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CHANGES IN THE ALADIN OPERATIONAL SUITE IN CROATIA IN THE PERIOD 2011-2015

Izmjene u operativnoj prognozi modelom ALADIN u Hrvatskoj u razdoblju 2011-2015

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Abstract: National weather services issue weather forecasts based on the output from the numerical weather prediction models. Particular weather phenomena that have significant effect on safety can be characteristic of a certain country or region and may require specific model set-up in terms of model resolution and complexity to be forecast. However, the computational expenses of model set-up for operational purposes are limited by the available computer resources. In Meteorological and Hydrological Service (DHMZ) the operational numerical weather prediction uses ALADIN model. This paper describes the current NWP system and the changes introduced to the operational suite during the last few years. The operational suite in 8 km resolution and the dynamical downscaling of the wind field to 2 km resolution is run with higher frequency, the large scale model that provides the prognostic lateral boundary conditions has changed, operational forecast uses new model version with changes in model physics, dynamics and vertical discretization. Non-hydrostatic set-up of ALADIN has been running in 2 km resolution and 4 km resolution forecast using ALADIN model has been introduced. Here we show that improvements in the model physics that are beneficial for certain weather types, can deteriorate forecast quality otherwise. Although the increase in horizontal and vertical resolution improves the forecast, it partially restores the moist bias in the upper troposphere.

Keywords: model ALADIN, changes in Croatian NWP operational suite, introduction of the new version

Sažetak: Nacionalne meteorološke službe izdaju vremensku prognozu utemeljenu na produktima numeričkih modela za prognozu vremena. Vremenske prilike koje imaju značajan utjecaj na sigurnost mogu biti karakteristične za neku zemlju ili regiju te njihova prognoza može zahtjevati specifične postavke modela u obliku rezolucije i kompleksnosti modela. Međutim, računalni zahtjevi tih istih postavki modela za operativnu prognozu su ograničeni dostupnim računalnim kapacitetima. U Državnom hidrometeorološkom zavodu (DHMZ) operativna numerička prognoza vremena koristi model ALADIN. Ovaj rad opisuje izmjene u operativnoj prognozi provedene u posljednjih nekoliko godina. Operativna prognoza na 8 km i dinamička prilagodba na 2 km se provodi češće, promjenjen je model koji se koristi za prognostičke lateralne rubne uvjete, operativna prognoza se računa novom verzijom modela s izmjenama u fizici, dinamici i vertikalnoj diskretizaciji modela. Pored nehidrostatske prognoze na 2 km rezoluciji, uvedena je i prognoza na 4 km rezoluciji. Ovdje prikazujemo kako poboljšanja u fizici modela koja popravljaju prognozu u nekim vremenskim prilikama, pogoršavaju kvalitetu prognoze u drugim. Iako povećanje rezolucije modela u horizontali i vertikali popravlja prognozu, djelomično vraća vlažni bias u gornjoj troposferi.

Ključne riječi: model ALADIN, izmjene u hrvatskoj operativnoj numeričkoj prognozi vremena, uvođenje nove verzije

1. INTRODUCTION

An accurate weather forecast relies on the operational output from the numerical weather prediction (NWP) models. Global NWP models provide weather forecast fields covering the whole planet for seven and more days in advance, but often miss details characteristic for weather at a particular location. National weather services often rely on forecast provided by limited area models (LAMs) that focus on the particular region. These details can be important since they better simulate the high impact weather events that affect local population and require severe weather warnings.

ALADIN (Aire Limitée Adaptation Dynamique développement InterNational, ALADIN International Team, 1997) LAM is used for the operational weather forecast in the Meteorological and Hydrological Service (DHMZ) of Croatia since 2000 in pre-operational mode run daily and from 2002 as operational. Details of the operational suite in 2013 were described in Tudor et al. (2013). However, meanwhile, considerable changes have been introduced to the operational forecast suite enabled by the increase in the available computer resources. This article describes these changes with respect to the forecast performance and high impact weather phenomena that are typical for this region.

The operational forecast run in 8 km resolution is initialized using the data assimilation (DA) procedure. DA is procedure that uses observational data and a priori estimation of model state (background; short range forecast) in order to provide "as best as possible" approximation of true atmospheric state. The time span between the availability of the measured data and the production of the LAM NWP forecast products should be kept as short as possible since the value of the products degrades with time. The computational time required for each forecast step is determined by technical limitations such as the capacity of data transfer and storage, the size of the model grid, length of the time step and the speed of the mainframe computer (Ivančan-Picek et al. 2011). This requirement poses a restriction on the amount of measured data used in the data assimilation as well as on the level of complexity utilized in the model set-up used for operational forecast. However, considerable improvements in the available computing power enable us to investigate possible improvements gained by introducing more data to the data assimilation and more complex model set-ups that is always a result of a compromise between quality and time of delivery of model products.

The next section describes the operational ALADIN system in DHMZ including the recently introduced changes. Third section describes the new ALADIN model version and its quality with respect to the previous one. Section four describes the high resolution non-hydrostatic run in the operational suite. Fifth section briefly describes the 4 km resolution suite. The last section brings conclusions and plans for the future developments in the operational forecast.

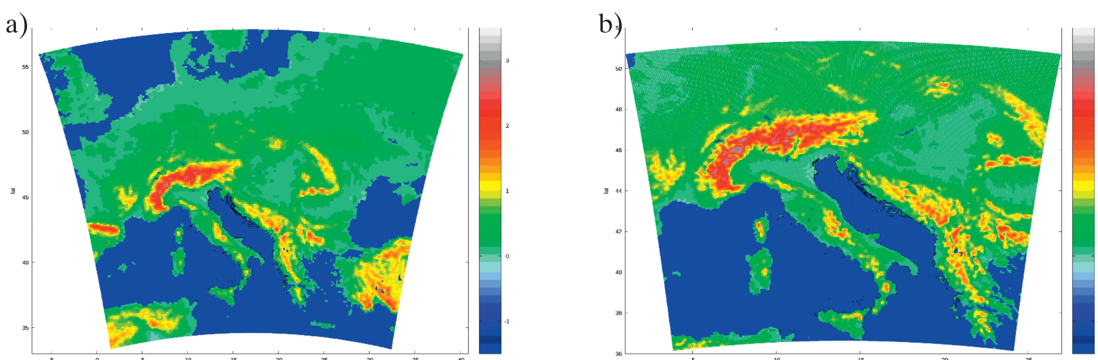

Figure 1. The domain and terrain height (shaded in km, points that contain mostly water surface are forced to blue) in the coupling file from IFS (a) and 8 km resolution domain (b).

Slika 1. Domene i visina terena (osjenčano u km, točke modela koje pretežno pokriva voda prikazane plavom bojom) u datoteci sa IFS rubnim uvjetima (a) i domeni s 8 km horizontalnom razlučivošću (b).

Table 1. Domains and configurations used in the operational forecast. The table lists the abbreviation used in the text, number of grid-points in x and y direction (including the E zone), horizontal resolution and number of levels in the vertical, source of initial and LBCs, forecast integration time and choices for physics and dynamics.

