# SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

| | |
|---|---|
| **Project Title:** | Regional European re-analysis with ALADIN for UERRA (RERA) |
| **Computer Project Account:** | SPSERERA |
| **Start Year - End Year :** | 2017 - 2018 |
| **Principal Investigator(s)** | Heiner Körnich<br>Per Undén |
| **Affiliation/Address:** | SMHI<br>Folkborgsvägen 17<br>601 76 Norrköping<br>Sweden |
| **Other Researchers (Name/Affiliation):** | Richard Mladek (ECMWF) |

The following should cover the entire project duration.

## Summary of project objectives

(10 lines max)

This project is a continuation for the production of a regional European re-analysis data set from 1961 to present-day with the shared ALADIN-HIRLAM system. The resolution is 11 km horizontally and 65 levels vertically. In this continuation project we will finish the historical runs and the data will be archive on MARS. Over a shorter period, a sensitivity study will be performed to examine the impact of dynamic vegetation on the regional reanalysis. The results from the proposed project will contribute directly to the European FP7 project UERRA - Uncertainties in Ensembles of Regional Re-Analyses with 12 institutes from 7 EU countries, Switzerland, Norway and an international organisation (ECMWF), coordinated by Per Undén. UERRA will provide long-term datasets of Essential Climate Variables (ECVs) on the European regional scale in order to support adaptation action and policy development.

## Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

- Some jobs timed out while waiting for ECFS.
- Occasional long queueing times
- Some errors in archived data were discovered, e.g. for 100 % relative humidity and cloud cover, which were corrected.
- A bug in the reanalysis production was discovered: TKE and some cloud parameters were not initialized, causing some degradation in the first forecast hours.

## Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

Our experience with the special project framework is positive. The administrative aspects are kept to a meaningful amount. Regular e-mail reminders for upcoming deliverables are appreciated. The amount of available SBUs is limited but useful for our project. Especially for our project, disk space was vital, and it appears to us that the available disk space lags behind the increase in computational resources.

## Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

A regional re-analysis with a horizontal resolution of 11 km has been produced for an area covering Europe over a time period of 58 years, from 1961-2018. The regional re-analysis includes upper air observations introduced by a variational data assimilation scheme as well as surface observations assimilated by an optimal interpolation algorithm. During the last year, we have continued the production of the reanalysis for the recent months and we have analysed the quality of the reanalysis. As the number of available observations increase over time and at the same time improve in quality and distribution there is an improvement in forecast skill over the time period. The increased quality of the boundary conditions moving from ERA-40 to ERA-interim, for the same reasons, also contributes to the improved forecast quality. With a re-analysis over such a long period it is also possible to study climatological changes and consistency over time for different variables. For example, a clear temperature increase has been seen through the 55 years of the reanalysis. Verification against observations has been made for the regional re-analysis as well as to the global re-analysis for comparison. In general the regional reanalysis show good results compared to global re-analyses. This is most clear at the surface where the small scales are most important. There are a few problematic areas though such as moisture and precipitation, especially in complex terrain. Climatology in UERRA and extreme events were investigated and showed both good results and some problems. Unfortunately, a bug was discovered in the generation of the regional reanalysis, namely the fields of TKE and some cloud parameters were set to zero in the analysis. This causes some degradation of the forecast in the first hours. This degraded the hourly time history of the intense storm Gudrun in 2005. Corrections were extensively tested and showed to improve the extreme winds but there were also some longer forecast term impact which were probably good but it would affect the properties of the running reanalysis so it was not implemented in the operational UERRA, unfortunately.

A scientific report is attached with the manuscript in preparation by Ridal et al. (2018).

## List of publications/reports from the project with complete references

Borsche M, Kaiser-Weiss A K, Undén P and Kaspar F (2015). Methodologies to characterize uncertainties in regional reanalyses Adv. Sci. Res. 12, 207-218

Kaiser-Weiss, Andrea; Borsche, Michael; Niermann, Deborah; Kaspar, Frank; Lussana, Cristian; Isotta, Francesco; van den Besselaar, Else; van der Schrier, Gerard; Undén, Per (2019). Added value of regional reanalyses for climatological applications. Submitted to Environ. Res. Comm.

Ridal, M., Körnich, H., Olsson, E., and Andrae, U. (2016a). Preliminary report of the first period of the ra. Technical report, UERRA. UERRA deliverable D2.6. Available at http://www.uerra.eu/publications/deliverable-reports.html

Ridal, M., Körnich, H., Olsson, E., and Andrae, U. (2016b). Report of results and datasets of two physics harmonie runs for spread estimation. Technical report, UERRA. UERRA deliverable D2.5. Available at http://www.uerra.eu/publications/deliverable-reports.html

Ridal, M., Olsson, E., Undén, P., Zimmermann, K., and Ohlsson, A. (2017). Harmonie reanalysis report of results and dataset. Technical report, UERRA. UERRA deliverable D2.7. Available at http://www.uerra.eu/publications/deliverable-reports.html

Ridal, M., U. Andrae, J. Bojarova, A. von Kraemer, H. Körnich, E. Olsson, P. Undén, and K. Zimmermann (2018): A 55 year regional re-analysis over Europé. Manuscript to be submitted.

Von Kraemer, A. (2018): Temporal Consistency of the UERRA Regional Reanalysis: Investigating the Forecast Skill. ISSN 1650-6553, Master thesis at the Institution for geosciences No. 422, Uppsala. Available at http://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Auu%3Adiva-342027

## Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The production of the regional European reanalysis continues under a service contract for Copernicus Climate Change. SMHI has the lead for the contract. As part of the contract, a new regional European reanalysis will be generated with a higher production. The contract goes from 2017 to 2021.

# A 55 year regional re-analysis over Europe

Martin Ridal, Ulf Andrae, Jelena Bojarova, Adam von Kraemer, Heiner Körnich, Esbjörn Olsson, Per Undén, and Klaus Zimmermann

*Swedish Meteorological and Hydrological Institute*

**Abstract**

The demands for high resolution regional re-analyses are becoming more common as the interest in local climate variations increases. To meet these requests a regional re-analysis with a horizontal resolution of 11 km has been produced for an area covering Europe over a time period of 55 years, from 1961-2015. The regional re-analysis includes upper air observations introduced by a variational data assimilation scheme as well as surface observations assimilated by an optimal interpolation algorithm. As the number of available observations increase over time and at the same time improve in quality and distribution there is an improvement in forecast skill over the time period. The increased quality of the boundary conditions, for the same reasons, also contribute to the improved forecast quality. With a re-analysis over such a long period it is also possible to study climatological changes and consistency over time for different variables. For example, a clear temperature increase has been seen through the 55 years of the re-analysis. Verification against observations has been made for the regional re-analysis as well as to the global re-analysis for comparison. In general the regional re-analysis show good results compared to global re-analyses. This is most clear at the surface where the small scales are most important. There are a few problematic areas though such as moisture and precipitation, especially in complex terrain.

