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The COSMO Priority Project CORSO

Final Report

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Contents

1 Introduction

The latter Winter Olympic Games were hold in Sochi, Russia. Sochi–2014 region is very complicated for numerical modeling because of the mosaic surface properties determined by the close proximity of the Black Sea coast line combined with the mountainous terrestrial conditions. The local mesoscale circulation causes numerous weather phenomena at the differently oriented mountain slopes and valleys. It requires high resolution numerical model, particularly COSMO-Ru model, which was selected for meteorological support of the Games. The model should have to be able to predict meteorological conditions in the region with highly variable terrain. Specificity of physical variables had to be predicted for different sporting events on the basis of large amount of observational and forecasting data.

Annually registered number of weather hazards is very high in the Northern Caucasus, especially in winter. The high variability of local small-scale conditions (differently oriented slopes, valleys, significant high gradients) and proximity of non-freezing Black Sea generating medium-scale energy fluxes require the ensemble approach, improvement of model resolution to the scale of relief features, i.e. in the case of COSMO weather forecasting model the grid step had to be lesser than existing 2.2 km. It also required the improvement of the postprocessing methods of forecasting certain meteorological characteristics (wind, snow cover, visibility, humidity, etc.).

CORSO project was proposed to enhance and demonstrate the capability of COSMO-based systems of numerical weather prediction in winter conditions for mountainous terrain and to assess the effect of practical use of meteorological information in support of Sochi–2014 Olympic Games. The peculiarity of the Sochi region justified the development and adaptation of the available COSMO technologies. The insurance of the best performance of the COSMO system at the Sochi-2014 Olympics was required. It assumed a development of modeling techniques including. data assimilation for near-surface and land-surface parameters, model physics and dynamical core. Ensemble forecasting, applied post-processing and downscaling, comprehensive verification and other predictive components were crucially important for the enhancement of the Sochi-2014 meteorological services.

Significantly the PP CORSO for preparation and providing the meteorological services for Olympics Sochi-2014 is based on solving the tasks determined in the COSMO Science PLAN 2010-2014, where it stated (p. 11): "From the scale of the targeted processes it becomes clear that the mesh-size of the model system has to be of the order of 1–2.2 km. The COSMO Steering Committee decided to focus on the development of a model-system for the short to very short range forecasting considering convective-scale resolution".

In the region of the Sochi–2014 the additional observational network was developed since the end of 2011. It includes the automatic stations for near-surface measurements, meteorological radar, and aerological stations. This additional information could be used as a new source for data assimilation, model verification and for testing and adaptation of certain algorithms.

The improvements introduced to the COSMO system during this activity widened its applicability to regions with complex terrain characterized by frequent severe weather events, which could benefit COSMO as a whole.

CORSO project can be considered as a COSMO-related part of FROST–2014 project (FROST — Forecast and Research in the Olympic Sochi Testbed), initiated by WMO (Kiktev et al., 2017)..

2 Actions proposed

Development of the COSMO model version adjusted for the region with complex terrain, improvement of operational forecasts based on the COSMO-Ru7/So2 model and development of the version of this model with resolution approximately 1 km. Identification of the gaps, adaptation of data assimilation techniques, analysis of numerical aspects using the high resolution and modification of parameterization schemes (Task1).

Development and adaptation of approaches for post-processing downscaling and possible forecasters feedback (Task 2).

Adjustment of the COSMO EPS's techniques (COSMO-LEPS) for the Sochi area and to specific requirements of winter Olympics. Development of COSMO-RU-EPS system (Task 3).

All developed systems and technologies had to be validated and made available to forecasters during trials well before the Olympics. Forecast products were transferred to Olympic forecasters via web-based tools.

Available expertise within COSMO

COSMO-LEPS (ARPA–SIMC);
High-resolution modeling and post-processing for the Alps (DWD, MeteoSwiss, ARPA-SIMC);
Experience of MeteoSwiss and of DWD in meteo-support of winter sporting events in the mountains;
Developed tools ("nudging-process", Fieldextra, VERSUS);
Experience of Torino–2006 Olympics (ARPA Piemonte).

Links to other projects or work packages

Cooperation with all working groups will be required (as needed), during the lifetime of the project. Some activities are supposed to include expansion of actions considering the results and experience obtained within the framework of PP COLOBOC (external parameters, snow cover investigations), verification tools (VERSUS2), improvement of turbulence schemes (UTCS).

3 Tasks, brief description

3.1 TASK1 "High resolution COSMO-modeling for mountainous regions", *(TL G. Rivin)*

Motivation:

The pre-operational version of COSMO-RU07/So2 (resolution 2.2 km) for the North-Caucasian region was developed in Roshydromet in 2010–2011 (nested into OSMO-Ru07 (without regional DAS). OSMO-Ru07 is based on the use of the initial data, received from the GME modeling system (30 $\longrightarrow$ 20 km) of DWD and external parameters prepared as an output of the COSMO EXPAR system (2.2 km)).

Preliminary tests sometimes showed a presence of significant errors in meteorological fields predicted by the COSMO-RU07/So2 near land surface (primarily in air temperature, and as a consequence, conditions of boundary layer stability and the precipitation phase).

It was detected that certain inaccuracies in determining of initial values of T2m, snow-properties (the mask and water equivalent WE), as well as some external (geographic) parameters, such as mask and absolute height.

The goal of the starting actions of TASK1 is the identification of contribution of regional data assimilation for COSMO-RU07 forecasting based on comparison of skill scores of COSMO-RU and COSMO-EU (with assimilation) for the area of COSMO-RU, including the region of Sochi-2014. In parallel, inclusion of nudging continuous cycle using all available data for both (COSMO-RU7 and nested COSMO-RU/So2) is expected. It will be based on the standard network measurement and new additionally added observational network in the Sochi 2014 region. The techniques of correction of temperature in upper soil levels was based on T2m measurements. This technique was previously developed in Roshydromet. It should be coupled with nudging continuous cycle and corrected snow mask from satellite observations.

The more precise modeling of the near surface meteorological parameters taking into account the fractional relation of snow cover and stable and mosaic thermal stratification is one of the problems of numerical weather forecasting. It was obvious for Sochi-2014 weather forecasting support. Previously, based on a study of the COSMO-RU model forecasts for the large winter periods for the entire domain of COSMO-Ru07 it was revealed that the model produces the highest T2m errors in case of heating over the partial snow cover and some modification of TERRA was proposed and tested. TASK1 was expended to develop and test the modified algorithms of TERRA and to propose the modification of algorithms for turbulent diffuse parameterization scheme to improve the forecasts for certain cases.