Tablica 1. Domene i postavke modela korištene za operativnu prognozu. U tablici se nalaze nazivi ("Abbreviation") korišteni u tekstu za razne postavke modela, broj točaka modela u x i y smjeru (uključujući točke u zoni matematičkog proširenja), horizontalnu razlučivost i broj vertikalnih nivoa, izvor inicijalnih i rubnih uvjeta, dužina prognostičkog razdoblja modela te izbor paketa fizikalnih parametrizacija i vrsta dinamike

Abbreviation	HR88	HR44	HR22	HRDA
No. points	240x216	480x432	450x450	450x450
Resolution	8 km	4 km	2 km	2 km
Vert. levels	37	73	37	37
Initial file	3D-var + OI	OI	HR88	HR88
LBCs	IFS	IFS	HR88	HR88
Forecast integ. time (hours)	72	72	24	0.5 (x73)
Physics	Alaro0 baseline	Alaro0 baseline	Early Alaro0 (CY36T1)	Only turbulence
Dynamics	hydrostatic	hydrostatic	non-hydrostatic	hydrostatic

2. The operational suite and introduced changes

Here we describe the operational forecast suite in DHMZ that uses ALADIN model with an emphasis on recently introduced changes. The operational forecast suite consists of forecast in 8 km horizontal resolution on 37 levels in the vertical (HR88, domain shown in Figure 1) and dynamical adaptation of wind field to 2 km resolution (DADA). Both of these features used to be run twice per day, for 00 and 12 UTC analyses up to 72 hours forecast. The number of runs per day has increased, so both HR88 and DADA are run four times per day, starting from 00, 06, 12 and 18 UTC analyses since 1st January 2014. The operational forecast in 2 km resolution using the complete physics package started in July 2011 (HR22) and it is run only once per day, starting from 6 hours forecast of the 8 km resolution run, covering period from 06 UTC to 06 UTC next day. This 2 km full 24 hours forecast is running in parallel with 8 km run and 2 km wind field forecast. From the February 2015, 4 km run at 73 model levels started in pre-operational mode (HR44), at the moment only for 00 UTC run. HR88, DADA and HR22 are run simultaneously, HR44 afterwards, to optimize the use of computer resources. Details are given in Table 1.

2.1. The new computer

As mentioned before, an increase in computer power, storage availability and capacity of communication lines enables introduction of higher levels of complexity in the operational forecast suite that were omitted before due to computational demands. In February 2013, DHMZ upgraded its mainframe computer to SGI UV 2000 (shared memory system) with Numalink 6 interconnect consisting of 38 Intel Xeon E5 processors. Each processor contains 6 cores of 2,9 GHz and 15 MB cache CPUs, total 608 GB RAM with total 228 cores. These cores are pre-defined so that 6 are dedicated to the operational system, 6 are for interactive work, 24 are for mono jobs (both operational and research) and the remaining 192 cores are for multi-processor jobs (both operational and research). Working disks have 6.6 TB of space, installed are Intel Fortran and C++ compilers version 13.1.0 20130121 and scheduler PBSPro, SGI management software, Fibre Channel and Gigabit etherneth.

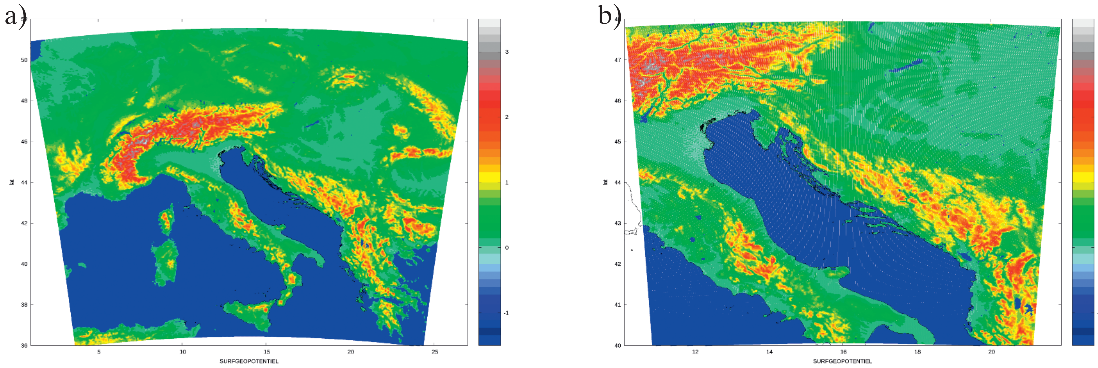

Figure 2. The domain and terrain height (shaded in km, water points forced to blue) in the 4 km resolution domain (a) and 2 km resolution domain (b).

Slika 2. Domene i visina terena (osjenčano u km, točke modela koje pretežno pokriva voda prikazane plavom bojom) za domene s 4 km (a) i 2 km (b) horizontalnom razlučivošću.

2.2. Model domains

All three operational ALADIN domains in DHMZ are in Lambert conformal projection and all have an 11 points wide extension zones towards north and east and 8 points wide coupling zones along all the lateral boundaries. The 8 km resolution domain is 240x216 points including the E zone (Figure 1b). The 4 km resolution domain is 480x432 points, and covers the same area as the 8 km resolution domain (Figure 2a). The grid of the 2 km resolution domain contains 450x450 points (Figure 2b), it is used for both dynamical adaptation of wind field and high resolution non-hydrostatic forecast using complete physics package. See Table 1 for summary.

2.3. Lateral boundary conditions

In order to provide a weather forecast, LAMs need forecast data along the lateral boundaries. The lateral boundary conditions (LBC) data contribute to the quality of the weather forecast due to advection of weather systems through boundaries. LBCs are usually taken from a NWP model covering larger geographical area run in lower resolution. There are two sources that provide LBC data to DHMZ. One set of LBCs is from the Integrated Forecast System (IFS, ecmwf.int/research/ifsdocs/) run operationally in the European Centre for Medium-Range Weather Forecast (ECMWF). The alternative are the ARPÈGE (Action de Recherche Petite Echelle Grande Echelle, http://www.cnrm.meteo.fr/ gmapdoc/meshtml/ guide_ARP/arpege.html) global NWP model run at Météo-France, used for operational run till the end of 2013. IFS LBC data are used in the operational system since beginning of 2014, while ARPÈGE LBC data were used before.

LBC fields provided by ECMWF and Météo-France do not cover the whole globe, the global forecast fields are interpolated to a limited-area Lambert projection grid covering a slightly wider geographical area than the local LAM (that uses them) to optimize the data transfer and storage (Figure 1a). LBCs are in a resolution similar to the one of the global model. The number of levels in the vertical is reduced since the atmospheric processes as high as the stratosphere top and mesosphere that affect weather forecast in the range of 10 to 15 days have a negligible impact in the 72 hour forecast range used for LAM. LBC fields contain the meteorological data covering the whole domain in the form of spectral coefficients, and not only the data on the lateral boundaries because ALADIN is a spectral model. This is particularly useful for verification purposes, as will be explained later.

On 1st January 2014, the operational ALADIN forecast suite in DHMZ has switched from ARPÈGE to IFS forecast data for LBCs because it provided LBCs up to 78 hours, four times per day. ARPÈGE model data used to be the primary choice since it is available earlier than the IFS model data (the data assimilation procedure of operational IFS waits longer to assimilate more measured data). LBCs from both IFS and ARPÈGE are used with an interval of 3 hours, but the data from

IFS are stretched up to 78 hours in advance, while the forecast range of the ARPÈGE data is 72 hours, and only 60 hours for the 18 UTC run. However, the IFS LBC data are provided in 15.4 km resolution on 60 levels in the vertical (operational IFS currently runs in 16 km resolution on 137 levels), while the ARPÈGE data are provided in 10.61 km resolution on 70 levels (allowed by the stretched grid of ARPÈGE that has higher resolution above Europe). Météo-France has moved to 8 km resolution LBC data provided on 105 levels in the summer 2015. ECMWF announced a move to higher resolution for the spring 2015, but it was postponed.

