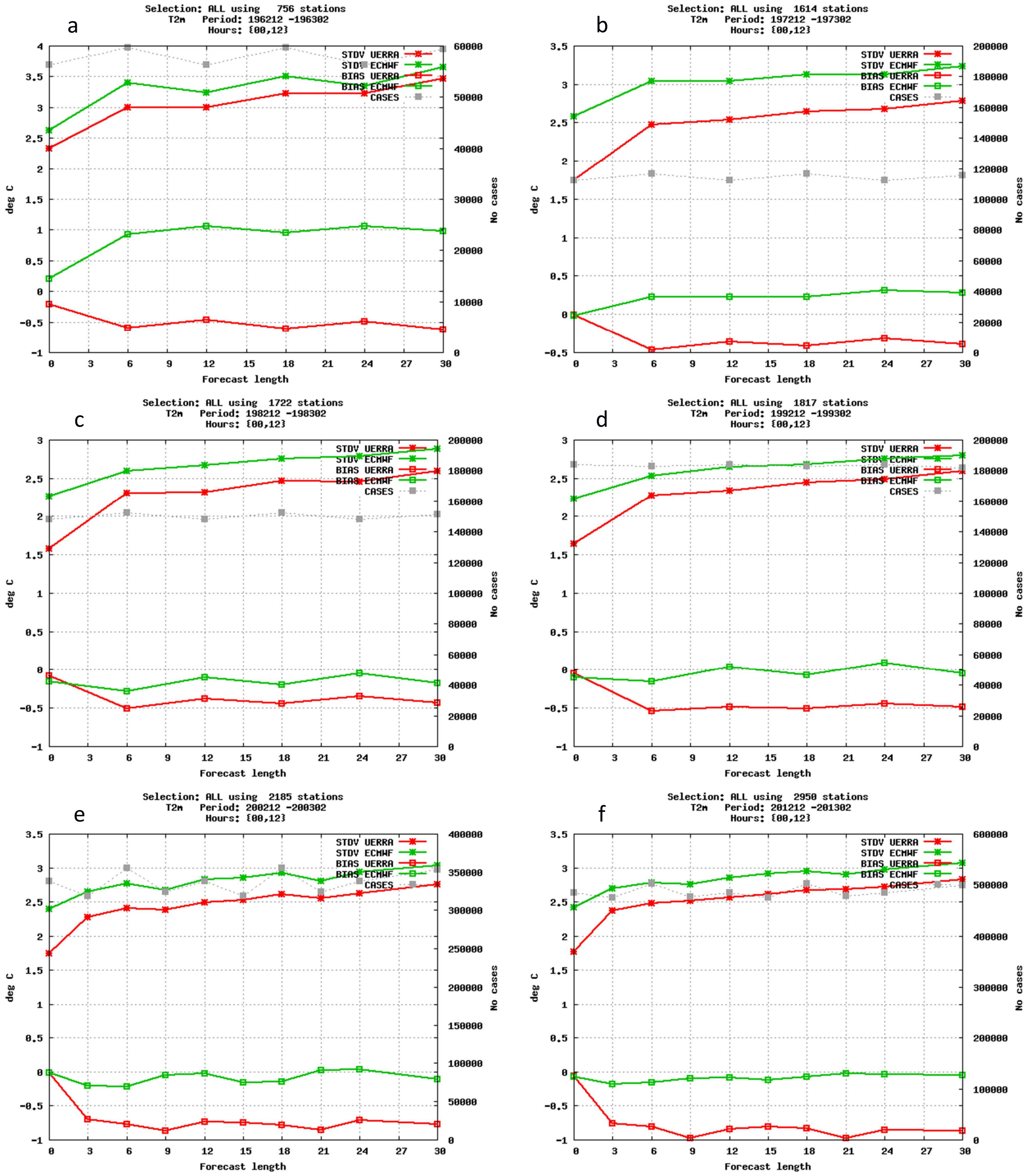

Figure 12. As Figure 11 but for the winter months December, January and February.

In order to summarise the verification results a scorecard has been constructed where a few parameters are subjectively evaluated for each decade and compared with the corresponding verification for ERA40 and ERA-Interim. The scorecard is presented in Figure 13 and it can be seen that for the surface parameters (mean sea level pressure (PMSL), two metre temperature (T2m), wind at ten meters (U10m) and cloud cover (CC)), except the relative humidity (Rh2m), HARMONIE-ALADIN re-analysis performs better (green triangles) or as good as (circles) the ERA re-analyses compared to observations when it comes to standard deviation (STDV). For the profiles of temperature (Temp), wind speed (WS) and geopotential height (Geop), i.e. higher altitudes the results are more mixed except for the relative humidity (RH) where ERA is better for all periods.

