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Introduction

Within the European Union funded project European Reanalysis and Observations for Monitoring (EURO4M), the work started to answer the need for regional re-analyses (RRA) with a high resolution compared to what the global RA can provide. EURO4M delivered RRA products at an intermediately high-resolution (22 km) and also with downscaled versions to higher resolutions (Dahlgren et. al 2016).

EURO4M was followed by the pre-operational FP7 project "Uncertainties in Ensembles of Regional Re-Analyses (UERRA, www.uerra.eu). UERRA has increased the resolution even further to address some limitations of EURO4M and also focus on the uncertainties in the re-analyses. The time period of the RRA 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 was 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 has already been described in the UERRA 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 made within the UERRA project, 1961-2015, to avoid as many mistakes, errors and bugs as possible.

The long HARMONIE-RRA within the UERRA project 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. Two reports presenting the results from the UERRA re-analysis are available where the first report describes preliminary results. The second report contains results from the entire period from 1961 to 2015. The reports are available as UERRA deliverables D2.6 (Ridal et. al 2016b) and D2.7 (Ridal et. al 2017) respectively.

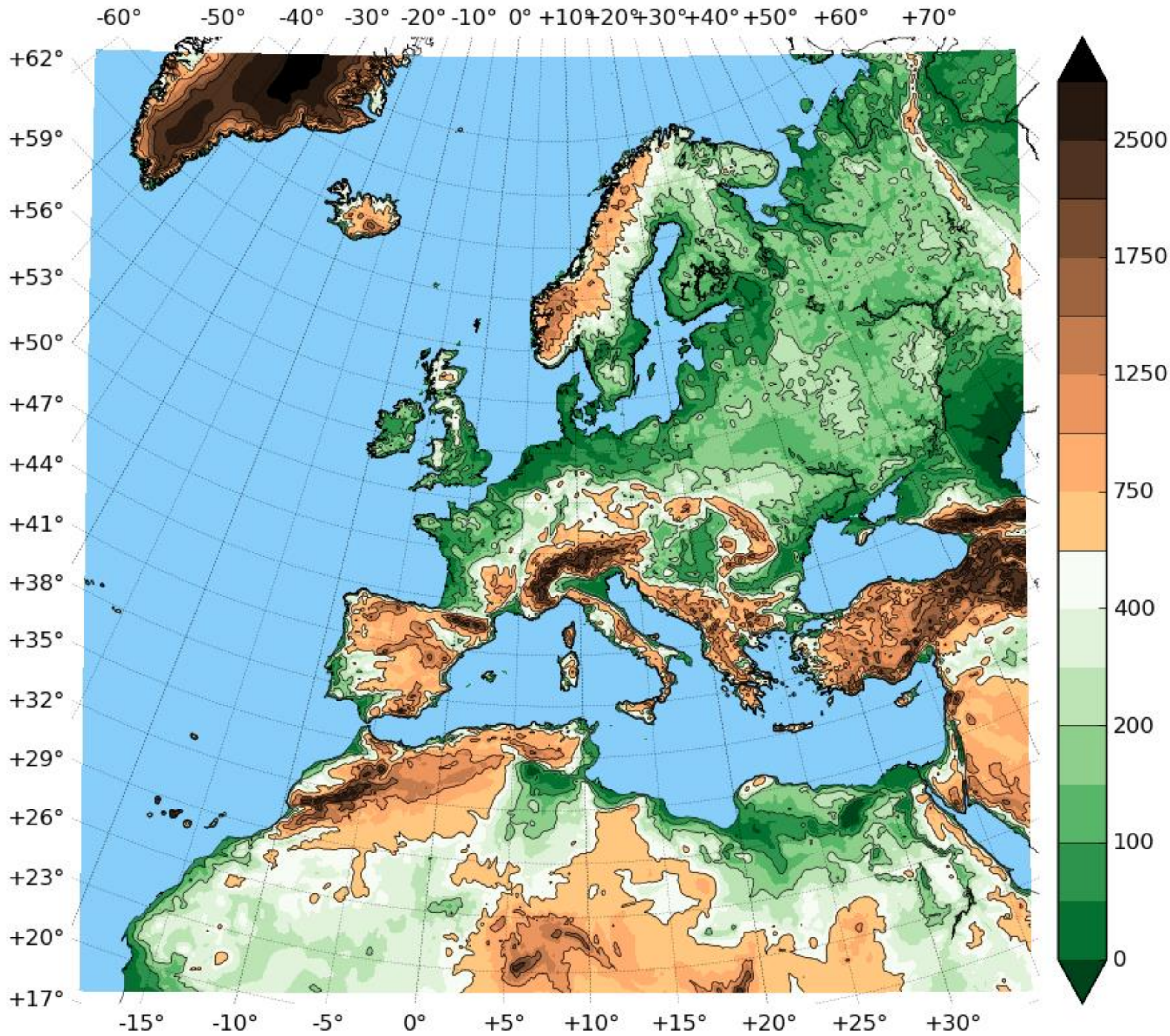
Within the current service contract (C3S_322_Lot1) the UERRA system will continue to run in parallel with the development of a new system with even higher resolution (5.5 km). This will extend the UERRA data set to near real time. Currently it has been completed with the years 2016 and 2017 (January to November). The production will continue until the new system is ready for production, which is scheduled for September 2019.