The ALADIN forecast is coupled to LBC fields from IFS in "lagged" mode. This means that 6 hour forecast from 18 UTC run of IFS is used as initial LBC for 00 ALADIN run of the next day, 9 hour forecast from 18 UTC run of IFS is used as LBC for 3 hour forecast for 00 ALADIN run of the next day, and so on. The coupling at the lateral boundaries is performed in a zone 8 grid-points wide using Davies (1976) relaxation scheme. LBCs have to be time dependent and periodic (Haugen and Machenhauer 1993) and applied at the very beginning or end of the grid-point computations (Radnoti 1995). An overview of LAM deficiencies caused by LBCs is given in Warner et al. (1997). However, the largest error arrives from linear interpolation of LBC data in time (Tudor and Termonia 2010) due to a long interval (3 hours) between available large scale data that are applied at lateral boundaries every LAM time-step (5.5 minutes for 8 km resolution run). The operational non-hydrostatic forecast run in 2 km resolution uses hourly LBC data from the operational 8 km resolution forecast.

2.4. The data assimilation procedure

The operational 8 km resolution forecast used to be run using digital filter initialization (DFI, Lynch et al. 1997) applied to the initial file from the global model ARPÈGE. ALADIN forecast quality benefits from improved initial conditions, especially in the severe precipitation events (Ivatek-Šahdan and Ivančan-Picek 2006). This has lead to the decision of implementation of the data assimilation (DA) procedure that consists of several ingredients. First, preparatory steps were taken in writing procedures that would collect and treat the measured data automatically and prepare them for the data assimilation procedure. Then the background error covariance matrix was computed for the operational domain and resolution (Stanešić 2011). A period of parallel suite followed, when two sets of forecast were run, one operational forecast was run starting from the fields interpolated from the initial fields of the global model ARPÈGE (that were initialized using the data assimilation) and initialized with DFI, and another forecast run performed starting from the initial conditions computed using local data assimilation. During the parallel suite, one could fix possible failures of the operational suite due to the data assimilation part that occurred mostly due to missing measurement data and other technical problems.

The data assimilation is procedure that combines two sources of information (observations and a priori estimate) to give "as best as possible" approximation of true state of atmosphere. In order to achieve this, analysis is presented as linear combination of a priori estimate (background) and correction that is dependent on some weight and distance of background from observations (calculated in observation space, Berre 2000, Bölöni and Horvath 2010). Several method can be used to solve this linear problem (Kalnay 2003) and all of them use some simplifications in order to make computations feasible in operational environment. Two methods are used in data assimilation system at DHMZ: Optimal Interpolation (OI, Courtier 1999) for land surface analysis and 3D variational analysis (3DVAR, Hollingsworth et al 1998, Fischer et al. 2005) for upper-air fields.

Observational data at DHMZ comes from two sources. One is OPLACE (Observation Preprocessing for the Limited Area Central Europe, central LACE preprocessing facility located in Hungary) and another source is the local data from national automatic stations. Data from OPLACE includes: surface observations from the Global Telecommunication System (GTS) and local LACE country automatic stations, aircraft measurements, radio soundings, GEOWIND atmospheric motion vectors (derived from satellite pictures) and data from polar and geostationary satellites.

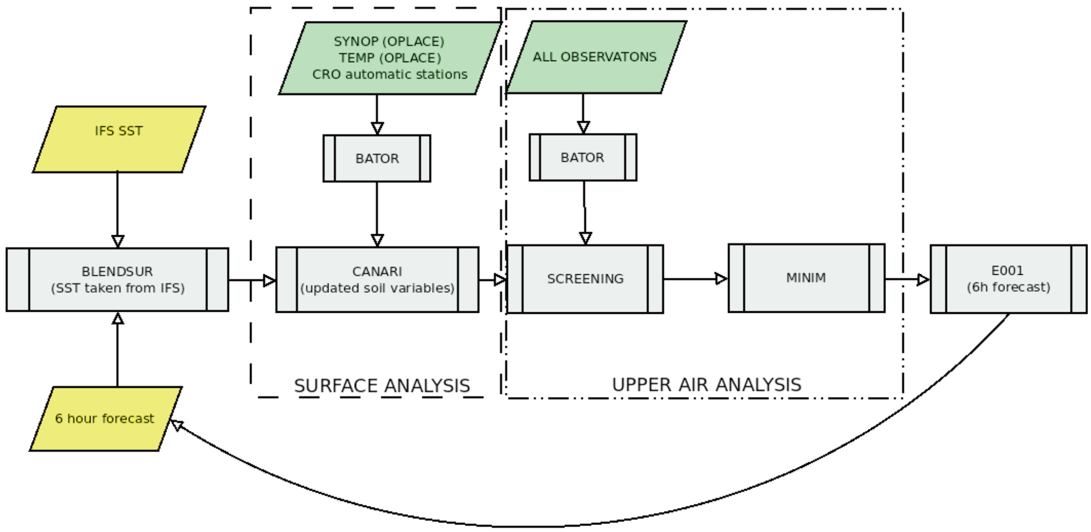

Figure 3. Scheme of the assimilation cycle at DHMZ. The 6 hour forecast is used as the first guess in the next cycle. BLENDSUR - procedure that makes SST replacement between two ALADIN files. BATOR - procedure that takes meteorological observations in different formats and writes them in Observational Database (ODB; developed at ECMWF for efficient handling of large amount of observational data). CANARI - procedure that performs surface analysis. SCREENING - procedure that performs Quality Control of observations used in upper air analysis. MINIM - procedure that performs upper air 3DVar analysis. E001 - forecast performed with ALADIN model.

Slika 3. Shematski prikaz asimilacijskog ciklusa u DHMZ-u. Za pretpostavljeno (početno) stanje koristi se 6 satna prognoza iz prethodnog ciklusa. "BLENDSUR" - procedura za zamjenu temperature mora između dvije ALADIN datoteke, "BATOR" - procedura za zapis mjerenja iz više različitih formata u posebnu bazu podataka mjerenja (ODB). "CANARI" - prizemna analiza podataka metodom Optimalne Interpolacije. "SCREENING" - kontrola kvalitete mjerenja koja prethodi visinskoj analizi. "MINIM" - visinska trodimenzionalna varijacijska analiza. "E001" - prognoza ALADIN modelom.

The number of data before screening used in one random analysis is shown in Figure 4.
As there are little direct measurements of land surface characteristics, for surface analysis observations of 2 m temperature and relative humidity are used in two step approach. In first step 2 m increments (difference between background and analysis) are calculated using OI method. In second step those increments are used to update the land surface variables Mahfouf (1991). Much more observations are available for upper air fields and more complex 3D variational method was chosen for obtaining upper air analysis. More details on implementation of 3DVar and OI at MHS can be found in Stanešić (2011). The complete data assimilation system at DHMZ is used to obtain initial state for integration of 8 km ALADIN model while for 4 km ALADIN model only surface analysis is used (as upper air analysis is still under construction) and upper-air fields are just interpolated from the LBC file.

Practical implementation of data assimilation system consists in forming so-called data assimilation cycle that is sequence of short range forecast that represents background and analysis that provides initial state for subsequent short range forecast. At DHMZ, 6 hour cycling is used, which means that every 6 hours analysis is made providing initial state for subsequent 6 hour forecast. Scheme of such assimilation cycle is shown at Figure 3.

In first step the sea surface temperature (SST) in 6 hour forecast from previous cycle (background) is replaced with SST from IFS LBC. This is done in order to update SST as no local SST analysis is available. In second step 2 m observation are used to compute surface analysis and in following step all other observations are used to calculate upper air analysis. Using this analysis as initial state and IFC LBC 6 hour forecast for next cycle is computed.