The perspective plan of COSMO for 2014 stipulated the development of 1-km modeling techniques. Some results were obtained by DWD, MeteoSwiss and ARPA-SIMC. The united efforts of COSMO partners focus on the activities, which could potentially accelerate the development of 1-km COSMO techniques. The collaboration and coordination between DWD, MeteoSwiss, ARPA-SIMC, and Roshydromet is expected.

Task1 consists of two subtasks:

Subtask 1.1: "Improvement of technology of deterministic forecasting of weather conditions with model resolution 2.2 km for the North-Caucasian area (Sochi-2014), (including the operational support)",

Subtask 1.2: "Development of COSMO-So-1km"

<u>Goals RDP:</u>

Develop 1km version for Sochi-2014.

The strategy depends of available technical resources and results obtained by participants.

Deliverables:

Research technology COSMO-So1 with horizontal resolution ≈ 1 km (RDP).

3.2. TASK2 "Downscaling/post-processing for Sochi area and applications", *(TL I.Rozinkina)*

Motivation:

The local mesoscale circulation in the Sochi-2014 area causes multiple weather phenomena at the mountain slopes and valleys. The local values of meteoparameters for this region, including area of Olympics venues (coastal or mountainous clusters) may be identified considering the processes of the scales not modeled explicitly even at high resolution.

Forecasting for the Olympic Games may be complicated by the necessity to predict parameters, which are not explicitly included in the models output (i.e., visibility, wind chill, hill fog, katabatic winds). Furthermore it is requested that the exceeding of certain thresholds are accurately predicted (precipitation amount, fresh snow amount, visibility, wind, temperature, humidity, wind chill) in order to assess whether to confirm or to cancel open air competitions.

This implies the development and implementation of downscaling and post-processing methods. The goals are the following:

– Improve the skill of numerical forecasting and obtain reliable results for the specific points of the venues, the clusters, or the entire Sochi-2014 area;

– Target on the specific parameters needed for organizing committee and the assessment of the critical thresholds for different competitions.

In the Sochi-2014 region, the information from additional automatic stations for near-surface measurements of T, V, Q, precipitation, visibility, and snow parameters can be used as an additional source for development of algorithms for downscaling.

The following algorithms are presently available at Roshydromet: linear regression of COSMO-SIB-14 output for Altay mountains (trial period: 2 weeks), MOS on IFS/GFS (experimentally used also with COSMO-RU-7/WRF), trial period: 2 years, empirical rules based on manual weather classification for forecasting of significant weather phenomena. This experience allows to develop the new techniques for the region of interest with shorter (several days) training period, i.e Kalman Filter techniques firstly for improvement of T2m measurements at observational points. The experience of COSMO-countries in utilizing the Kalman-filter correction techniques with mountain weather conditions (Firstly, Switzerland) is very important. The data sets - rows "model – measurements"for some points for the area with similar geographical conditions (subtropical mountains near sea) are also useful to obtain the statistics for large variety of weather phenomena in stage of development and tuning of Kalman-filter algorithms. (In particular the data obtained in the Greek mountain areas could be useful for obtaining flexible algorithm).

The implementation of the automated weather classification systems together with climatological series of local observations can be used for forecasting relevant phenomena in the Sochi-2014 region. Furthermore, the project will take the opportunity to use the practical experience of the COSMO countries in their meteorological support to winter sports in mountainous regions. The previous results obtained in WG4 in the domain of conditional verification and the interpretation of model results will also be used.

The collaboration with MeteoSwiss and HNMS is expected.

Task2 consists of two subtasks:

Subtask 2.1. (FDP): "Adapted downscaling techniques for winter conditions in the mountains and IOC requirements"

Subtask 2.2. ($FDP + RDP$): "Determination of typical COSMO model inaccuracies for typical climatological / synoptic situations"

3.3. TASK3 "Development and adaptation of COSMO EPSs for the Sochi region", *(TL E.Astakhova and A. Montani)*

Motivation:

Accurate assessment of probabilities of High-Impact Weather (HIW) events is the main challenge for regional ensemble prediction systems (EPS). For the winter Olympics, HIW are not necessarily linked with very intense or extreme meteorological phenomena. For outdoor sport events HIW forecasting also includes accurate representation of cross-zero temperature transitions (especially critical for cross-country skiing), precipitation phase and other sensible weather changes with respect to the prescribed decision-making thresholds. Development and demonstration of various HIW-related specific products is part of the ensemble component of the project CORSO.

COSMO-LEPS is an ensemble prediction system developed by the COSMO consortium. In the past years, COSMO-LEPS proved to be a valuable tool for the generation of probabilistic predictions of high-impact weather over complex topography and it is envisaged that it can be successfully used for the SOCHI region and provide useful support to bench forecasters during the Olympics. A 7-km COSMO-LEPS system for the Sochi region (COSMO-FROST-LEPS) is to be developed within the framework of the project and will be used for operational support of Sochi-2014 Olympics.

EPS with higher than 7-km resolution is desirable for better probabilistic prediction over the complex Caucasus terrain. Within the RDP part of Task 3 CORSO, the development and testing of COSMO-RU-LEPS 2.2 km is suggested.

COSMO-RU-SO-2.2 for the North-Caucasian region already runs operationally at Roshydromet. This technology is nested to OSMO-Ru07. On the other hand, COSMO-FROST-LEPS (also with 7-km resolution) will run daily during pre-trials, trials and Olympics and can provide initial and boundary conditions (ICs and BCs) for a higher-resolution ensemble system. This gives a possibility to develop a 2.2 km EPS based on COSMO-RU-SO-2.2 and ICs and BCs from SOCHMEL.

In collaboration and coordination with ARPA-SIMC

Task3 consists of two subtasks:

3.1. Adaptation of COSMO LEPS 7 km to the Sochi region and to specific requirements of winter Olympics. Operational ensemble forecasts during the Olympics (FDP)

3.2. Development and verification of COSMO-RU-LEPS 2.2 km for the Sochi region (with ICs and BCs from SOCHMEL7)

Goals:

Subtask 3.1 (FDP):

Development of a COSMO-LEPS system with a resolution of 7 km adapted to the Sochi region and to specific requirements of winter Olympics (SOCHMEL7) and operational support of the Sochi-2014 Olympics with COSMO-based 7-km ensemble forecasts:

- Adaptation of COSMO-LEPS 7 km to the Sochi region and to specific requirements of winter Olympics (SOCHMEL7). Organization of data transfer from ARPA -SIMC to RHMC.
- Development of visualization, interpretation and verification tools for SOCHMEL7. Coupling with post-processing techniques.
- COSMO-FROST-LEPS forecasts during the pre-trial (from 10 Dec 2011 to 31 Marh 2012) and trial (from 01 Dec 2012 to 31 Marh 2013) periods and their verification. Assessment of the effect of practical use of these forecasts.
- Operational ensemble forecasts during the Olympics and their verification. (The use of VERSUS with included EPS-verification tools is expected)

Deliverables (FDP):

A COSMO-LEPS system with 7 km resolution adapted to the Sochi region and to specific requirements of winter Olympics (SOCHMEL7). Operational ensemble forecasts during the Olympics. Technology of presentation and interpretation of the COSMO-FROST-LEPS results in operational mode.