1. Model setup

The UERRA reanalysis system builds on the HARMONIE system cycle 38h1.1. HARMONIE is basically a script framework that allows for different physics packages, surface schemes and data assimilation schemes. Within UERRA 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 optimal interpolation (OI) assimilation scheme for the surface observations. This is described in more detail below.

The UERRA system is setup with a horizontal resolution of 11km and covers entire Europe (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.

Figure 1. Orography and ocean points in the UERRA setup. The orography is plotted for land points whereas all oceans points as defined by the land-sea mask are plotted in blue.



1.1 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 (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 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 only made 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 geopotential height from synoptic stations, ships and drifting buoys. Wind information is included from ships, buoys, aircraft observations and radio soundings. From the latter two also temperature is used for the analysis and finally moisture from the radiosondes. No remote sensing data is used for these experiments.
Before the observations enter the minimisation they are passed through a quality control step, screening, where a few basic controls are made. Such controls include a background check to make sure that the observation does not differ unreasonable much from the model first guess as well as a redundancy check. There is also a check to see if the observation or observation source is blacklisted. The blacklisting removes observations or observation sources that are known to have quality problems or should not be used for some other reason.
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). In the UERRA-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) (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 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 of the assimilated observations in each grid point based on observations minus first guess. In the next step, a consistent update of the SURFEX control variables is made based on analysis increments interpolated to all grid points by CANARI. The control variables in SURFEX are soil temperature and soil wetness, both in two layers, and the snow water equivalent.

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.

1.2 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.

2. 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 forecasts are stored on given pressure and height levels to reduce the data amount. In total about 6.5 Tb of data are stored for each year from the HARMONIE-ALADIN re-analysis production.

2.1 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 in the annex of deliverable D4.2 (Som de Cerff et al. 2016).

2.2 Forecasts

The HARMONIE-ALADIN is run with four forecasts cycles per day. They are initialized at 00, 06, 12, and 18 UTC. Whereas the cycles at 00 and 12 UTC run for a lead time of 30 hours the cycles initialized at 06 and 18 UTC stop after 6 hours. 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.

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

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

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.

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

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

Similar to the analyses there are a large number of surface parameters and essential climate variables (ECVs) archived for the forecasts. The complete list of variables is listed in annex 1 (section 6).

3. 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 the UERRA project, an observation monitoring system has been partly developed. It is still needed to be run manually for selected periods but it is very useful for diagnosing the re-analysis runs.

In Figure 2, the monthly means of the total number of observations used in the upper air data assimilation are shown for the data produced within the C3S service – Jan 2016 through Sep 2017 (blue line). Also shown are the individual observation types that are dominated by aircraft observations (red) and radio soundings (yellow). The reason that the radio soundings are so many is that each sounding observes at many vertical levels. The number of sounding stations is rather small. It can clearly be seen that there is an annual cycle in the number of both aircraft and radio sounding observations. The reason is fewer flights during winter and that the radio soundings don't reach as high in the winter as they do in the summer. Figure 3 shows the same as Figure 2 but without the aircraft and sounding observations to make the remaining observations more visible. Notable is that there are rather few PILOT and drifting buoy observations and a weak annual cycle in the number of ship observations.