Computation of the forecast fields using the initial conditions from the assimilation cycle is

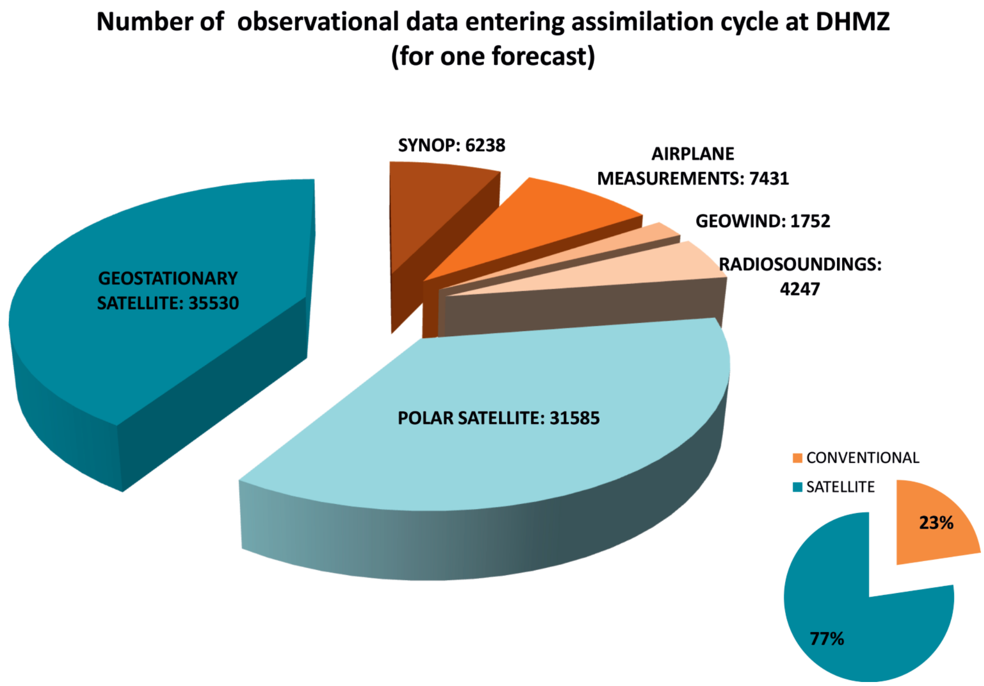

Figure 4. Number of observation data entering assimilation cycle at MHS for midday/midnight analysis before screening.

Slika 4. Broj podataka koji ulaze u asimilacijski ciklus u DHMZ-u u podne/ponoć prije kontrole kvalitete.

performed using the same steps but with several differences. Due to timing constraints for the availability of the 72 hour forecast, it is not possible to wait for all observations to become available (the time lag from the moment that observation was made to the time it is available can be up to 8 hours for certain observation types). The same time constraint prevents the operational suite to wait for the availability of the corresponding IFS forecast. Therefore, a smaller number of observations and lagged IFS LBC's are used when computing the forecast. On the other hand, assimilation cycle is performed with sufficient time lag that enables the usage of all observations and corresponding (non-lagged) IFS LBC's in the production (6 hour forecast) that is used as the first guess for the data assimilation.

2.5. The operational options used for the model dynamics

The ALADIN dynamical kernel consists of a single software package that can execute both non-hydrostatic and hydrostatic versions chosen by a logical switch. Both use a spectral Fourier representation of the model variables in both horizontal directions that requires the extension zone for the bi-periodization of the fields. This is accomplished using fast Fourier transforms (FFTs) from spectral to grid-point space and back in each model time step with elliptic truncation (Machenhauer and Haugen 1987) that ensures an isotropic horizontal resolution. The truncation wave-number M in one direction is computed from the number of grid-points N in the same direction. Operationally, quadratic truncation is used defined by the relation N>3M+1 so that the nonlinear terms of the model equations are computed without aliasing. Alternatively, linear truncation uses N>2M+1 allows for shorter waves but requires stronger numerical diffusion to remove excess energy that accumulates at shorter scales. Cubic truncation, defined by N>4M+1 is currently being tested in several NWP suites, including the ECMWF.

A semi-implicit time integration scheme (Robert 1982) treats implicitly a linearised form of the terms in the shallow water equations and solves the Helmholtz equation in spectral space with a second-order accurate treatment of the non-linear residual (Gospodinov et al. 2001). In a semi-implicit scheme, the implicit system is linearly partitioned using constant and horizontally uniform coefficients (Bubnová et al. 1995, Bénard 2004ab). The stability of the scheme, when used for the non-hydrostatic dynamics, depends on the choice of prognostic variables (Bénard et al. 2004, 2005) and the reference linear operator (Bénard 2004ab). A stable and efficient integration of fully elastic Euler equations of the non-hydrostatic dynamical kernel allows usage of the semi-Lagrangian advection schemes and two time level discretization at scales approaching 1 km in NWP applications (Bénard et al. 2010). Alternatively to the semi-implicit scheme, the centred implicit scheme (Bénard, 2003) is not used in operational applications due to additional computational cost.

Two-time-level semi-Lagrangian scheme computes the advection of the prognostic variables (Hortal 2002). The model grid-points are the arrival points of the trajectory and the origin point values are computed by interpolation. There is a choice of semi-Lagrangian interpolators in the model, as they can be more or less diffusive (Staniforth and Cote 1991). A common 4th order numerical diffusion is applied at the end of the time step to remove the accumulation of energy at the shortest wavelengths from the high layers of the atmosphere due to spectral blocking. It is combined with semi-Lagrangian horizontal diffusion (SLHD, Vá a et al. 2008), a more physical horizontal diffusion scheme that is based on the physical properties of the flow that combines two interpolators of different diffusivity with the flow deformation as a weighting factor.

The model equations are solved in the vertical on 37 (or 73) levels of hybrid pressure type eta coordinate using vertical finite elements (Untch and Hortal 2004) for the hydrostatic dynamics as opposed to finite difference method (Simmons and Burridge 1981) that was used previously (Tudor et al. 2013) still used in the operational non-hydrostatic run for which the finite elements are still under research (Simmaro and Hortal 2012).

The model prognostic variables treated by the semi implicit scheme in the hydrostatic version are surface pressure, the horizontal wind components, temperature and water vapour, with two more in the non hydrostatic dynamics: pressure departure and vertical divergence. However, there are more prognostic variables in the model computed in the model physics, advected by the semi-Lagrangian scheme and diffused by SLHD but not touched by the semi-implicit computations: cloud water and ice, rain and snow, convective entrainment, cloudiness, up-draft and down-draft vertical velocities and mesh fractions.

2.6. The physics parametrizations in the operational setup

The processes described by the model physics are said to be parametrized (Pielke 2002). Processes such as radiation, cloud microphysics and exchange with surface are fully parameterized, as well as sub-grid contributions from turbulence, convection and topography features. The physics contribution is coupled to the dynamics via a physics-dynamics interface. The interface is bases on flux-conservative system of equations (Catry et al. 2007).

Within the ALADIN community, a physics package had been developed for the convection permitting resolutions (instead of convection resolving resolution). The package has been named ALARO. It is used for the operational forecast in a number of countries, members of ALADIN and HIRLAM consortia since 2008 (at least 13 in 2015). In DHMZ, operational forecast was performed using ALARO developments in turbulence, resolved cloudiness and precipitation schemes since February 2008. The improvements in the radiation scheme did not improve the cloud and temperature forecast in the stratus and fog case (Tudor 2010) so only the exchange with surface was introduced and most of the additions were switched off through the namelist switches. The developments of prognostic convection were not available for operational purposes at the time.