# 1 Introduction

As compared to long observation series, global re-analyses of the atmosphere provides a spatially complete and physically consistent data set of the best estimate of the state of the Earth's atmosphere (Dee et al., 2014). Examples of global re-analyses are the ERA-40 (Uppala et al., 2005) and ERA-Interim (Dee et al., 2011) produced by the European Centre for Medium-range Weather Forecasts (ECMWF), the Japanese JRA-55 (Kobayashi et al., 2015) and the American Modern-Era Retrospective Analysis for Research and Applications (MERRA (Rienecker et al., 2011)), and the NCEP/NCAR global re-analysis (Kalnay et al., 1996). These are run with a horizontal resolution of 60-70 km horizontal resolution or lower.

As smaller scale information and more realistic representation of extreme events, for example of precipitation, compared to global re-analyses are more and more demanded by users, the interest of spatially highly resolved regional re-analyses (RRA) is increasing. These also require long time periods as the interest in trends of various variables and phenomena is similarly increasing.

During 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 er-analyses can provide. EURO4M delivered RRA products at an intermediately high-resolution (22 km) but also with a downscaling to higher resolutions (Dahlgren et al., 2016).

A few other RRAs have also been produced covering smaller areas or run for shorter time periods such as the COSMO-REA6 by Deutsche Wetterdienst covering almost the same area as EURO4M with 6 km resolution but only for 1 year (Bollmeyer et al., 2015) or the Met Éirann reanalysis (MÉRA) at 2.5 km covering Ireland and the British Islands (Gleeson et al., 2017).

The European Unions seventh Framework Programme (EU FP7) project Uncertainties in Ensembles of Regional Re-Analyses (UERRA) has increased the resolution even further, compared to EURO4M, to address some limitations of the latter 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 RRA, Advanced Ensemble Data Assimilation was used for a long time period. High-resolution deterministic RRA 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 model setup is together with some results and verifications is described in the UERRA deliverables D2.5 (Ridal et al., 2016b), D2.6 (Ridal et al., 2016a) and D2.7 (Ridal et al., 2017), available from the UERRA home page (http://www.uerra.eu). In the first part of the project two versions of model physics were used to create a mini ensemble over five years, 2006-2010 (Ridal et al., 2016b). The experiments also served as a preparation for the long re-analysis to avoid as many mistakes, errors and bugs in the long re-analysis as possible. The HARMONIE-RRA 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 re-analyses a large scale constraint has been added to the cost function.

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 the observation monitoring is presented which is a very important part of the monitoring of the model behaviour. Examples of output fields from the re-analysis, how they change over the years and how they compare to observations and to the global re-analyses ERA40 and ERA-Interim is presented in Section 5. The report is concluded in Section 6.

# 2 Model setup

The 55 year re-analysis 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. For the long re-analysis 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 HARMONIE-

RRA 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 re-analysis 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 HARMONIE-RRA is setup with a horizontal resolution of 11 km and covers entire Europe as displayed in Figure 1. The model domain consists of 565x565 grid points, located on a Lambert conformal conic grid, and 65 vertical levels. The model runs with semi implicit, semi Lagrangean, hydrostatic dynamics.

## 2.1 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, $J$ (e.g. Gustafsson et al. (2001); Lindskog et al. (2001); Brousseau et al. (2008)):

$$J(x) = J_b + J_o = \frac{1}{2}\left(\mathbf{x}-\mathbf{x}_b\right)^T B^{-1}\left(\mathbf{x}-\mathbf{x}_b\right) + \frac{1}{2}\left(\mathbf{y}-H\mathbf{x}\right)^T R^{-1}\left(\mathbf{y}-H\mathbf{x}\right) \quad (1)$$

where $\mathbf{x}$ is the model state vector to be determined by the minimisation, $\mathbf{x}_b$ is a model background state, in our case a 6-hour forecast while $\mathbf{y}$ represents the observation vector. $H$ is the observation operator that transforms the model state into the observed quantities. The matrices $B$ and $R$ are the covariances of the errors of the background field and observations, respectively. 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 generated using downscaling from the ensemble assimilation dataset available at ECMWF. This generates a large number of 6 hour forecasts from which the forecast errors can be estimated. The calculations are made only once, a mix of one summer and one winter month, 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 (Equation 1). 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 by an optimal interpolation (OI) method using CANARI (Code for the Analysis Necessary for ARPEGE for its Rejects and its Initialization) and SURFEX (surface externalisée). In the HARMONIE-RRA, only 2 meter temperature (T2m), 2 meter relative humidity (RH2m) and Snow Water Equivalent (SWE) obtained from synoptic stations are used for the surface data assimilation.

CANARI (Taillefer, 2002) is a part of the IFS/ARPEGE (Integrated Forecast System/Action de Recherche Petite Echelle Grande Echelle) (Bubnova et al., 1995) 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., 2010).

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.

## 2.2 The ALADIN setup

The basis for the ALADIN setup is the limited area model (LAM) version of the ARPEGE-IFS (Bubnova et al., 1995). It comprises a non-hydrostatic spectral dynamical core with semi-implicit time stepping and semi-Lagrangian advection. In the horizontal resolution used in the HARMONIE-RRA, 11 km, 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 Rapid Radiative Transfer Model (RRTM) scheme for longwave radiation (Mlawer et al., 1997) and the six-band FouquartMorcrette scheme for short-wave 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 Lacarrere (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).

As mentioned earlier, ALADIN is coupled to the externalized version of the Méso-NH surface scheme, SURFEX. The Town Energy Budget (TEB) scheme used for urban tiles (Masson, 2000) simulates urban micro climate features, such as urban heat islands. Sea tiles use the Exchange Coefficients from Unified Multicampaigns Estimates (ECUME) parametrization (Belamari and Pirani, 2007). It is a bulk iterative parametrization developed in order to obtain an optimized parametrization covering a wide range of atmospheric and oceanic conditions. 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. Physiography data are initialized due to the ECOCLIMAP database (Masson et al., 2003) at 1-km resolution.

# 3 Archiving

Output data from the HARMONIE 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-RRA.

## 3.1 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 (http://www.uerra.eu) in the annex of deliverable D4.2 (SomdeCerff et al., 2016).