Subtask 3.2 (RDP):

Investigation of the capability of high-resolution (2.2-km) ensemble system in forecasting over a complex terrain.

- Development of COSMO-RU-LEPS 2.2 km for the Sochi region (with ICs and BCs from SOCHMEL7)
- COSMO-RU-LEPS 2.2 km forecasts during trials and forecasts verification (if feasible).
- Comparison of capability of high-resolution (2.2-km) ensemble system with SOCHMEL7.
- COSMO-RU-LEPS 2.2 km forecasts during the Olympic Games (if feasible). Analysis of the results.

Deliverables (RDP):

COSMO-RU-LEPS 2.2 km for the Sochi region (with ICs and BCs from SOCHMEL7)

4 Development of High resolution COSMO-modeling for mountainous regions *(G. Rivin, M. Shatunova, D. Blinov, D. Majewski, J. Förstner, J. Helmert, U. Schättler, C. Schraff, M. Arpagaus, G. de Morsier, P. Steiner)*

4.1 Data assimilation system (DAS) based on the nudging scheme for the Sochi region *(G. Rivin, D. Blinov, C. Schraff)*

DAS activities

(a) **The new version of COSMO-Ru7/2 operational technology including the nudging- assimilation was developed for Caucasian and Central regions.** The analysis of skill of forecasts of T2m, Td2m, winds at 10m, PMSL showed the essential improving of models results **for the first 3–6 hours** for the version with nudging-assimilation (Fig.1)

(b) The realization of continuous model runs based on continuous assimilation cycles has allowed organizing the optimal time of starts of operational runs of COSMO-Ru1, nested into COSMO-Ru7/2, adapted to the timetable of work of Olympic Organizing Committee.

(c) RDP: The module of correction of initial values of T at the low model levels and of soil based on the T2m observations was realized and tested. After the coupling with COSMO-Ru domestic research version it was detected the more realistic results for the forecasts of vertical profiles of temperature during all period of short-range forecasts and the little decreasing of the models precipitations. **The module is ready for coupling with operational technology and for nudging-cycles**, but needs the further testing for accumulation of larger statistics of forecasts for different synoptic situations and seasons.

Table 1: The number of used observations from RHM database for data assimilation

	number of measurements for one station per day	number of available stations (maximal value)			
		Database RHM	domain COSMO-RU07	domain COSMO-Ru2 (South)	domain COSMO-Ru2 (North)
SYNOP	8	7800	2950	155	180
TEMP, PILOT, TEMPSHIP	2	600	120	5	12
Sochi AMS	8–288	50	50	50	0