Figure 4 and Figure 5 show the aircraft observation at 275 hPa for one day in February 2016 and one day in July 2016 respectively. This shows the distribution of the observations and it is clear that the number of flights is larger during summer, ~6000 observations at this level, than in winter, ~3500 observations. 275 hPa was chosen since it is the level with the most observations. Similar plots can be produced for all observation types. Rejected and blacklisted observations can also be shown which is very useful in the evaluation of the observation usage and diagnostics of the data assimilation.

Figure 2. The number of observations used in the minimization during 2016 and 2017 (until September). Displayed are the monthly means for the total amount of observations (blue) and all the subtypes.

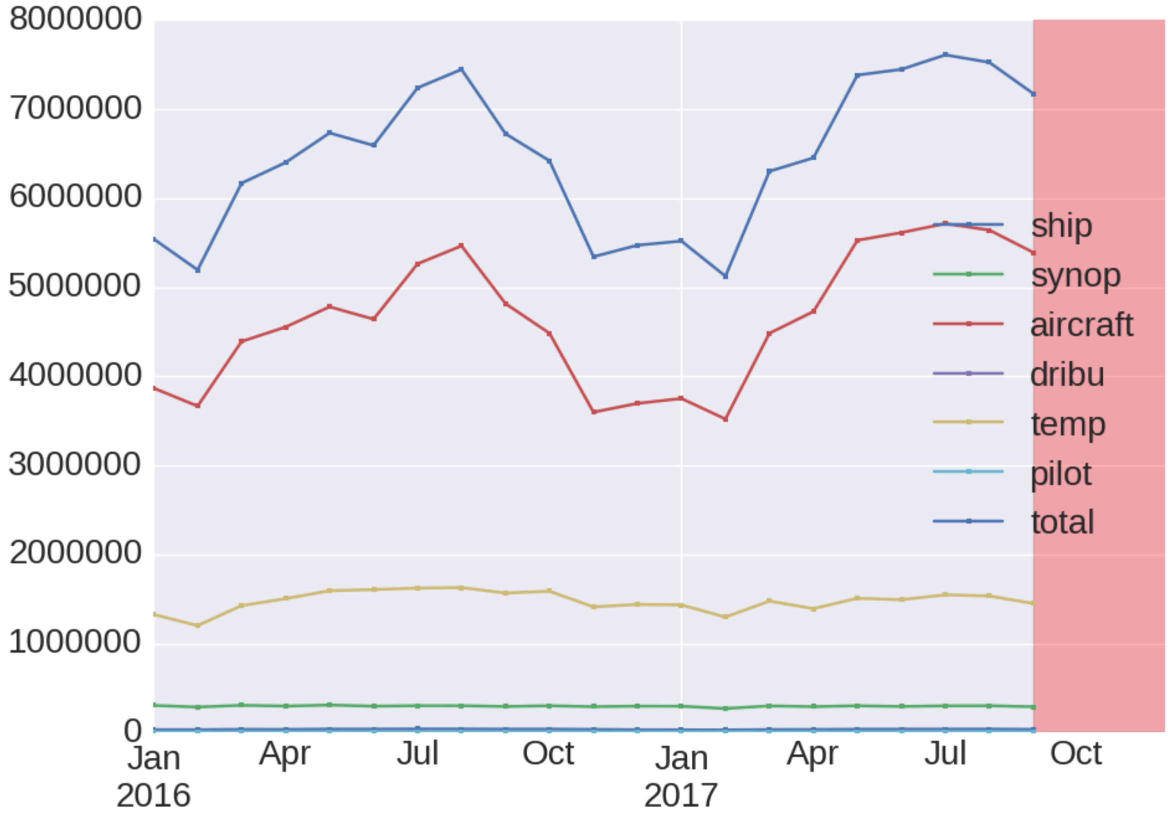


Figure 3. Same as Figure 2 but only for ship, SYNOP, DRIBU and PILOT observations.