## 3.2 Forecast

The forecasts from the analyses at 00 UTC and 12 UTC are stored every hour up to 6 hours and thereafter every third hour up to 30 hours lead time. For the intermediate forecasts at 06 and 18 UTC every hour is stored since they end at 6 hours lead time.

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.

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. Wind is provided as wind speed and wind direction on the height levels because it is envisaged that the user community interested in height levels is more interested in these parameters instead of the separate u and v components. For the height levels the fields archived are apart from the wind information also the same cloud information as for the pressure levels, relative humidity, pressure and temperature. The height levels are given in Table 2.

| 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 HARMONIE-RRA MARS archive

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

Table 2: Height levels in the HARMONIE-RRA 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 UERRA deliverable D4.2 (SomdeCerff et al., 2016), available from the UERRA home page (http://www.uerra.eu).

# 4 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.

Within UERRA an observation monitoring system has partly been developed. Figure 2 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.

Figure 3 shows the same thing as Figure 2 but with the aircraft and radiosonde observations removed. This is to make the remaining observation types more visible. It can be seen that the number of ship observations increases to around 1980 and then starts to decrease. Exactly why this is the case is still unclear. The abrupt decrease at the last year of the re-analysis, 2015, is due to a bug introduced when the aircraft observations was supplied in a new format. All station ID for ship observations was lost and thereby leading to a large reduction during the redundancy check. This is now corrected but the last year is not re-produced.

There are a few features in Figures 2 and 3 that need further investigation. One example is the number of radiosonde observations in the 1970s as well as the very large decrease in aircraft data in 2008. The spikes and short periods with many more observations is due to extra data from some measurement campaign or just that there were some extra observations locally available.

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 4 and 5 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 5) is smaller than the first guess departure (Figure 4) as expected.

# 5 Model performance

There are several ways to determine the model performance and for a data set like the HARMONIE-RRA there are many parameters and time periods to investigate and evaluate. Much work was made during the UERRA project and some reports and publications can be found at the UERRA home page (www.uerra.eu). The general conclusion was that the different regional re-analyses within UERRA generally perform very well. One is better comparing one parameter while the other is better for another parameter or time period. It can also differ depending on the geographical area of interest, however, all regional re-analyses outperform the global re-analyses. The main reason is the higher spatial resolution as well as the more frequent data assimilation. In this section some interesting results will be shown as well as some measures to establish the overall performance of the HARMONIE-RRA.

## 5.1 Climatology

A dataset like the HARMONIE 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

6 shows the mean value of T2m for January from 1961-1980 in the left panel and 1981-2015 in the right panel. The corresponding standard deviations for the two periods are shown in Figure 7.

Comparing the mean values for T2m from the HARMONIE-RRA with the corresponding mean values from ERA40 and ERA-Interim, presented in Figure 8 shows that they are very similar. The difference in resolution is obvious, especially in areas of steep topography. The standard deviations (Figure 8) are also very similar but more pronounced for the HARMONIE re-analysis.

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 10, 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.

For precipitation there are larger differences between the HARMONIE-RRA compared to ERA-Interim. In the left panel of Figure 11 the mean precipitation for July for the period 1981-2015 from the HARMONIE-RRA 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 the HARMONIE-RRA. 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 12, it is clear that the variability is much larger for the HARMONIE-RRA in the whole domain compared to that of ERA-Interim. 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 the HARMONIE-RRA produces exaggerated precipitation amounts in the Alpine region. It has also been seen that the ALADIN scheme in general, produces too much precipitation.

## 5.2 Forecast skill

One way to evaluate the forecast skill is to investigate the difference between a 30 hour forecast (fc30) and a 6 hour forecast (fc06) valid at the same time. If this is done for a longer time period the standard deviation (STD) and mean of this difference can be calculated. If fc30 is continuously close to fc06, the STD of their difference will be small, and fc30 is said to be skilful. On the contrary, if it is extremely jumpy it means that the STD of the forecast difference will be large, which means that fc30 is not very accurate, and that the forecast skill is lower. Furthermore, if the constant mean difference over a longer period fc30 is said to have a drift, meaning that the forecasting model is systematically too warm or too cold.

As examples of forecast skill the two meter temperature (T2m) and the geopotential at 500 hPa (z500) are shown in Figures 13 and 14 respectively. The upper lines show the standard deviation while the lower curves represent the model drift. The data for these examples are taken from the smaller area, denoted by the black lines in Figure 1. The reason is that a large ocean area, as well as Greenland and the northern Africa, tend to decrease the signal since the variation is smaller and there are very few observations in these areas. The T2m shows a small but consistent improvement over the re-analysis period in the standard deviation. There is a very small drift that also decreases by the end of the period. Access to more observations of better quality is the mail reason for the improvements. For z500 on the other hand we can see a very large dependence on the driving model. There is a clear jump in forecast skill when the lateral boundaries change from ERA40 to ERA-Interim in 1979. After this there is also more and more satellite data included in the ERA-Interim analyses that contribute to the better performance of the HARMONIE-RRA.

## 5.3 Verification

The HARMONIE verification system WebgraF has been used to verify the forecasts for the 55-year period. The forecasts are verified against the same observations that were used for the initial analysis. In a reanalysis like this there is a large amount of data as well and a long time period to verify as well as different seasons and areas. This will result in a large number of figures if all intersting features is shown. So, in an attempt to summarise the verification results, scorecards 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 scorecards indicate if the HARMONIE-RRA performs better (green triangles), equally good (circles) or worse (red triangles) than the ERA re-analyses. If the difference is large there is a bigger triangle in terms of standard deviation (STDV).

The first scorecard is presented in Figure 15 and shows the temperature (T2m) and relative humidity (RH2m) at 2 meter level, the 10 meter wind speed (U10m) and the surface pressure (PMSL). It can be seen that for these surface parameters, except the relative humidity (Rh2m), the HARMONIE-RRA performs better or as good as the ERA re-analyses compared to observations. This is somewhat expected since the surface is where the small scale features are more important and the HARMONIE-RRA is run on a higher horizontal resolution that both the ERA re-analyses. The cloud cover is better compared to ERA40 but not compared to ERA-Interim which probably is an effect of the poor relative humidity.

For higher levels of the atmosphere the larger scales are more important. It can be seen in Figure 16 that at 925 and 850 hPa the temperature (T) and wind speed (WS) is better for the HARMONIE-RRA wile for 700 hPa the global re-analyses starts to be better. Again there are problems in the HARMONIE-RRA with the relative humidity (RH) at all levels.