The diagnostic convection scheme, operational for the 8 km resolution forecast until 2015, is a mass flux scheme that computes changes in momentum, heat and moisture in the vertical due to the convective processes (Geleyn et al. 1994). Within ALARO0 physics package, there is modular multi-scale micro-physics and transport (3MT) scheme for precipitation and clouds (Gerard and Geleyn 2005; Gerard 2007; Gerard et al. 2009). The scheme uses prognostic variables for up-draft and down-draft vertical velocities and mesh fractions, entrainment and convective clouds. The 3MT scheme is operational since January 2015.

The processes of condensation, evaporation, freezing, melting, aggregation and growth of cloud water and ice into rain and snow are described by the micro-physics. Prognostic scheme for the cloud water and ice, rain and snow and a statistical approach for sedimentation of precipitation (Geleyn et al. 2008) is derived upon the old diagnostic scheme based on the Kessler (1969) type scheme with modifications (Geleyn et. al. 1994). The scheme is retuned in order to avoid fibrillations that occur due to a combination of melting and sublimation parameters (Tudor 2013).

The transfer, scattering, absorption and reflection of the short-wave solar radiation and long-wave thermal radiation of the Earth's surface and clouds are parametrized in radiation scheme (Geleyn and Hollingsworth, 1979, Ritter and Geleyn 1982). The scheme uses only one spectral band for long-wave and one for short-wave radiation. The net exchange rate has been introduced in the scheme (Geleyn et. al. 2005a, 2005b) and recently switched on in the operational forecast set-up. This radiation scheme is computationally cheap, so the computations are done each model time-step, avoiding possible numerical instability (Pauluis and Emmanuel 2004).

The vertical transfer of heat, momentum and moisture due to impact of the unresolved motion and surface roughness are described by turbulence parametrization that uses prognostic turbulent kinetic energy (TKE) that is advected, diffused (Geleyn et al. 2006) combined with modified Louis (1982) dependency on stability (Redelsperger et al., 2001). The contribution of the shallow convection to the evolution of model variables is computed in the turbulence scheme (Geleyn 1987).

The soil properties and their impact on the meteorological model variables is described by the surface scheme Interaction Soil Biosphere Atmosphere (ISBA, Noilhan and Planton 1989) that is also used in the assimilation of surface data (Giard and Bazile 2000). The values of wind, temperature, relative and specific humidity at the heights of measurement (10 and 2 meters above surface) are computed using the fields from the lowest model level and surface using stability functions and Monin-Obukhov similarity theory (Geleyn 1988).

2.7. Dynamical adaptation of wind to 2 km resolution

High resolution forecast of the 10 m wind is computed using the method of dynamical adaptation (Žagar and Rakovec 1999). The meteorological fields are interpolated from 8 km resolution grid to a 2 km resolution one and from 37 to 15 vertical levels (but the lowest 10 levels are on similar heights). A hydrostatic ALADIN is run for 30 time-steps of 60 seconds using only turbulence parametrization (moist and radiation processes are omitted). The result is improved operational forecast of the 10 m wind (Ivatek-Šahdan and Tudor 2004) which is used in the case studies of severe wind (Tudor and Ivatek-Šahdan 2002) and research impact studies (Bajić et al. 2007, Horvath et al. 2011).

The method works well for wind that is at least moderate in strength, while it can produce artificial features around isolated island when wind is weak. Unfortunately, when strong wind is not a consequence of large scale forcing, but connected to a local pressure disturbance, the prediction is not so good and a full non-hydrostatic run is needed (Tudor and Ivatek-Šahdan 2010) in order to model the small scale disturbances in the pressure field. This is why the non-hydrostatic ALADIN run using the complete ALARO0 physics package has been introduced to the operational suite on 1 July 2011.

2.8. The schedule of the operational forecast

The operational ALADIN forecast used to be run twice per day, starting from 00 and 12 UTC analyses until the end of 2013. Since 1st January 2014, it runs four times per day, with two additional forecast starting from 06 and 18 UTC analyses. All 8 km resolution forecasts are run up to 72 hours in advance. It takes about 30 minutes on 3 nodes (18 cores) to compute the forecast. The domain is in a Lambert projection with 8 km horizontal resolution on 37 hybrid sigma pressure levels in the vertical (Simmons and Burridge 1981). Opera-

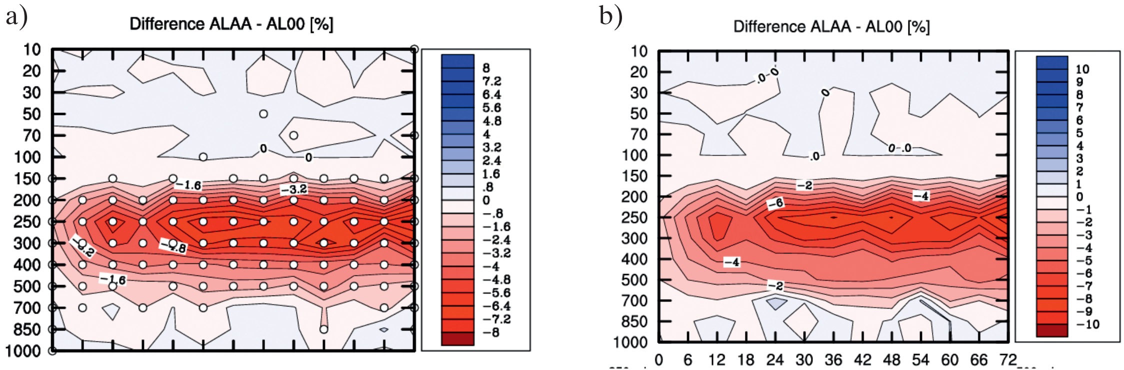

Figure 5. The dependency of the difference in root mean square error (a) and bias (b) between ALARO0 (ALAA) and operational forecast (AL00) for relative humidity on the vertical (pressure coordinate) and forecast hour (from 0 to 72 hours) for 31 forecasts starting from 00 UTC during January 2014.

Slika 5. Ovisnost korijena srednje kvadratične pogreške (a) i pristranost srednjaka (b) za ALARO0 paket fizikalnih parametrizacija (ALAA) i operativnu prognozu (AL00) za relativnu vlažnost zraka u ovisnosti o visini (vertikalna koordinata tlak) te u ovisnosti o prognostičkom razdoblju (od 0 do 72 sata) za 31 prognozu tijekom siječnja 2014. za početak prognoza u 00 UTC.

tional forecast produces forecast fields with hourly output (but only 3 hourly output is stored, since January 2015 hourly data are stored for 00 UTC run).

High resolution wind field forecast using a dynamical adaptation procedure (Ivatek-Šahdan and Tudor 2004) produces 2 km resolution forecast of 10 m wind speed and gusts using the hourly output from the 8 km resolution run. It takes about 30 minutes on 6 nodes (36 cores) to adapt the wind dynamically. Therefore, the 2 km resolution dynamical adaptation also produces the wind forecast with hourly interval up to 72 hours in advance.

Since 1st July 2011, the operational forecast includes a 2 km resolution ALADIN forecast that uses the non-hydrostatic (NH) dynamics and full set of physics parametrizations of ALARO0, including the convection scheme (Tudor and Ivatek-Šahdan 2010). This forecast is computed once per day, till the end of 2013 following the 00 UTC operational 8 km forecast and parallel to it since the beginning of 2014. It uses 20 nodes (120 cores) to compute the forecast in 30 minutes). The forecast range is 24 hours, until the 06 UTC of the next day in order to be comparable with the precipitation data from the dense national network of rain-gauges.