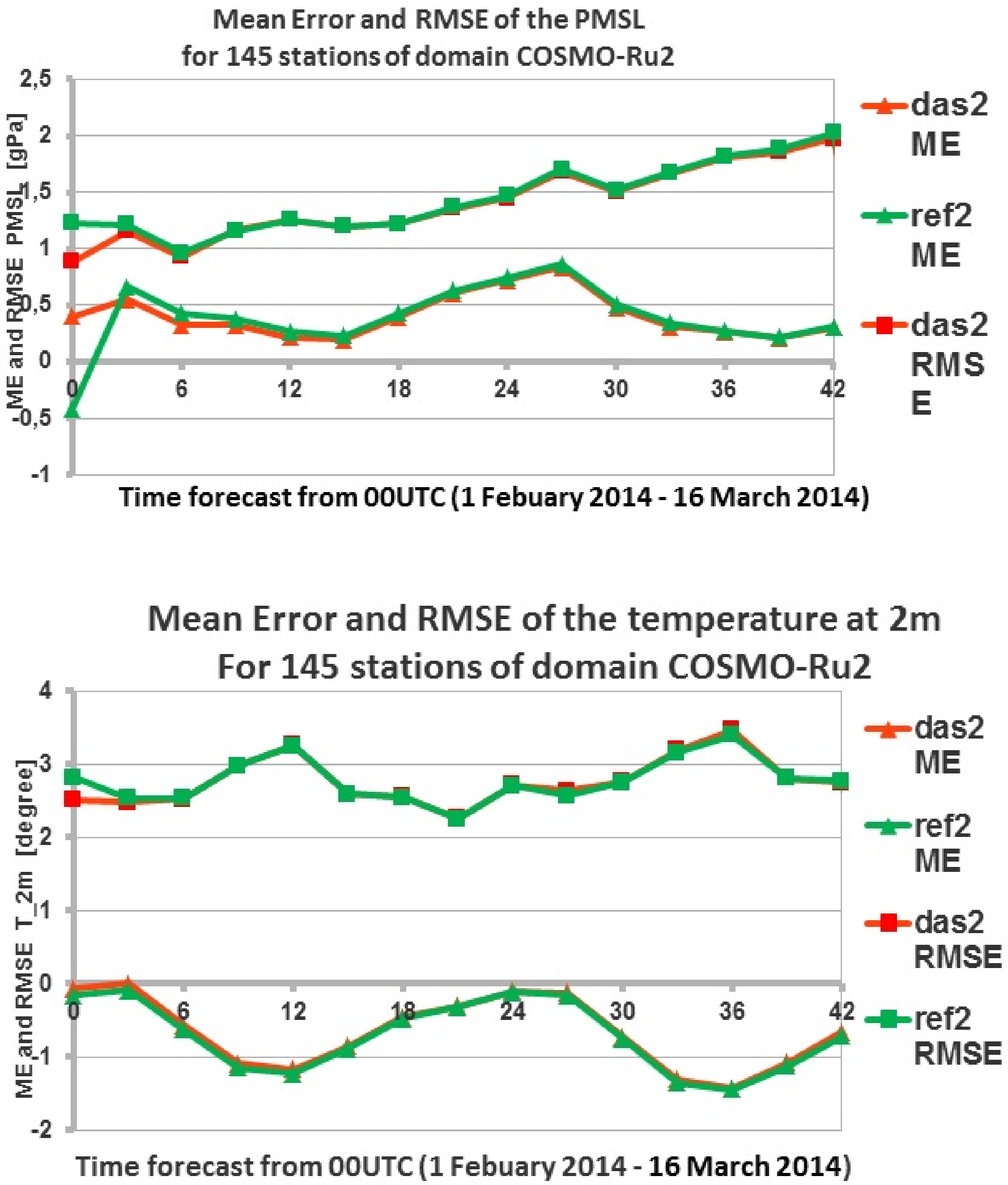
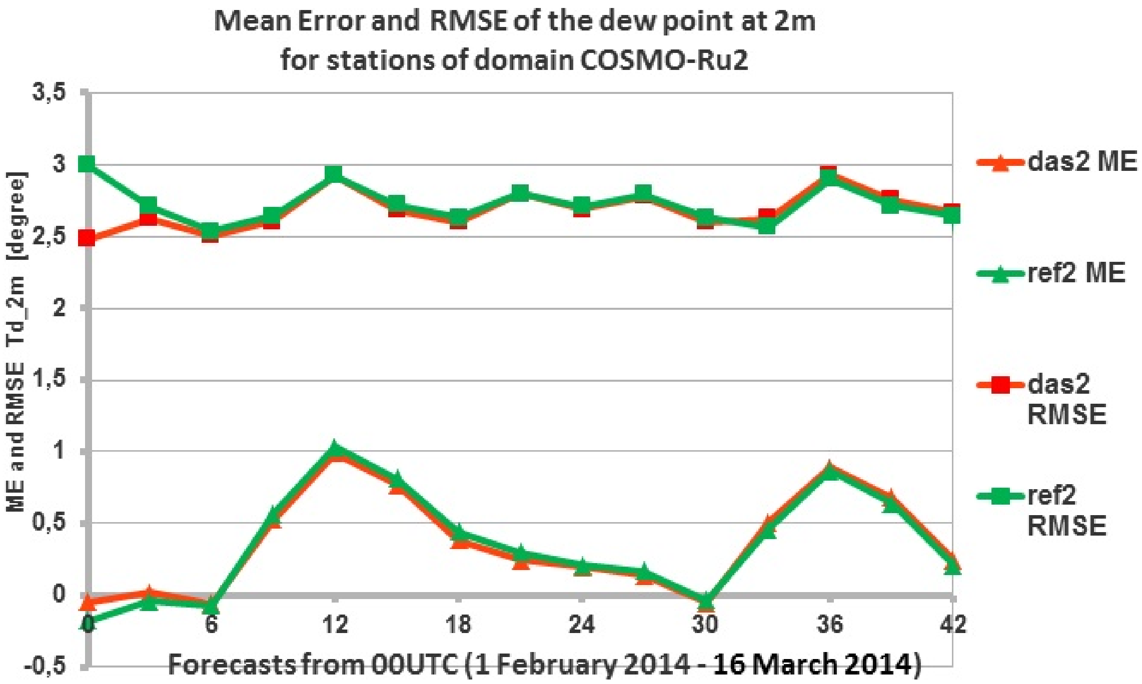
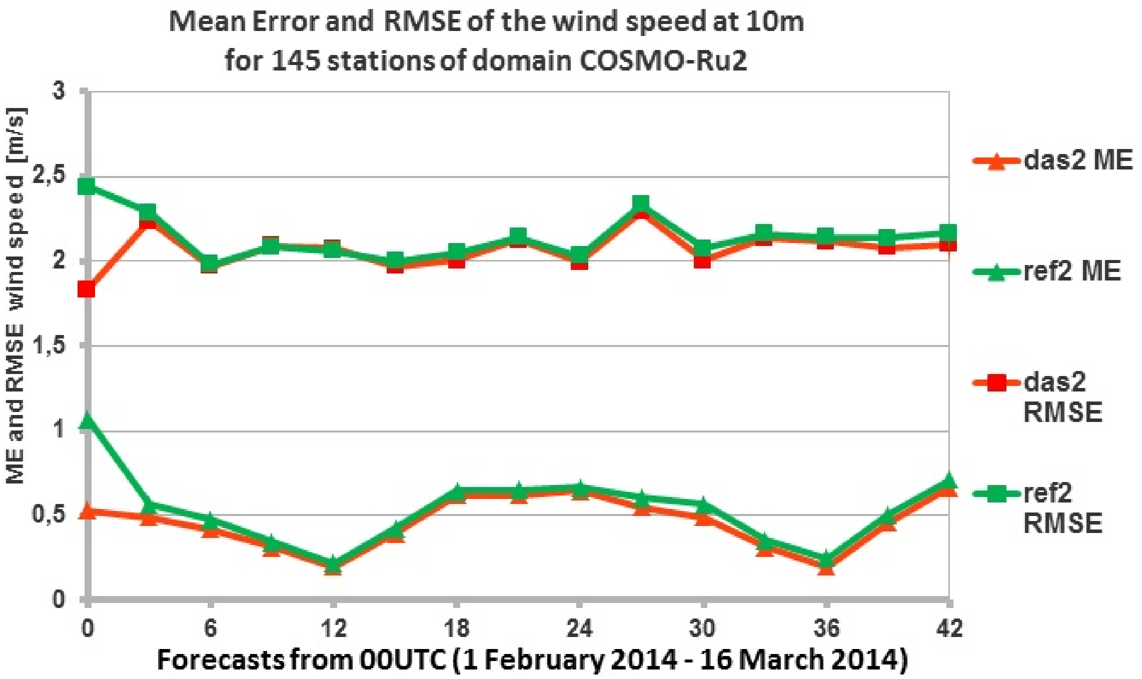


Figure 1: Mean error (ME) and Root Mean Square Errors (RMSE) of forecasts COSMO-Ru2 with DAS (red line) and without (green line) for PMSL, T_2m, Td_2m and wind speed respectively for Olimpic period 1 February – 16 March 2014

Cont. Fig.1.


Mean Error and RMSE of the dew point at 2m
for stations of domain COSMO-Ru2
ME and RMSE Td_2m [degree]
3,5
3
2,5
2
1,5
1
0,5
0
-0,5
0
6
12
18
24
30
36
42
Forecasts from 00UTC (1 February 2014 - 16 March 2014)
das2 ME
ref2 ME
das2 RMSE
ref2 RMSE


Mean Error and RMSE of the wind speed at 10m
for 145 stations of domain COSMO-Ru2
ME and RMSE wind speed [m/s]
3
2,5
2
1,5
1
0,5
0
0
6
12
18
24
30
36
42
Forecasts from 00UTC (1 February 2014 - 16 March 2014)
das2 ME
ref2 ME
das2 RMSE
ref2 RMSE

4.2 Development of High resolution COSMO-modeling for mountainous regions *(G. Rivin, M. Shatunova, D. Majewski, J. Förstner, J. Helmert, U. Schättler, D. Blinov, M. Arpagaus, G. de Morsier, P. Steiner)*

4.2.1 Model installation (and domain size selection)

Version of the COSMO model with horizontal resolution 1.1 km, named COSMO-Ru1, was installed on cluster-based architecture Tornado in Roshydromet. First COSMO-Ru1 version was released for domain size 450 x 450 grid points with lateral boundary conditions (LBC) from COSMO-Ru2SFO (with grid step 2.2 km for Southern Federal Region) for the same initial time run. COSMO-Ru1 is nested into COSMO-Ru2 but rotated grids of these models have different pole.