# 6 Conclusions

Within the UERRA project the HARMONIE system was set up over Europe and a long re-analysis 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 re-analysis, the approach of an additional term in the cost function is employed. It has been seen that the performance of the model is very much dependent on the boundary conditions and large scale mixing fields, especially for the more large scale parameters, like geopotential at 500 hPa. Smaller scale parameters, like relative humidity or temperature near the surface, is less dependent on the driving model.

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). Aircraft data becomes available in the 1980s and increase dramatically from the end of the 1990s. This is when they become automatically reported instead of manually. Aircraft data is by far the most numerous observation and it also provides some valuable profile information during take off and landing.

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 the HARMONIE-RRA there seems to be a good balance.

Comparing the output fields with the ERA re-analyses show that the HARMONIE-RRA and the ERA re-analyses looks similar for temperature but HARMONIE produces a bit more precipitation. It is obvious that the higher resolution in the HARMONIE-RRA 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 HARMONIE re-analysis was conducted for numerous near-surface variables as well as for vertical profiles. It seems that HARMONIE performs equal or better compared to the corresponding ERA re-analyses for many variables, especially near the surface where the higher resolution has a larger influence. There are however variables where HARMONIE performs worse at all levels. One example is the relative humidity where we have seen that the HARMONIE-RRA is not performing so well. Any possible reasons for this will be investigated in order to avoid the same problems in coming re-analyses or other projects.

There are a few known issues in the data set and there will probably be more as the use of the data becomes more frequent. Some problems might be fixed and re-archived while other would need a total re-run which is not possible. Those will instead be corrected and included in the next generation of regional re-analyses.

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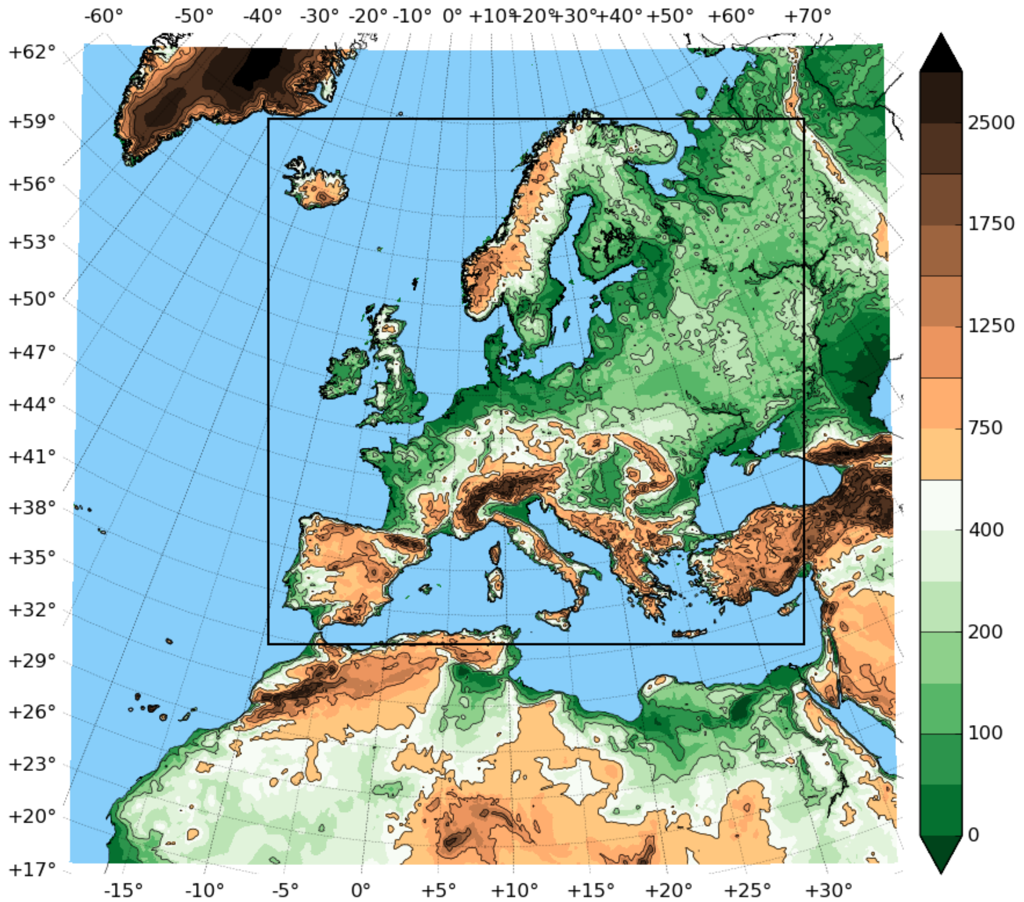



Figure 1: The HARMONIE-RRA domain. The orography is plotted for land points whereas all oceans points as defined by the land-sea mask are plotted in blue. The black lines represent the smaller domain used in section 5.2

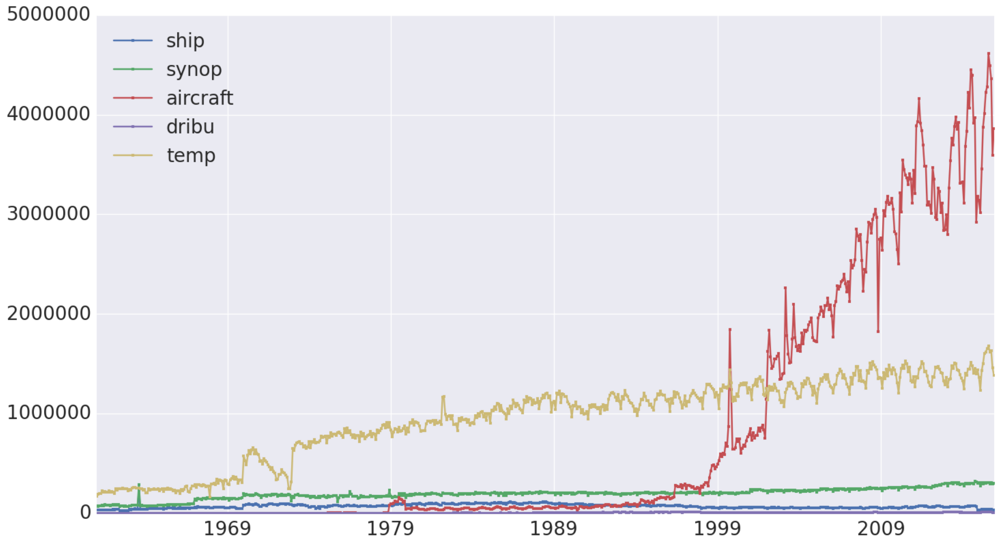



Figure 2: Monthly mean of number of observations used in the upper air analysis from 1961 to 2015. Both the total number of observations (blue) as well as the different observation types are shown.