A 4 km resolution run has been introduced on 1st February 2015, the forecast is computed once per day, from 00 UTC analysis up to 72 hours in advance, and the products are available in the morning. IFS LBCs are used in combination with surface data assimilation. The forecast is run on the domain covers roughly the same area as the 8 km resolution one, on 73 levels in the vertical using a time-step of 3 minutes. Therefore the overall additional computational expense is about 16 times more than for the 8 km resolution run. The forecast is computed using 32 nodes (all 194 cores intended for multiprocessor jobs) in one hour. The size of the output files is also 8 times larger (if they are stored with the same frequency as the 8 km resolution forecast and even more if stored with an hourly frequency). This poses a considerable effort for the computational and archive capabilities of MHS.

3. THE NEW MODEL VERSION IN OPERATIONAL FORECAST

Until January 2015, the operational forecast in 8 km resolution was run using ALADIN model version (released as CY32T3) with prognostic micro-physics and TKE, but diagnostic deep convection scheme. The 2 km resolution non-hydrostatic run uses model version CY36T1 that includes an early version of the 3MT scheme with prognostic convection that allows running the model in convection permitting scales (where it is only partially resolved). The new operational model version (released as CY38T1) includes the complete ALARO0 baseline and was tested extensively

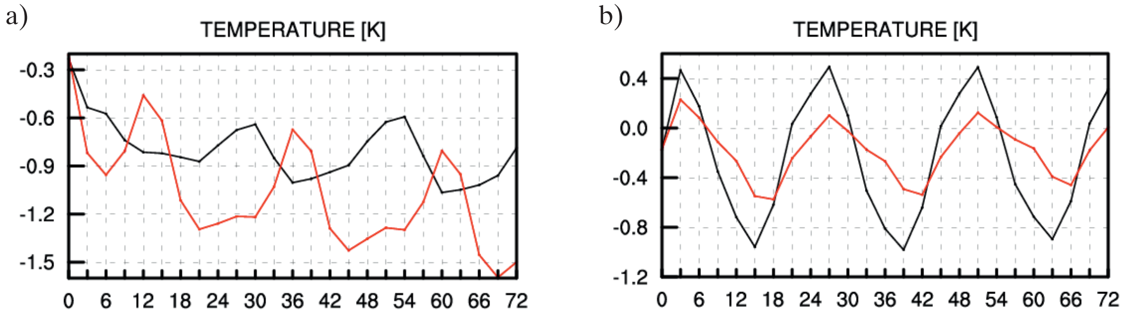

Figure 6. Bias computed for the operational forecast (black) and using ALARO0 (red) for 2 m temperature dependency on forecast time (from 0 to 72 hours) for 31 forecasts starting from 00 UTC during January (a) and May (b) 2014.

Slika 6. Pristranost srednjaka za operativnu prognozu (crno) i za verziju modela sa ALARO0 paketom fizikalnih parametrizacija (crveno) za temperaturu zraka na 2 m u ovisnosti o prognostičkom razdoblju (od 0 do 72 sata) za po 31 prognozu tijekom siječnja (a) i svibnja (b) 2014. godine te za početak prognoza u 00 UTC.

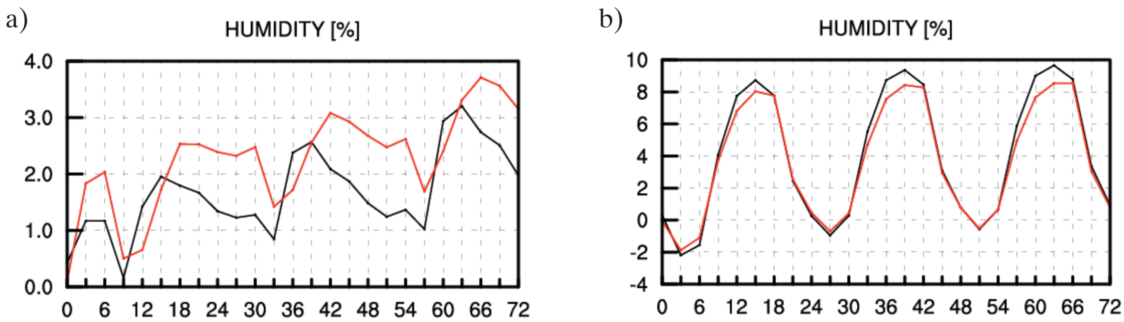

Figure 7. As Figure 6, but for relative humidity.

Slika 7. Kao i slika 6, ali za relativnu vlažnost zraka.

on the operational domain with 8 km resolution on 37 levels in the vertical. For each experiment, two sets of 72 hour forecasts were run, for January and May 2014, for each day, starting at 00 UTC. Additionally, ALARO0 baseline was run for one whole year, starting with 1st July 2013.

The operational forecast of relative humidity using CY32T3 suffered from a large positive bias in the upper portion of the troposphere and a less pronounced negative bias in the layers below 700 hPa (Figure 5). This bias is reduced using the new model version over the whole tested period. Much of the contribution to this improvement arrives from the sedimentation of cloud condensates introduced to the micro-physics.

The operational forecast of temperature at 2 meters suffered from a cold bias during winter, for January 2014 (Figure 6a). The bias had a pronounced diurnal cycle for May 2014 (Figure 6b), model forecast of 2 meter temperature was too cold in the afternoon and too warm in the night. The amplitude of this diurnal cycle in the bias of 2 m temperature was reduced for May 2014 using the new model version (CY38T1) with the complete ALARO0 physics (red line in Figure 6b), but it increased for January 2014 (red line Figure 6a). Both model versions have a positive bias in relative humidity at 2 meters that exhibits a pronounced diurnal cycle (Figure 7).

The source of the deterioration in the forecast of the 2 m temperature in January 2014 was traced to the random maximum overlap assumption used in the computation of the cloud cover. The old model version used random overlap assumption that allowed diagnosing more clouds than the random maximum assumption. More clouds mean that less shortwave radiation arrives to the surface (so 2 m temperature is colder during the day) but these clouds emit longwave radiation that heats the ground during the night. The forecast that uses the random overlap assumption

performs better than the forecast using random maximum assumption in winter when the weather is characterized by low stratus and fog, but not in spring and summer with more cumulus clouds.
The new model version is therefore expected to provide worse forecast in cases with low stratus and fog during extended stable conditions in winter. The formation and distribution of fog is controlled by subtle variations in relative humidity and temperature. Successful forecast of such cases requires to maintain a sensitive balance between the advection, radiation and turbulent fluxes, but the radiation fluxes depend on the diagnosed cloud cover.

The positive bias of the relative humidity forecast in the upper troposphere can be reduced by tuning the coefficients that control the cloud ice condensation and sedimentation, consequently the negative bias below can be reduced too. But the relative humidity fields from both sets of coupling files, from IFS and ARPÈGE global models, have the same positive bias in the upper troposphere and a negative bias below. Since the excess moisture arrives from the lateral boundaries, alternative tuning options reduce the error, but the model is forced to do something non-physical only to get better scores.

4. THE NON-HYDROSTATIC 24 HOURS FORECAST IN 2 KM RESOLUTION

The forecast abilities of high resolution dynamical adaptation is limited to the severe wind-storms related to a synoptic forcing. Omitting moist and radiation processes prevents it from being useful in forecasting other phenomena that could benefit from the high resolution, such as local convective storms. The wind-storm that is a consequence of a local pressure disturbance requires a full forecast run in 2 km resolution using more complex NH ALADIN model set-up (Tudor and Ivatek-Šahdan 2010). Several air crash investigations have revealed that this "full-run" high resolution ALADIN forecast using non-hydrostatic dynamics and full physics package enables the prediction of lee waves and zones of increased turbulence as well as icing zones. Several case studies of high-impact weather phenomena have been used to set-up the model configuration used operationally. The results from these studies have provided encouraging results.