Model run time on cluster-based architecture Tornado for 24 hours forecast using 18 processors (244 cores) was approximately 50 min.

Because of limited computing resources and taking into account timing of the all COSMO-Ru models it was decided to reduce COSMO-Ru1 domain size for future operational use.

Forecasts for two versions of simulation domains were evaluated. Specifications of COSMO-Ru1 for experimental runs are presented in Table 2; positions of two domains are shown in Fig.2 along with COSMO-Ru2SFO domain.

Table 2: Specifications of COSMO-Ru1 experimental version

Domain size (grid points)	200 x 200 // 450 x 450
Horizontal grid spacing (degree / km)	0.01 / 1.1
Number of layers	50
Time step (seconds)	5-10
Forecast range (hours)	24-48
Initial time of model runs (UTC)	00, 06, 12, 18
Lateral Boundary conditions	COSMO-Ru2SFO
LBC update frequency (hours)	1
Initialization	none
COSMO version	4.27
Hardware	RSK Tornado
No. of cores used	224 (of 1152)

Assessment of the temperature at 2 m and precipitation forecasts showed that changes of domain size had greater effect on precipitation forecast than on temperature forecast. The difference in T2m forecast for two different domains would not exceed 0.5° (see Fig.3) while for precipitation forecast, especially for heavy precipitation cases, the difference varies from 30 % (for 24 h accumulated precipitation) to 100 % (for 1 h sums).

It is evident that change of the simulations domain size lead to changes in spatial (see Fig.4) and temporal (see Table 3) distribution of predicted precipitation. Assessment of results for two domains by comparison 3h and 24 h accumulated precipitation with observed values does not allow a definite conclusion about preferable domain.

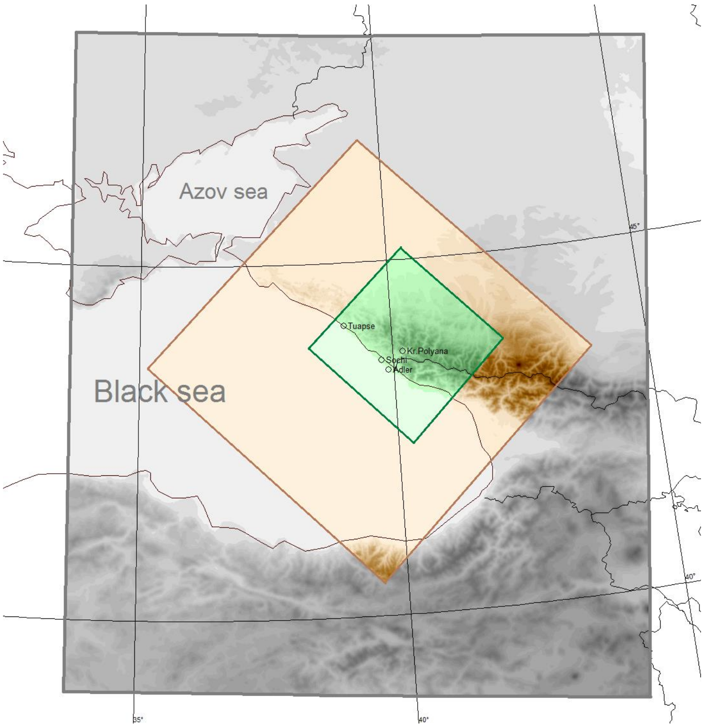


Figure 2: Location and size of COSMO-Ru2 domain (outer grey rectangle) and COSMO-Ru1 domains used in experiments: 450 x 450 grid points (brown-colored square) and 200 x 200 grid points (inner green-colored square)

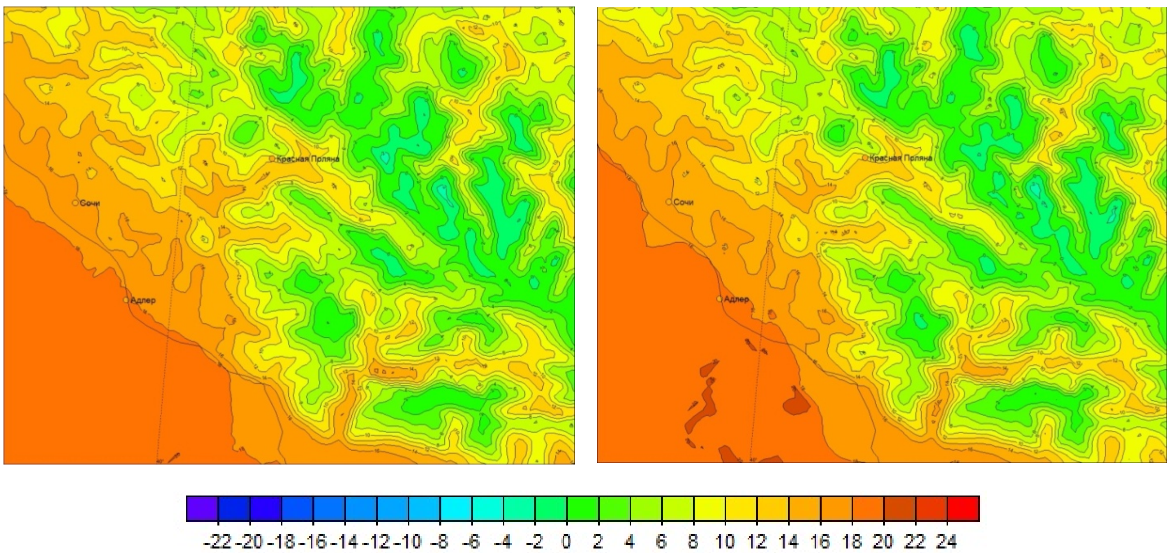


Figure 3: T2m 12 h forecasts from 24.09.2013, 00 UTC obtained in experiments with simulations domain 200 x 200 grid points (left) and 450 x 450 grid points (right)