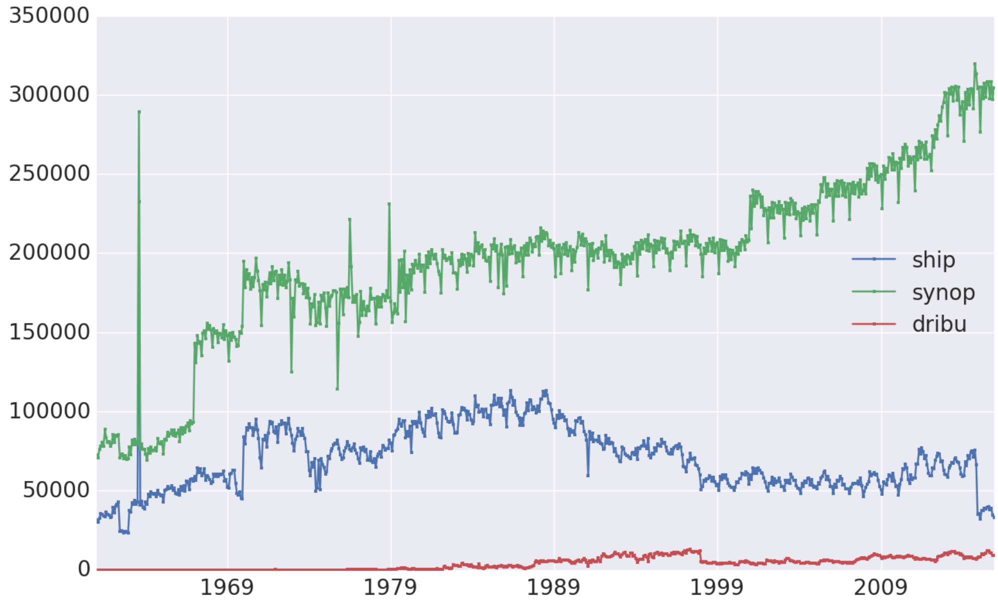



Figure 3: Same as Figure 2 but with aircraft and radiosonde observations removed to make the other observation types more visible.

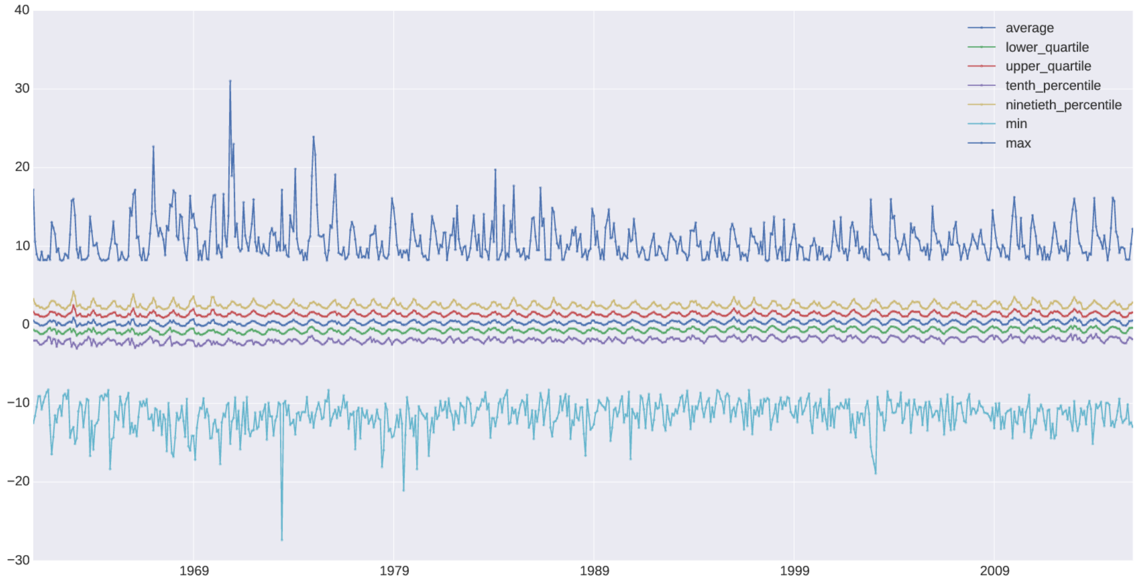



Figure 4: The first guess departure of T2m from observations. Monthly mean is shown (blue) together with the upper and lower quartiles, 10th and 90th percentiles and the max- and min departures.

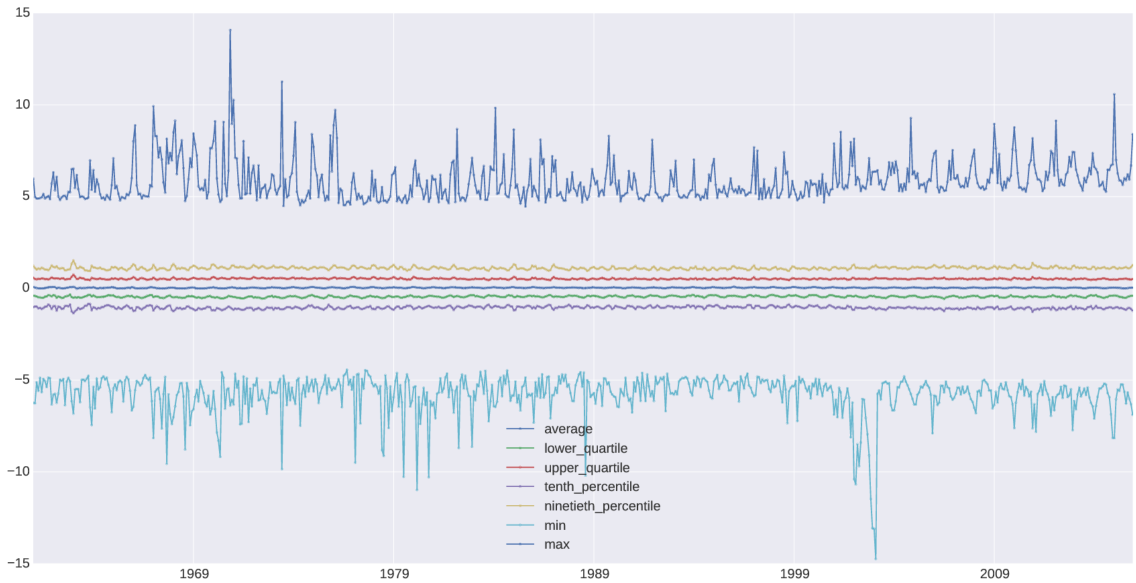



Figure 5: The analysis departure for T2m from observations. Monthly mean is shown (blue) together with the upper and lower quartiles, 10th and 90th percentiles and the max- and min departures.