	1961-1969	1970-1979	1980-1989	1990-1999	2000-2010	2011-2015
PMSL STDV	▲	▲	●	●	●	●
T2m STDV	▲	▲	▲	▲	▲	▲
U10m STDV	▲	▲	▲	▲	▲	▲
Rh2m STDV	●	▾	▼	▾	●	▴
CC STDV		▲	▼	▼	▼	▾
Temp prof STDV	▴	▴	●	●	●	●
WS prof STDV	▾	▾	▾	▾	▾	●
Geop prof STDV	▴	▴	●	●	●	●
RH prof STDV	▼	▼	▼	▼	▼	▼

Figure 13. Scorecard for HARMONIE-ALADIN compared to ERA40 and ERA-Interim. Green indicates that HARMONIE-ALADIN is better while red indicates that ERA is better. Circle means no noticeable difference between the two.

5. Conclusions

Within the UERRA project the HARMONIE system was set up over Europe and a long reanalysis data set was produced for the years 1961 to 2015. The ALADIN physics package was used. The so called conventional observations were used in the data assimilation for the upper air and data from SYNOP stations was introduced in the surface assimilation. For the inclusion of the large-scale information from the global reanalysis, the approach of an additional term in the cost function is employed.

The monitoring of the observation usage is very important to secure that the model runs correctly. During UERRA a partly new observation monitoring system was developed. The number of observations increases over the years even if the available observations can vary from year to year, especially during the first part of the period (1960-70). The number of radio soundings actually decrease slightly in the later period since it is a rather expensive observations type. Aircraft data becomes available in the 1980's and increase dramatically from the end of the 1990s. This is when they become automatically reported instead of manually. During the last year of production however, almost all aircraft observations are missing. This is due to a change in the reporting template that we were not aware of. This has been corrected and the last year (2015) will be re-run including December 2014.

The comparison of the first guess and the analysis with the observations shows also that the observations are used in a desirable way. This means that they affect the model so that the analysis is closer to the observations compared to the first guess. The analysis should not be too close to the observations on the other hand since this will cause imbalances with the model environment. The analysis may look very good but the following forecasts will perform worse. In UERRA there seems to be a good balance.

Comparing the output fields with the ERA re-analyses show that UERRA and ERA looks similar for temperature but UERRA produces a bit more precipitation. It is obvious that the higher resolution in UERRA gives more details and that the values of different variables are different, like for precipitation, but the general structures are still the same.

The verification of the UERRA re-analysis was conducted for numerous near-surface variables as well as for vertical profiles. It seems that UERRA performs equal or better compared to the corresponding ERA reanalyses for many variables but there are also variables where UERRA performs worse. One example is the relative humidity where we have seen that UERRA is not performing so well. Any possible reasons for this will be investigated in order to avoid the same problems in coming reanalyses or other projects.

References

ALADIN International Team, 1997: The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research. WMO Bull., 46, 317–324.

Bechtold, P., Bazile, E., Guichard, F., Mascart, P., and Richard, E.: A mass flux convection scheme for regional and global models, Q. J. Roy. Meteor. Soc., **127**, 869–886, 2001.

Belamari, S., and A. Pirani, 2007: Validation of the optimal heat and momentum fluxes using the ORCA2-LIM global ocean-ice model. Marine environment and security for the European area. Integrated Project (MERSEA IP), Deliverable D4.1.3, 88 pp.Berre, L.: Estimation of synoptic and mesoscale forecast error covariances in a limited-area model. *Mon. Wea. Rev.*, **128**, 644–667, 2000.

Bougeault, P.: A simple parameterization of the large-scale effects of cumulus convection, Mon. Weather Rev., **113**, 2108–2121, 1985.

Bougeault, P. and Lacarrère, P.: Parameterization of orography-induced turbulence in a mesobeta-scale model, Mon. Weather Rev., **117**, 1872–1890, 1989.

Bouteloup, Y., Bouyssel, F., and Marquet, P.: Improvments of Lopez's prognostic large scale cloud and precipitation scheme, ALADIN Newslett., **28**, 66–73, 2005.

Brousseau, P., and coauthors: A prototype convective-scale data assimilation system for operation: The AROME-RUC. *HIRLAM Tech. Rep*., **68**, 23–30, 2008.

Brousseau, P., L. Berre, F. Bouttier, and G. Desroziers: Flow-dependent background-error covariances for a convective-scale data assimilation system. *Q. J. R. Meteorol. Soc.*, **138**, 310–322, 2012.

Bubnova, R., Hello, G., Bnard, P. and Geleyn, J.-F. 1995. Integration of the fully-elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of the ARPEGE/ALADIN NWP system. Mon. Weather Rev. 123, 515–535.