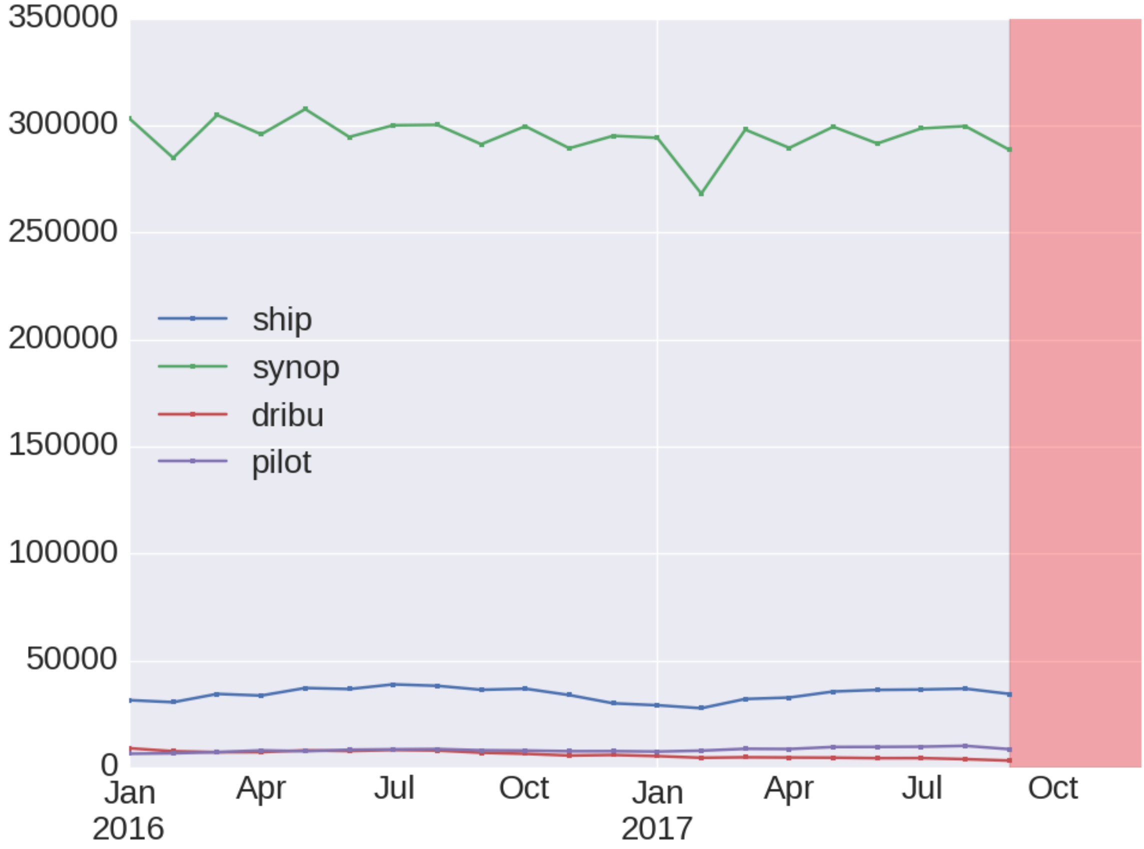


Figure 4. Aircraft observations used in the minimization at February 29, 12Z, 2016. Displayed is the level of 275 hPa.