In the situations with weak wind (less than 3.4 m/s), dynamical adaptation can create bursts of wind especially obvious around islands (Figure 8a), when Island is resolved in 2 km resolution and not in 8 km resolution. These outbursts are unrealistic and do not exist in

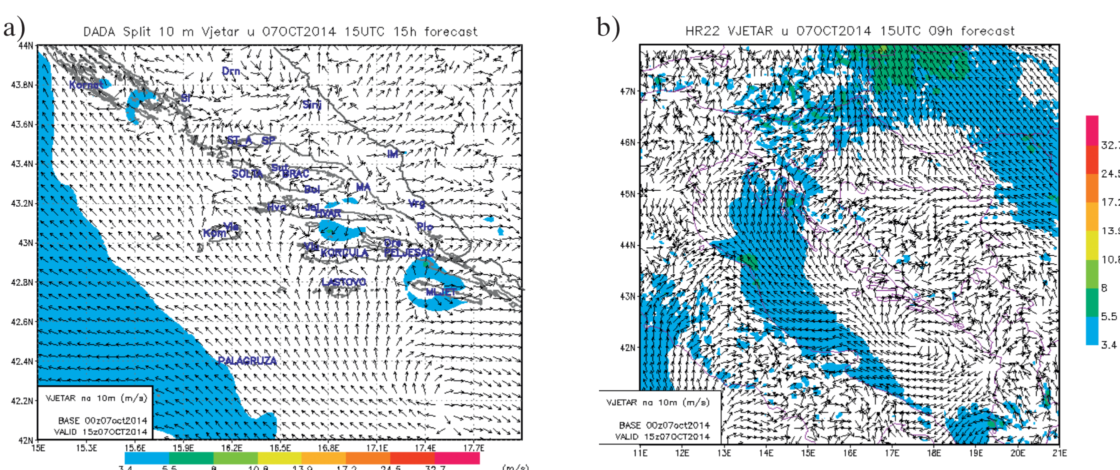

Figure 8. Forecast of 10 m wind using high resolution dynamical adaptation (a) and non-hydrostatic run using complete physics package (b) for 15 UTC 7th October 2014 (see text for details).

Slika 8. Prognoza vjetra na 10 m visine na velikoj horizontalnoj razlučivosti izračunata: metodom dinamičke adaptacije (a) i nehidrostatskom verzijom modela sa uključenim cijelim paketom fizikalnih parametrizacija (b) za 15 UTC 7. listopad 2014. godina (više detalja u tekstu).

Table 2. Experiments performed in 8 km resolution in order to provide references for experiments in 4 km resolution. All runs were performed in 8 km resolution using ALARO0 baseline. The experiment (Exp), number of levels (levs), dynamics (dyn, hy for hydrostatic, nh for non-hydrostatic), initial file (oper from the operational cycling, ARP for interpolated ARPÈGE), LBCs and brief description of the results of each experiment are listed.

Tablica 2. Popis testova napravljenih na 8 km horizontalnoj razlučivosti u svrhu izrade referentnih verzija za eksperimente na 4 km horizontalnoj razlučivosti, Svi testovi su napravljeni na horizontalnoj razlučivosti 8 km sa “ALARO0 baseline” postavkama fizikalnog paketa. Naziv testa (“Exp”), broj vertikalnih nivoa (“levs”), vrsta dinamike (“dyn“; “hy” za hidrostatsku verziju i “nh” za nehidrostatsku verziju), korištena inicijalna datoteka (“init”; “oper” za operativni asimilacijski ciklus, “ARP” za interpolirana polja modela “ARPÈGE“), vrsta rubnih i graničnih uvjeta (“LBC“) i kratki opis rezultata za svaki eksperiment (“Results“).

Exp	levs	dyn	init	LBC	Results
AA	37	hy	oper	IFS	Reference, currently operational forecast in 8 km resolution
AG	37	hy	ARP	IFS	There are differences with respect to AA only in the first 6 hours. The forecasts converge in 6 hours.
80	37	hy	ARP	ARP	Slightly worse than exp. AA
81	37	nh	ARP	ARP	There is no significant difference with respect to exp. 80
82	73	hy	ARP	ARP	Improved temperature and worse humidity at 2 m and close to tropopause, wind indecisive, with respect to exp. 80
83	73	nh	ARP	ARP	Similar to 82

the full run forecast (Figure 8b). These features have encouraged the introduction of the 2 km resolution 24 hour forecast with NH ALADIN set-up using the complete set of physics parametrizations to the operational suite at the beginning of summer 2011. The non-hydrostatic run is run once a day with ALARO physics in 2 km resolution on 37 levels up to 24 hours on the same domain as the dynamical adaptation. The initial conditions are the interpolated fields from the 6 hourly forecast of the 8 km resolution 00 UTC run initialized using scale selective digital filter initialization (Termonia 2008).

5. PRE-OPERATIONAL TESTS OF ALARO0 BASELINE IN 4 KM RESOLUTION

It is intended to replace the 8 km resolution operational domain with one in 4 km resolution. ALARO0 baseline was applied and tested on 37 and 73 levels in the vertical using hydrostatic and non-hydrostatic dynamics.

5.1. The problem of initial and lateral boundary conditions

Operationally, lateral boundary conditions that are used for the coupling data can be used as the initial conditions. The operational forecast in the 8 km resolution is coupled to IFS and the initial file is obtained through the data assimilation cycle. It was possible to create initial file for the 8 km resolution model on 73 levels directly from the initial file on 37 levels by spectral post processing that used only vertical interpolator. It is not possible to use the initial file in 8 km resolution for the 4 km run since this required horizontal interpolation and data from areas not covered by the operational initial files.

The interpolated fields of IFS as initial fields without any data assimilation produce an error larger than any error due to change in the model version, because IFS and ALADIN use different surface schemes. So an alternative reference was established in the 8 km resolution by running ALARO0 baseline in AL38T1 coupled to ARPÈGE or IFS and using interpolated fields of ARPÈGE as initial fields without any data assimilation (see Table 2 for the list of experiments and short description of the results). This produced two references, one for LBCs from ARPÈGE and another from IFS. However, both used the interpolated fields from ARPÈGE as the initial conditions.

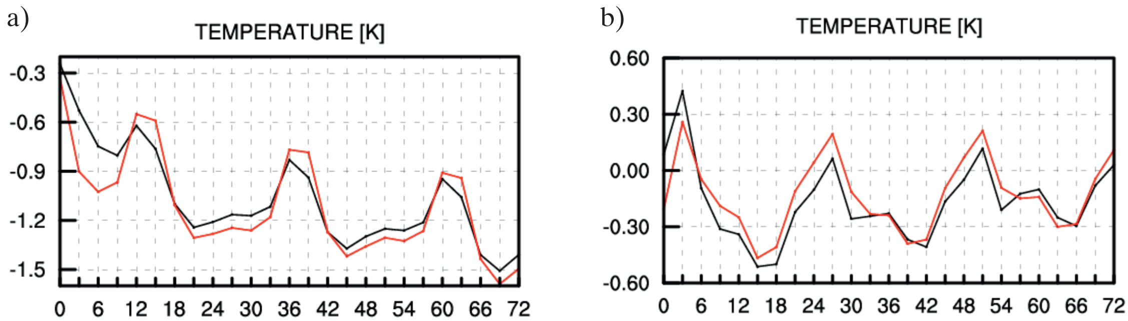

Figure 9. Bias computed for the 4 km resolution forecast (black) and 8 km (red) using ALARO0 for 2 m temperature dependency on forecast time (from 0 to 72 hours) for 31 forecasts starting from 00 UTC during January (a) and May (b) 2014.