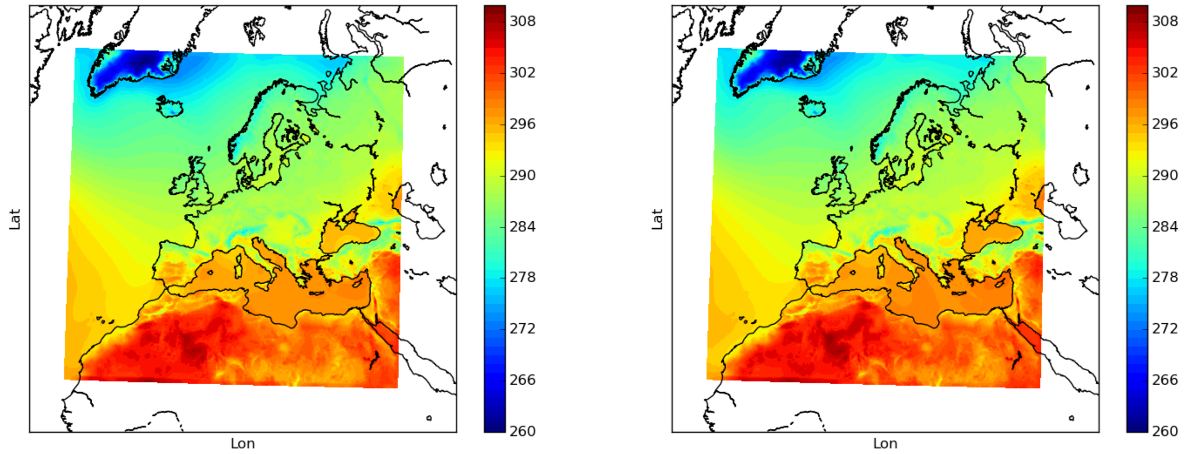



Figure 6: Mean values of two meter temperature for July during the periods 1961-1980 (left) and 1981-2015 (right).

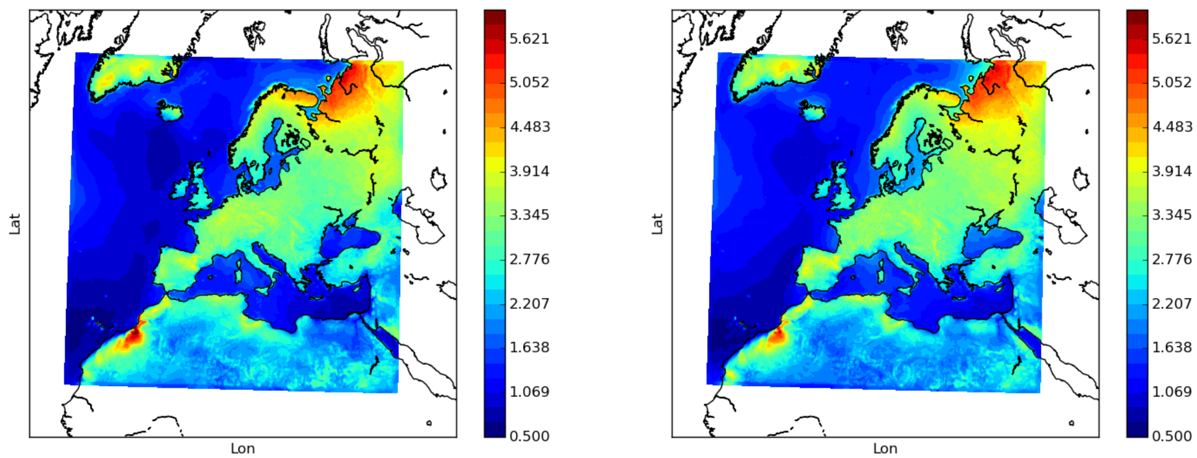



Figure 7: Standard deviation for the mean values presented in Figure 6.

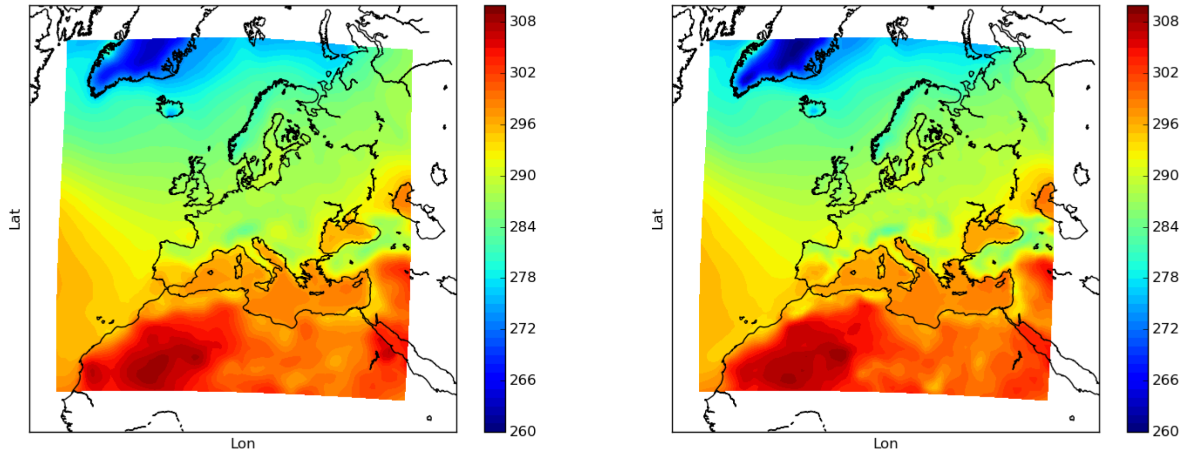



Figure 8: Mean values of two meter temperature for July from ERA40 1961-1980 (left) and ERA-Interim 1981-2015 (right).