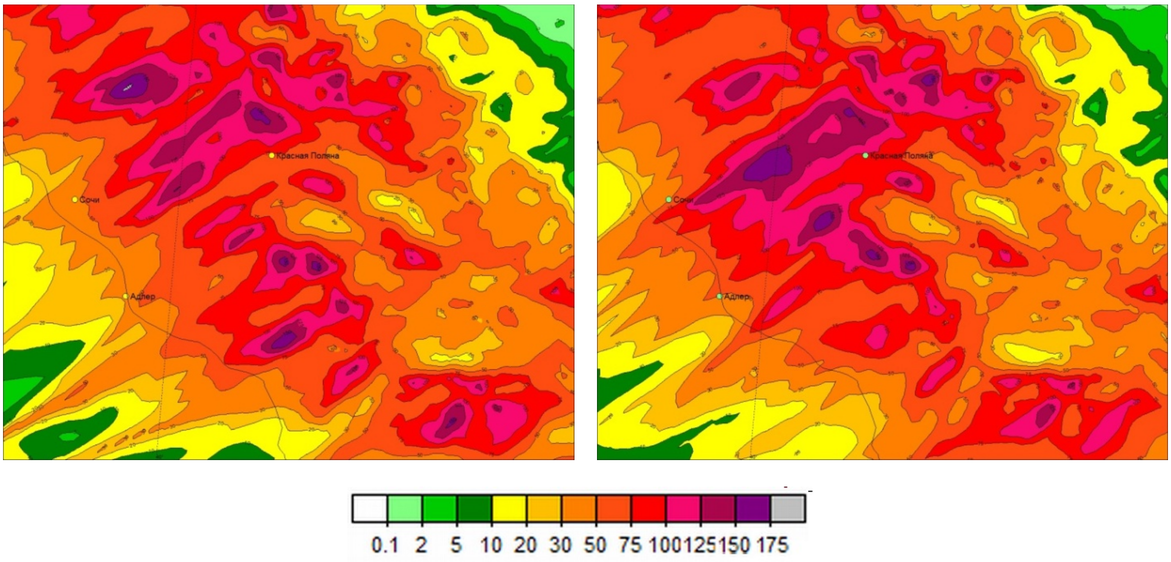


Figure 4: The same as figure 3 but for 12h precipitation sum

4.2.2 COSMO-Ru1 model orography options

Initially COSMO-Ru1 model orography was based on GLOBE *(The Global Land One-km Base Elevation Project)* data (NOAA/NGDC) (http://www.ngdc.noaa.gov/mgg/topo/globe.html). Great differences between height of observation points and height of the nearest model grid nodes forced us to check model orography by comparison with high-resolution ASTER *(Advanced Spaceborne Thermal Emission and Reflection Radiometer)* data (METI/NASA) (http://asterweb.jpl.nasa.gov/gdem.asp) that has resolution 1"($\sim$ 30 m). This comparison revealed a discrepancy between model orography and "real"one that reached 500 m for some nodes.

In December 2013, new orography data from EXTPAR based on ASTER GDEM2 became available and replaced COSMO-Ru1 model orography. The following orography filters were used: $ilow\_pass\_oro = 4$, $ilow\_pass\_xso = 5$, $rxso\_mask = 625$.

Numerical experiments shown a positive effect of new orography data on the temperature, wind and precipitation forecast. Some errors in ASTER data locations discovered by EXTPAR developers later were insignificant for forecast quality.

Difference between observation site height and height of corresponding grid node became smaller. That lead to better agreement between observed and predicted values of T2m and wind speed (see Fig.5). For Gornaya Karusel height difference reduced to -32 m (previously -568 m), for Krasnaya Polyana 7 m (previously 248 m), for Aibga -194 m (previously -443 m). Improvement of T2m forecast was below 3° for some sites depending on weather conditions.

Model orography replacement affected also the predicted precipitation spatial and temporal distribution. Fig.6 shows forecasts with different model orography in comparison with observations for two sites: Gornaya Karusel-1500 and Krasnaya Polyana. Both sites are located within the mountain valley, height changes of the model grid node are mentioned above. Impact of new orography on forecasted accumulated precipitation can be seen better on the bottom graphs where differences "forecast – observation"for two variants of the model orography are presented. For Gornaya Karusel-1500 errors are the same: overestimation for the 4 first and the 4 last hours of the event and large underestimation of the accumulated precipitation at 2 (first maximum of the event) and 6 UTC 19.10. However, for the period

Table 3: Observed and predicted 3h precipitation sum for 24.09.2013

	Period, h								
	00–03	03–06	06–09	09–12	12–15	15–18	18–21	21–00	00–24
Krasnaya Polyana									
Observations	0.6	3.8	17.1	30.6	13.6	25.4	19.1	4.6	114.8
COSMO-Ru1 (200 x 200 g.p.)	13.0	29.1	11.9	12.1	31.9	28.9	3.8	0.8	131.5
COSMO-Ru1 (450 x 2450 g.p.)	12.5	30.4	22.7	22.6	26.5	11.9	2.9	0.1	129.5
COSMO-Ru2	4.7	41.5	21.7	11.3	40.4	12.4	4.4	1.8	138.1
Gornaya Karusel-1500									
Observations	0.5	10.5	28.7	34.6	16.6	20.1	20.2	1.7	132.9
COSMO-Ru1 (200 x 200 g.p.)	8.2	31.1	11.9	20.9	8.6	17.7	3.5	1.5	103.4
COSMO-Ru1 (450 x 2450 g.p.)	8.4	35.8	26.9	24.2	18.7	13.9	3.6	0.0	131.5
COSMO-Ru2	5.7	25.6	26.1	15.9	19.5	15.1	4.2	0.1	112.2
Roza Khutor-4									
Observations	0.5	9.7	19.0	33.0	31.8	29.6	26.4	4.4	154.4
COSMO-Ru1 (200 x 200 g.p.)	7.2	31.4	30.5	50.3	19.6	25.6	3.1	1.1	168.9
COSMO-Ru1 (450 x 2450 g.p.)	7.5	43.2	41.4	36.6	33.5	32.2	3.9	0.0	198.4
COSMO-Ru2	1.4	10.9	16.7	18.5	22.3	22.3	4.6	0.1	96.6
Roza Khutor-7									
Observations	0.3	10.5	25.9	34.1	26.1	28.0	25.0	5.0	154.9
COSMO-Ru1 (200 x 200 g.p.)	5.3	24.7	31.1	48.4	21.6	28.6	3.5	0.9	164.2
COSMO-Ru1 (450 x 2450 g.p.)	5.6	29.9	36.5	33.7	29.2	31.4	3.3	0.0	169.7
COSMO-Ru2	2.7	17.7	26.1	24.7	26.4	21.9	2.8	0.1	122.4

7-18 UTC forecast with new orography is better, errors have opposite sign. For Krasnaya Polayna forecast improvement is not obvious, errors are mostly the same or even greater.