Catry, B., Geleyn, J. F., Bouyssel, F., Cedilnik, J., Brozkova, R., Derkova, M., and Mladek, R.: A new sub-grid scale lift formulation in a mountain drag parametarisation scheme, Meteorol.Z., **17**, 193–208, 2008.

Charnock, H., 1955: Wind stress over a water surface. Quart. J. Roy. Meteor. Soc., **81**, 639–640.

Cuxart, J., Bougeault, P., and Redelsperger, J. L.: A turbulence scheme allowing for mesoscale and large-eddy simulations, Q. J. Roy. Meteor. Soc., **126**, 1–30, 2000.

Dahlgren P.: Using Jk in AROME 3DVAR: Some initial tests HIRLAM Newsletter No. 59 Dec 2012, p3-9, 2012.

Desroziers G, Berre L, Chapnic B, Poli P, Diagnosis of observation, background and analysis error statistics in observation space, *Quart. J. Roy. Meteor. Soc.*, **131**, 3385–3396, 2005.

Fouquart, Y. and Bonnel, B.: Computations of solar heating of the earth's atmosphere: a new parameterization, Beitr. Phys. Atmosph., **53**, 35–62, 1980.

Guidard V. and Fischer C.: Introducing the coupling information in a limited-area variational assimilation, *Q. J. R. Meteorol. Soc.*, **134**, 723-736, 2008.

Gustafsson, N., Berre, L., Hörnquist, S., Huang, X.-Y., Lindskog, M., Navascués, B., Mogensen, K.S., Thorsteinsson, S.: Three-dimensional variational data assimilation for a limited area model. Part I: general formulation and the background error constraint. *Tellus*, **53A**, 425–446, 2001.

Lindskog, M., Gustafsson, N., Navascués, B., Mogensen, K.S., Huang, X.-Y., Yang, X., Andræ, U., Berre, L., Thorsteinsson, S., Rantakokko, J.:. Three-dimensional variational data assimilation for a limited area model. Part II: observation handling and assimilation experiments. *Tellus*, **53A**, 447–468, 2001.

Liu, W. T., K. B. Katsaros, and A. Businger, 1979: Bulk parameterization of air–sea exchanges of heat and water vapor including the molecular constraints at the interface. J. Atmos. Sci., **36**, 1722–1735.

Lopez, P.: Implementation and validation of a new prognostic large-scale cloud and precipitation scheme for climate and data-assimilation purposes, Q. J. Roy. Meteor. Soc., **128**, 229–257, 2002.

Masson V (2000) A physically-based scheme for the urban energy budget in atmospheric models. Boundary-Layer Meteorol, **94** ,357–397

Masson, V., J.-L. Champeaux, F. Chauvin, C. Meriguet, and R. Lacaze, 2003: A global database of land surface parameters at 1-km resolution in meteorological and climate models. J. Climate, **16**, 1261–1282.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., and Clough, S. A.: RRTM, a validated correlated-k model for the longwave, J. Geophys. Res., **102**, 16663–16682, 1997.

Morcrette, J. J.: Radiation and cloud radiative properties in the ECMWF operational weather forecast model, J. Geophys. Res. D, **96**, 9121–9132, 1991.

Montmerle, T., and L. Berre: Diagnosis and formulation of heterogeneous background-error covariances at the mesoscale. *Q. J. R. Meteorol. Soc.*, **136**, 1408–1420, 2010.

Niermann D., M. Borsche, A. Kaiser-Weiss, E. van den Besselaar, G. van der Schrier, R. Cornes, E. de Vreede, C. Lussana, O. E. Tveito, L. Cantarello, C. Frei, F. Isotta, J. Davie, Preliminary report of assessment of regional reanalyses – first results, *UERRA deliverable D3.6*, 2017.

Noilhan J. and S. Planton: A Simple Parameterization of Land Surface Processes for Meteorological Models. *Mon. Wea. Rev.*, **117**, 536–549, 1989.

Ridal M., H. Körnich, E. Olsson and U. Andrae, Report of results and datasets of two physics HARMONIE runs for spread estimation. *UERRA deliverable D2.5,* 2016a.

Ridal M., H. Körnich, E. Olsson and U. Andrae, Preliminary report of the first period of the RA. *UERRA deliverable D2.6,* 2016b.

Seity Y., P. Brousseau, S.Malardel, G. Hello, P. Bénard, F. Bouttier, C. Lac and V. Masson: The AROME-France Convective-Scale Operational Model, *Monthly Weather Review*, **139**, 976-991, 2011.

Smith, R. N. B.: A scheme for predicting layer clouds and their water content in a general circulation model, Q. J. Roy. Meteor. Soc., **116**, 435–460, 1990.

Taillefer, F.: CANARI - Technical Documentation - Based on ARPEGE cycle CY25T1 (AL25T1 for ALADIN), available at htp://www.cnrm.meteo.fr/aladin/, 2002.