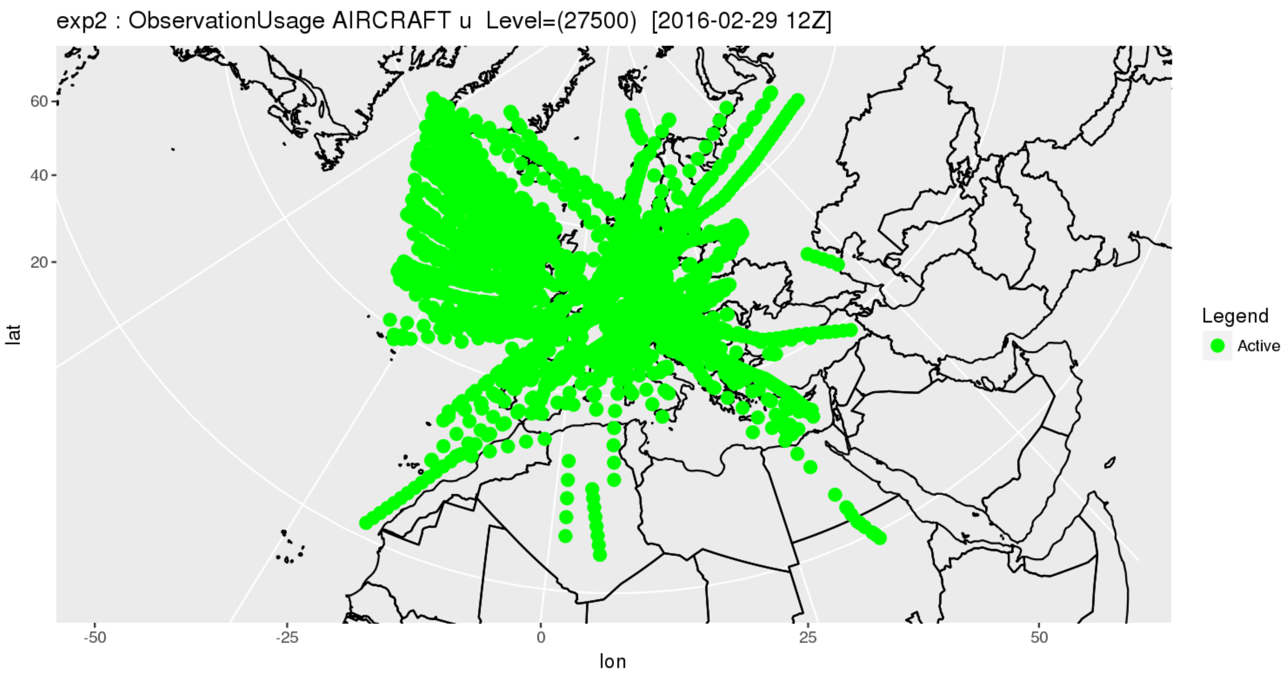
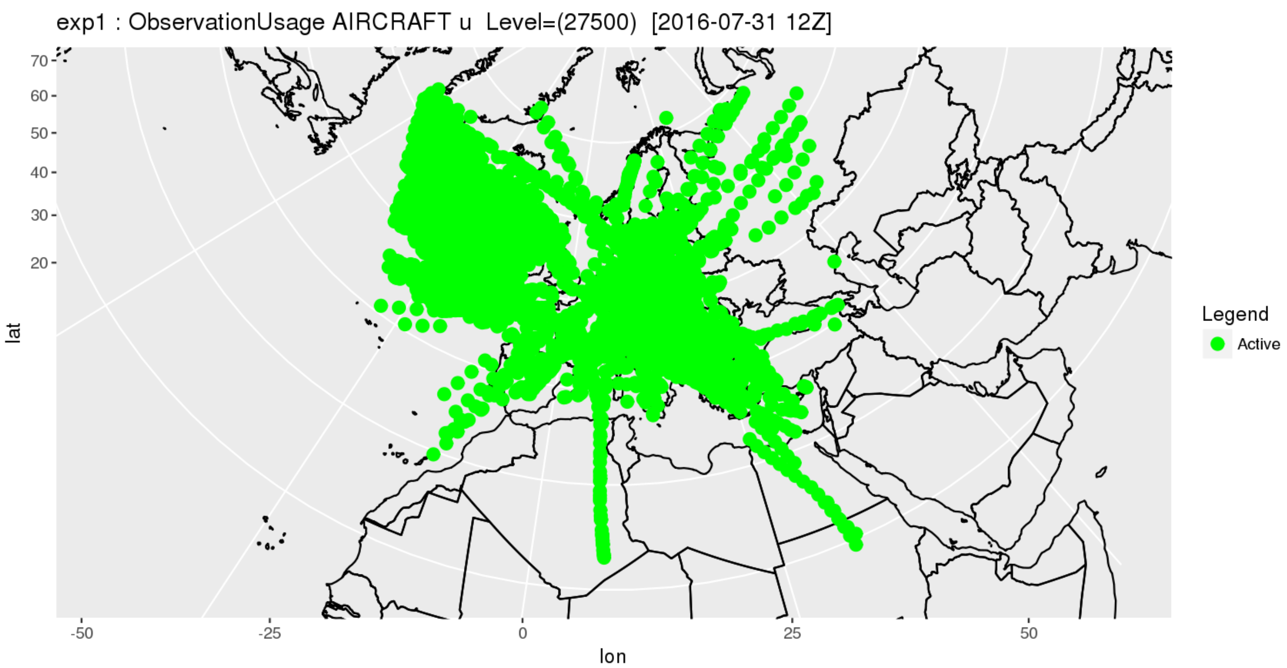


Figure 5. Same as Figure 4 but for July 31, 12Z, 2016.