4.2.3 COSMO-Ru1 operational use and verification

From January 29, 2014 COSMO-Ru1 run in operational mode is conducted 4 times a day. In order to perform forecast delivery schedule to forecasters COSMO-Ru1, COSMO-Ru2 and COSMO-Ru7 models run as priority tasks on additional cluster-based architecture ICE-X in Roshydromet during Olympics/Paralympics. Specifications of COSMO-Ru1 for operational use are presented in Table 4.

COSMO-Ru1 used initial and boundary conditions from COSMO-Ru2SFO from previous start-time (Fc-06h). The preliminary experiments demonstrated the capability of COSMO-Ru1 to produce satisfactory forecast with lead-time until 36 hours. It made possible to create operational forecast technology, which meets the requirements of forecasters, taking into account time difference (UTC+4) and need to provide forecast for the current day to forecasters on 5 a.m. local time (1UTC).

COSMO-Ru1 forecast were used by forecasters along with COSMO-Ru2 during SOCHI-2014 Olympic Games. Model output parameters were produced in form of forecast charts of individual meteorological characteristics or combination of them and those produced in form of meteograms. Forecast charts were prepared for the three regions with varying order of detail: for whole simulations domain, for the Sochi coastal region and for mountain cluster (see examples in Fig.7).

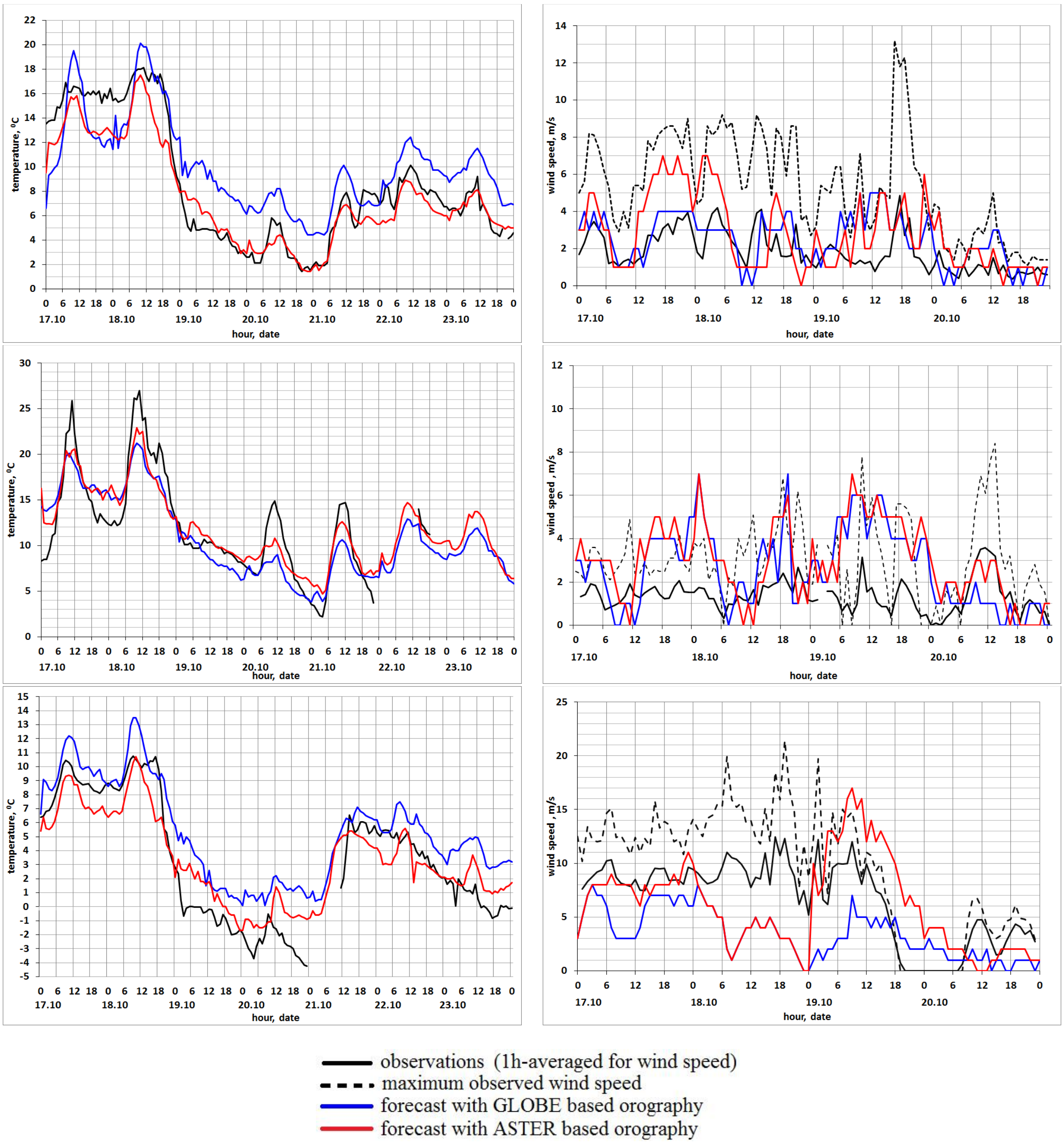


Figure 5: Series of 24 h forecasts for T2m (left) and wind speed at 10 m (right) from 00 UTC, for the period October, 17-23, 2013 (for T2m) and October, 17-20 (for wind) and observation data at Gornaya Karusel (top), Krasnaya Polyana (middle) and Aibga (bottom) for the same period