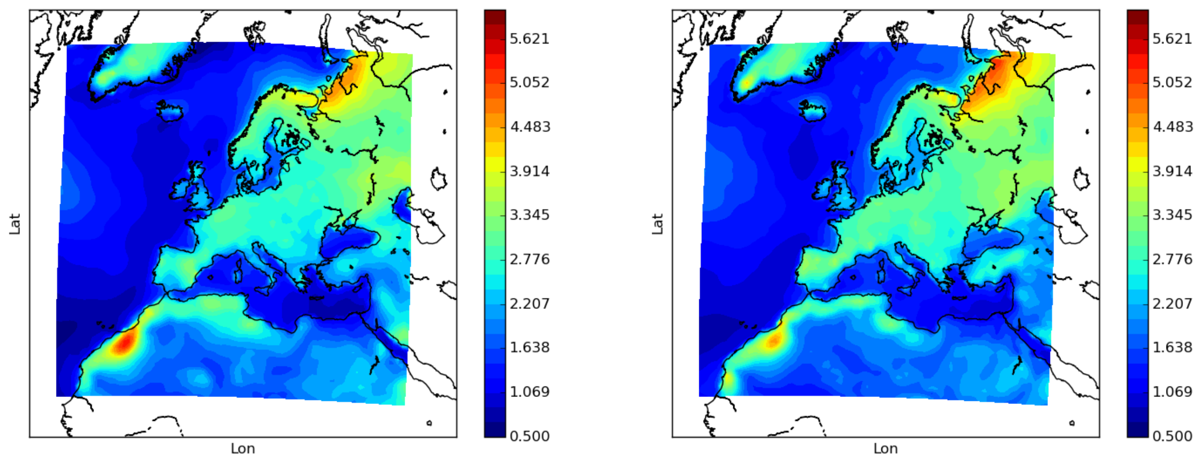
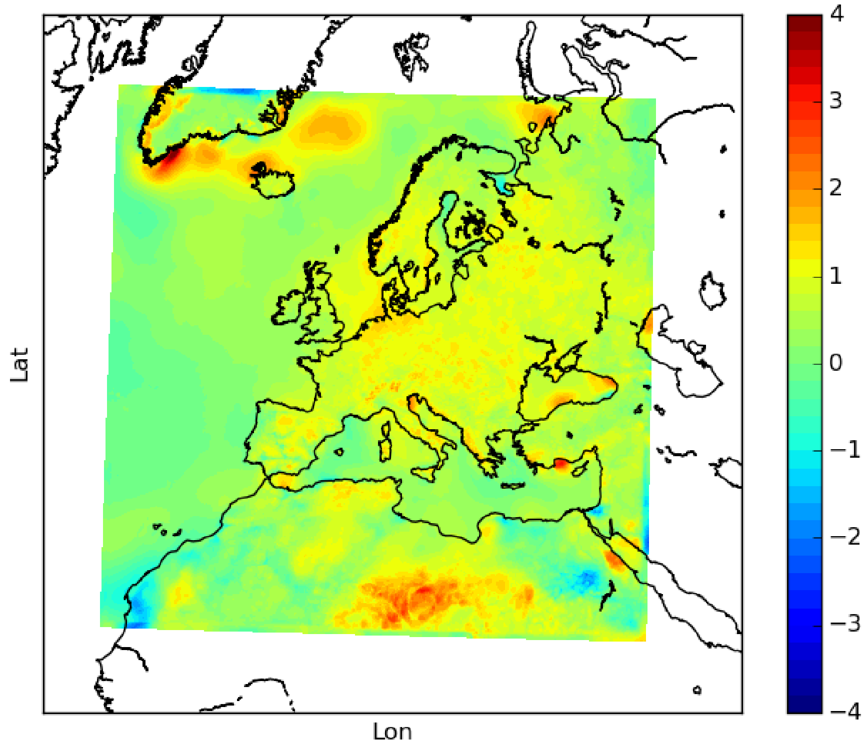



Figure 9: Standard deviation for the mean values presented in Figure 8.

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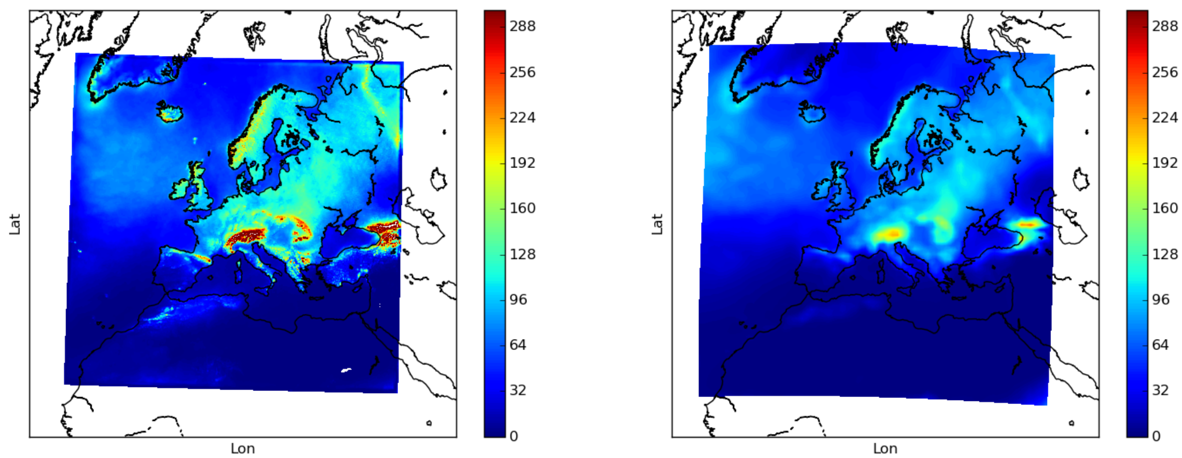


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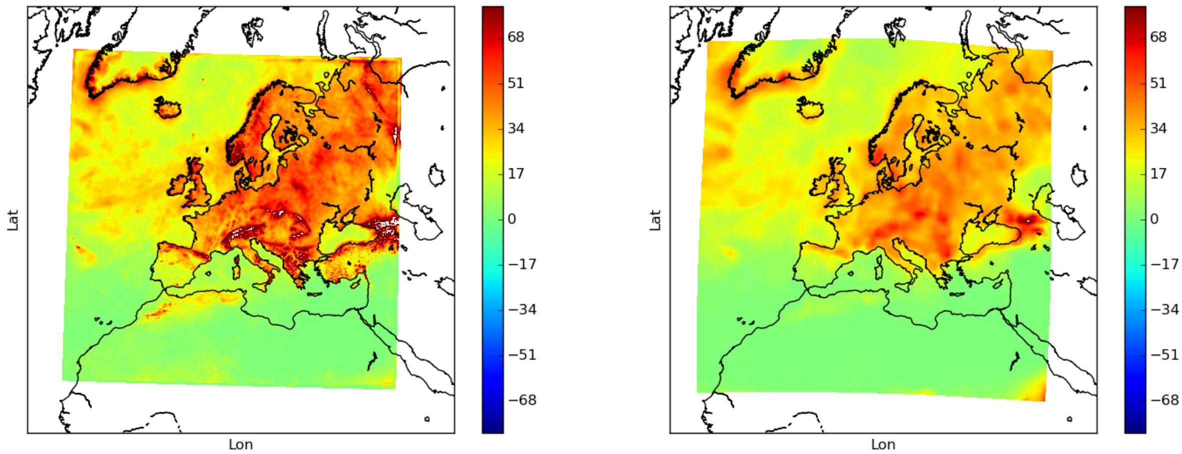



Figure 12: Standard deviation for the mean values presented in Figure 11.