4. Verification

The HARMONIE verification system WebgraF has been used to verify the UERRA forecasts together with the corresponding ERA-Interim forecasts for comparison.
A few examples of verification from a three month period, June to August, during the summer of 2016 is shown here. In all examples the verification of UERRA is represented by the red lines while the corresponding verification of ERA-Interim is represented by the green lines.
Figure 6 shows verification for the entire model domain of wind speed at 10 meter height where the upper two lines show the standard deviation (STD) error compared to observations while the lower two lines show the systematic errors or bias. It can be seen that the scores for UERRA are better than for ERA-Interim both for STD and the systematic errors.
Figure 7 shows the same as Figure 6 but for temperature at two metres above the ground. Again we see a better performance by UERRA. There is however a strange pattern in the bias which probably is related to a stronger diurnal cycle in UERRA compared to ERA-Interim.
Figure 8 shows the verification for relative humidity at two meters. Here we can see that the STD error is slightly smaller for UERRA but there is a wet bias present. This means that the model produces too much moisture. This is a known problem for the ALADIN model.
In Figure 9, the Kuiper Skill Score (KSS) for 12 hour precipitation forecasts is shown. For KSS a value closer to one means a better forecast. It can be seen that the excess of moisture in UERRA does not affect the precipitation forecast that much since UERRA performs better than ERA-Interim, especially for the higher precipitation amounts.
The excess of moisture does however affect the cloud cover shown in Figure 10. It is clear that the UERRA re-analysis performs worse than ERA-Interim for low cloud amounts. For higher cloud amounts on the other hand, UERRA is equal or even slightly better.

Figure 6. Verification for 10 meter wind speed from UERRA (red) and ERA-Interim (green) from forecasts starting at 00 and 12 UTC. The upper lines (asterisks) represent the STD error and the lower lines (squares) represent the bias. The dotted grey line gives the number of observations used for comparison.

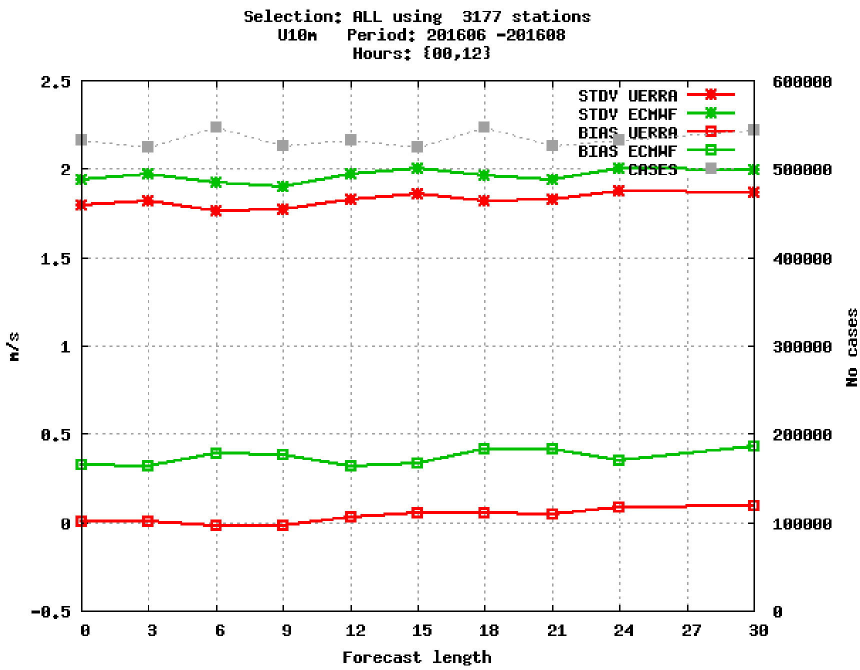


Figure 7. Same as Figure 6 but for two meter temperature.