Slika 9. Pristranost srednjaka za prognoze s 4 km (crna) i 8 km (crvena) horizontalnom razlučivošću koristeći paket fizike ALARO0 za temperature zraka na 2 m u ovisnosti o prognostičkom razdoblju (od 0 do 72 sata) za po 31 prognozu za siječanj (a) i svibanj (b) 2014. godine te za početak modela u 00 UTC.

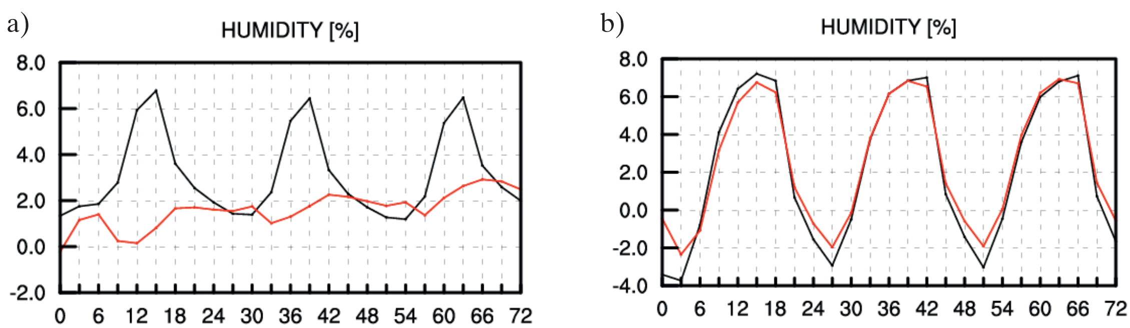

Figure 10. As Figure 9, but for relative humidity.

Slika 10. Kao slika 9, ali za relativnu vlažnost zraka.

Afterwards, a number of experiments was performed running Alaro0 baseline in 4 km resolution on 37 and 73 levels using interpolated ARPÈGE fields for initial conditions and IFS or ARPÈGE lateral boundary conditions. Both sets of LBCs were tested since the result depends on the coupling fields used at lateral boundaries. Since the future operational suite is to be coupled to the IFS and use assimilation cycle, the experiment with LBCs from IFS is used for more extensive testing.

5.2. Summary of experiments in 4 km resolution

The experiments were performed in which a set of 31 forecasts up to 72 hours in advance were run starting from 00 UTC initial files for each day in January and May 2014. The standard scores of forecasts in 4 km resolution are superior to the 8 km forecast. The results on 73 levels show improved forecast of 2 m temperature (Figure 9b) and relative humidity for May (Figure 10b), but worse forecast of relative humidity (Figure 10a) and temperature (Figure 9a) at 2 meters in January. The introduction of non-hydrostatic dynamics did not show substantial impact to the standard scores when computed for one whole month. The brief summary of the results for several experiments is given in Table 3. The operational suite currently assimilates surface data through optimum interpolation, while 3D-var is to be implemented once the background error covariance matrix is computed.

6. SUMMARY, CONCLUSIONS AND PLANS

This article gives an overview of the set-up of the operational NWP system in MHS with an emphasis of recently introduced changes. ALADIN is a state-of-the-art modern NWP model that allows a large choice of options for the model dynamics, data assimilation and physics parametrizations. The set-up of the operational forecast in terms of the size of the model domain, horizontal and vertical model resolution is limited by the computational resources (Ivančan-Picek et al. 2011). In order to predict the sub-synoptic weather features

Table 3. Experiments performed in 4 km resolution. All runs were performed in 4 km resolution using ALARO0 baseline, interpolated ARPÈGE initial file and LBCs from IFS. The experiment (Exp), number of levels (levs), dynamics (dyn, hy for hydrostatic, nh for non-hydrostatic), truncation (quadratic or cubic) and brief description of the results of each experiment are listed.

Tablica 3. Popis testova napravljenih na 4 km horizontalnoj razlučivosti. Svi testovi su napravljeni na horizontalnoj razlučivosti 4 km sa "ALARO0 baseline" postavkama fizikalnog paketa, interpolirana "ARPÈGE" datoteka korištena je za inicijalna polja, a rubni i granični uvjeti su iz "IFS" modela. Naziv testa ("Exp"), broj vertikalnih nivoa ("levs"), vrsta dinamike ("dyn"; "hy" za hidrostatsku verziju i "nh" za nehidrostatsku verziju), vrsta eliptičkog odsijecanja Fourierovih koeficijenata u spektralnom dijelu modela ("trunc"; "quad" za kvadratično i "cubic" za kubično odsijecanje) i kratki opis rezultata za svaki eksperiment ("Results").

Exp	levs	dyn	trunc	Results
4E	37	hy	quad	Reference, set-up most similar to AA (in 8 km resolution)
4F	37	nh	quad	There are subtle differences with respect to 4E.
4G	73	hy	quad	Slightly worse than exp. 4E at tropopause, improved forecast at 2 m, currently used for operational suite in 4 km resolution
4H	73	hy	cubic	Precipitation fields smoother than for 4G, improved scores
4I	37	nh	cubic	Precipitation fields smoother than for 4F
4J	37	hy	cubic	Similar to 4I
4K	73	nh	cubic	Similar to 4H
4L	73	nh	quad	Similar to 4G

forced by topography or other local characteristics (Horvath et al. 2009) one needs to resolve the upstream conditions and the topographic obstacles on the way, as well as the high-impact weather events of local character that can be absent in the main synoptic pattern. The predictability of the severe weather events can be improved via dynamical downscaling of the individual EPS members (Branković et al. 2007, 2008), however such implementation is quite demanding for the computer resources, so a common suite is established (Wang et al. 2011) that also uses perturbed LAM initial conditions. This suite runs operationally in the ECMWF and the products are available to all services members of the LACE consortium.

The operational suite based on the data assimilation is more complicated to develop and maintain, so even after the scientific issues were resolved, technical difficulties were detected and corrected during a period of parallel suite, when two sets of forecast were run in 8 km resolution, one initialized with DFI and another initialized using data assimilation. This period allowed to fix issues related to the measured data used as the input to the data assimilation procedure.

The operational dynamical adaptation of the 10 m wind to the high-resolution (currently 2 km) improves the prediction of severe wind variability and strength when wind is strong and connected to complex topography (Ivatek-Šahdan and Tudor 2004) and has been used in numerous studies. However, it provides only the wind field and has limited quality in situations with weak wind, so the full non-hydrostatic run (Tudor and Ivatek-Šahdan 2010) was established that runs only up to 24 hours due to its computational expense. New turbulence scheme (part of ALARO1) will be tested on both suites.

After a thorough pre-operational testing that involved research of the impact of most of the options included in the ALARO0 physics package by running the model on two months of forecasts, one for winter and another for late spring conditions, the operational model version has been replaced on 27th January 2015. The complete ALARO0 physics package is used for operational forecast in 8 km resolution (but still only on 37 levels since). Since 1st February 2015, a forecast is run at 4 km resolution on 73 model levels, once per day for 00 UTC using the ALARO0 baseline physics package and currently the surface assimilation. The complete variational data assimilation procedure for that resolution is being developed. Only after this step is completed and becomes operational, with 4 runs per day up to 72 hours, one could start replacing the 8 km resolution forecast with it. But the 8 km resolution run could remain operational for as long as users demand it.

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