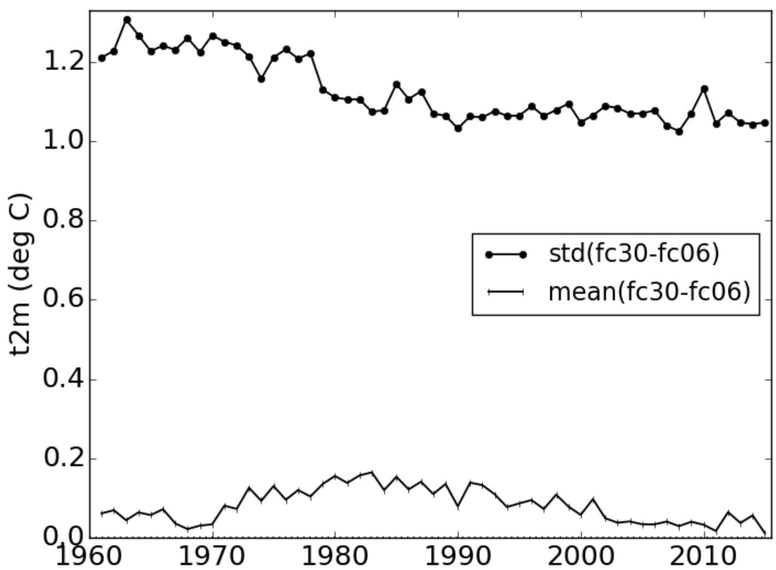
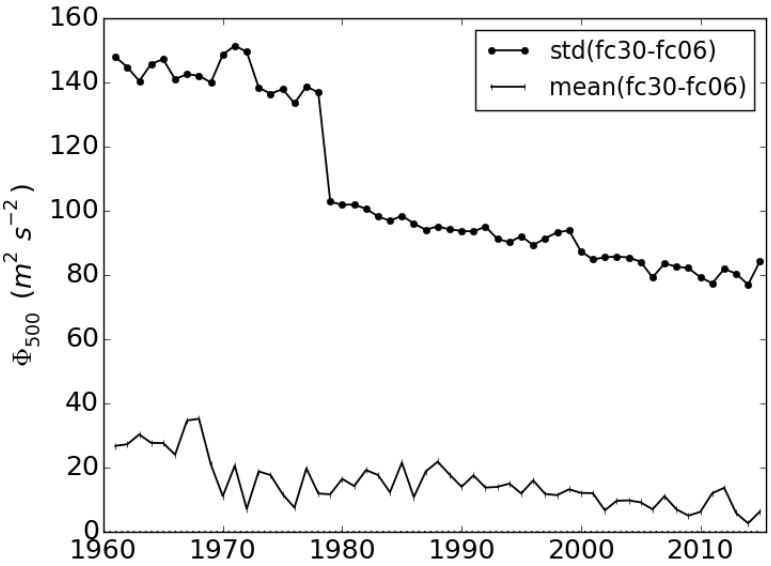



Figure 13: Yearly averages of the standard deviation and mean of the forecast difference fc30-fc06 for 2-meter temperature for every season. Only land points over Europe are included.

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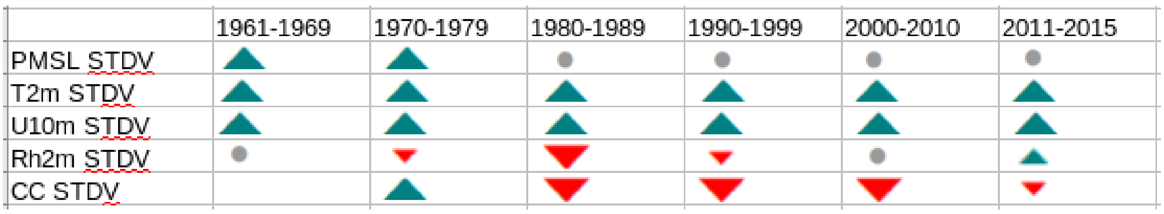
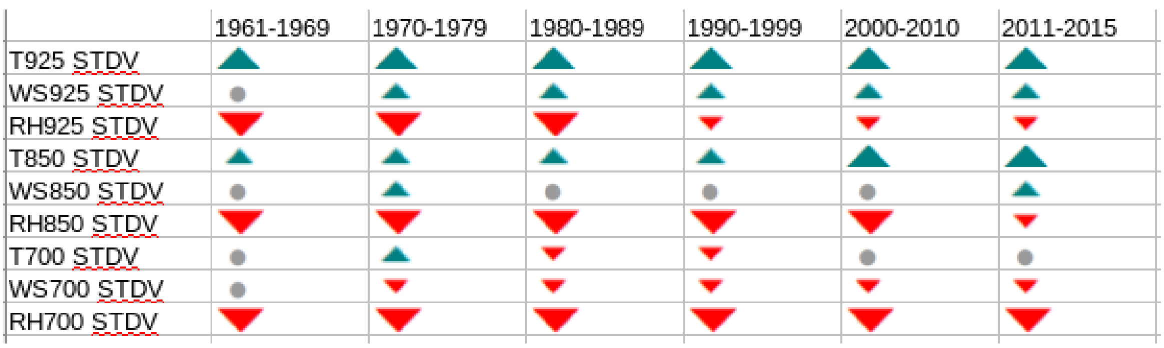



Figure 15: Scorecard for the HARMONIE-RRA compared to ERA40 and ERA-Interim for mean sea level pressure (PMSL), temperature and relative humidity at 2 meter level (T2m and Rh2m), wind at 10 meters (U10m) and total cloud cover (CC). Green indicates that the HARMONIE-RRA is better while red indicates that ERA is better. Bigger symbol means bigger difference. Circle means no noticeable difference between the two.

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