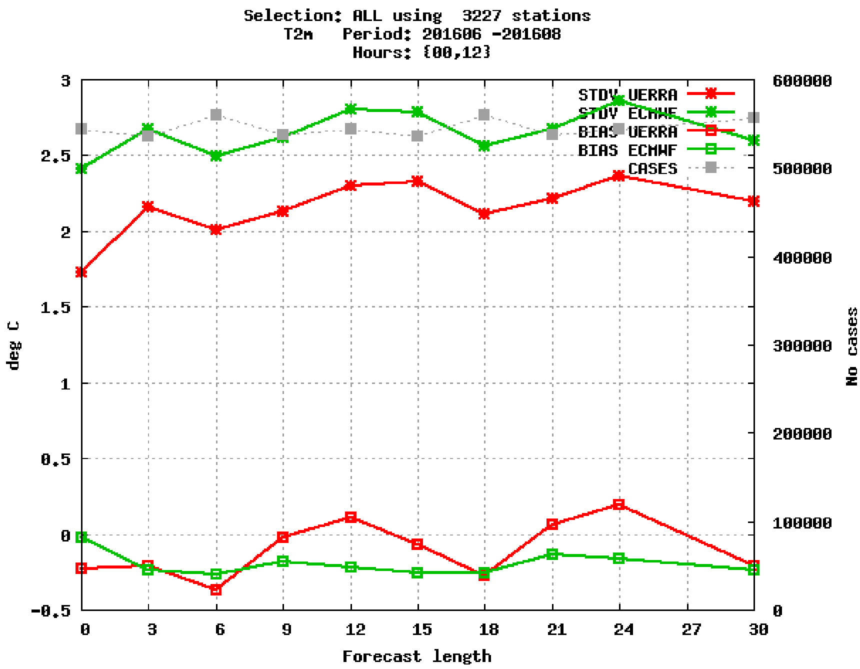


Figure 8. Same as Figure 6 but for two meter relative humidity.

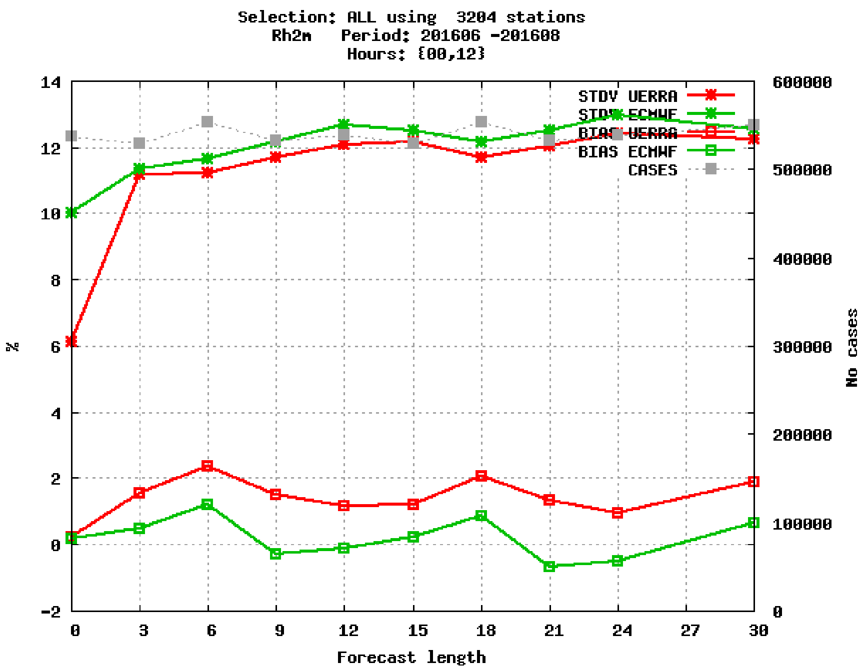


Figure 9. Kuiper Skill Score for 12 hour accumulated precipitation forecasts starting at 00 and 12 UTC for UERRA (red) and ERA-Interim (green).

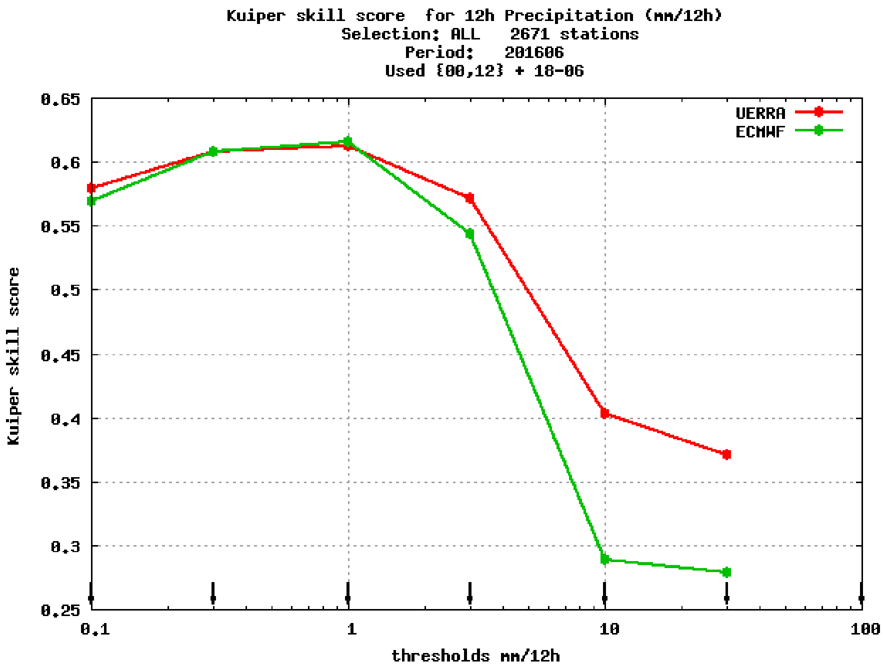
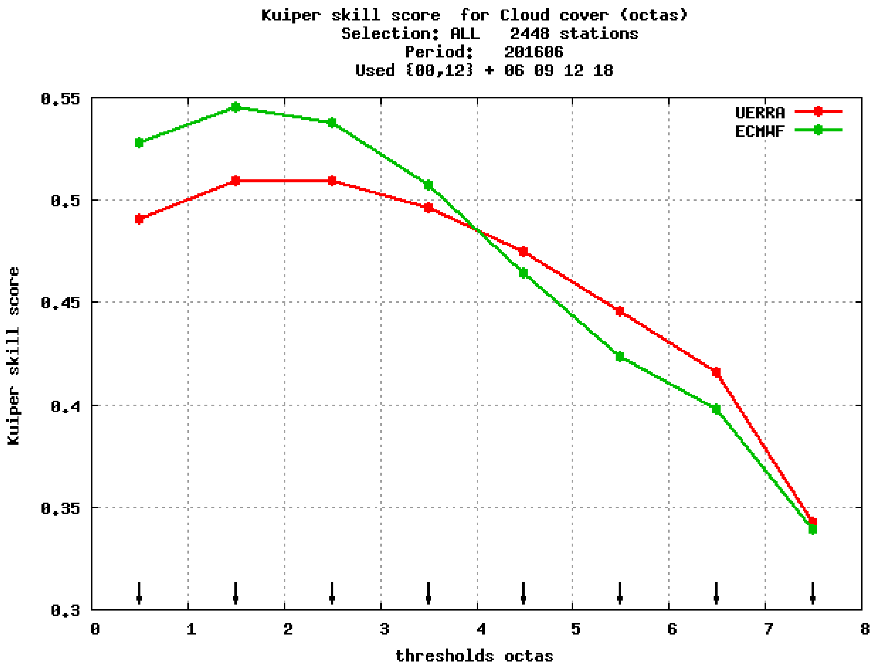


Figure 10. Kuiper Skill Score for cloud cover from forecasts lengths 6, 9, 12 and 18 hours starting at 00 and 12 UTC for UERRA (red) and ERA-Interim (green).



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6. List of ECVs available from UERRA

The following tables (Table 3 and Table 4) lists the variables which have been identified as ECVs by GCOS and are provided by the UERRA reanalyses. The list of ECVs conforms to the C3S indicative road map stage II. Only those ECVs are listed which are output by UERRA HARMONIE-RRA (this leaves out most of the oceanic parameters for instance).

Table 3. Surface ECVs archived by the UERRA HARMONIE-RRA

Air temperature
Wind speed and direction
Specific humidity
Total column water vapour
Precipitation
Pressure
Surface net solar radiation
Net short-wave radiation flux
Accumulated total snowfall
Water equivalent of accumulated snowfall
Snow depth
Snow density
Volumetric soil water layer 1-4
Albedo

Table 4. Upper air ECVs archived by the UERRA HARMONIE-RRA.

Temperature
Wind speed and direction
Specific humidity
Cloud cover
Cloud liquid water content;
Cloud ice content

Copernicus Climate Change Service

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