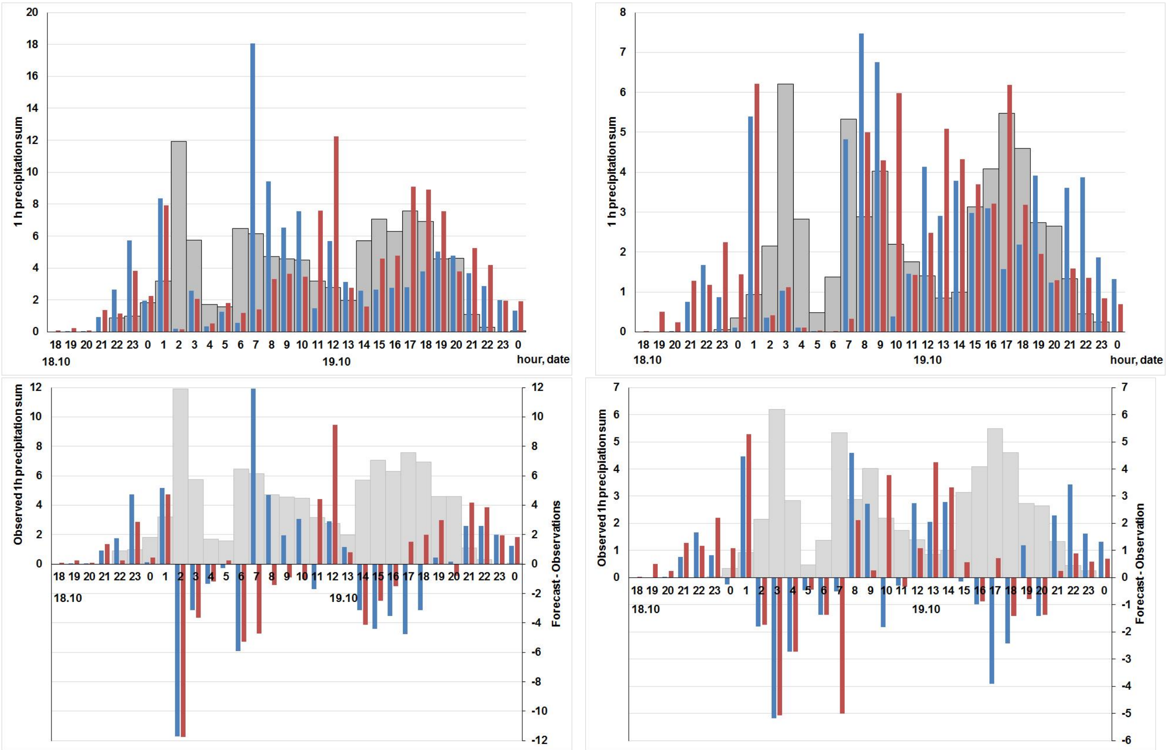


Figure 6: 1 h observed accumulated precipitation (grey column), forecasted by COSMO-Ru1 with different model orography: based on GLOBE data (blue) and ASTER data (red) for Gornaya Karusel-1500 (left) and Krasnaya Polyana (right). Comparison of 1h accumulated precipitation (top) and difference of two forecasts (bottom)

Table 4: Specifications of COSMO-Ru1 operational version during Olympics/Paralympics

Domain size (grid points)	190 x 190
Horizontal grid spacing (degree / km)	0.01 / 1.1
Number of layers	50
Time step (seconds)	5
Forecast range (hours)	36
Initial time of model runs (UTC)	00, 06, 12, 18
Lateral Boundary conditions	COSMO-Ru2SFO
LBC update frequency (hours)	1
Initialization	none
COSMO version	5.0
Hardware	SGI ICE-X
No. of cores used	660 (of 720)

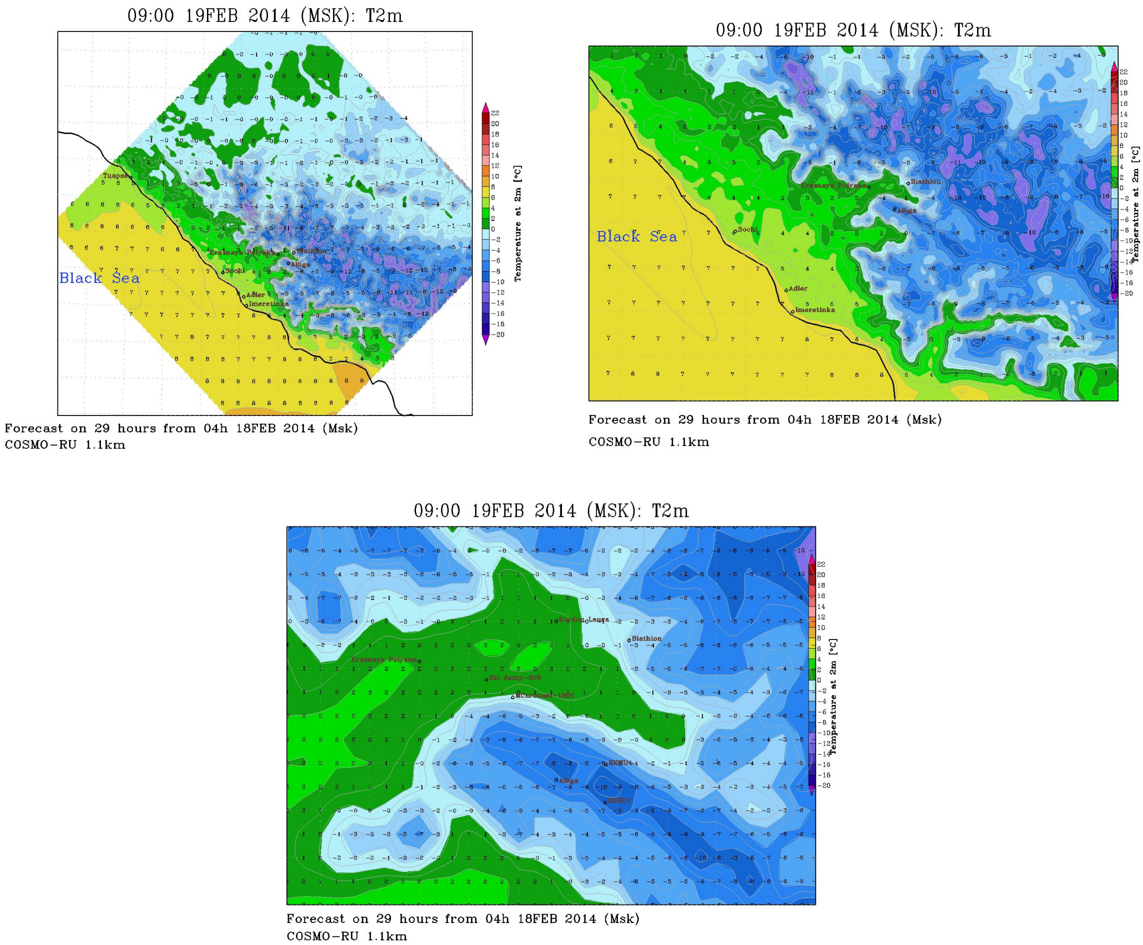


Figure 7: COSMO-Ru1 output presentation example. T2m forecast for the entire simulation domain (upper left), the Sochi region (upper right) and mountain cluster (bottom)

COSMO-Ru1 results were verified by VERSUS for the period of the Olympics/Paralympics along with COSMO-Ru2 and COSMO-Ru7. Some results for 00 UTC run are presented in Fig.8 *(by courtesy of Anastasia Bundel and Alexander Kirsanov)*. Verification made for 39 stations located at different altitudes in the mountain and coastal clusters for the period 29.01.2014 15.03.2014.

As for subjective verification, forecasters favored COSMO-Ru1 less than COSMO-Ru1 because COSMO-Ru1 began to run operationally just before the Olympics and they had no experience using products of this model. However COSMO-Ru1 forecasts for mountain cluster, such as combined charts “RH + streamlines”, proved to be very popular and useful in the preparation of synoptic forecasts.

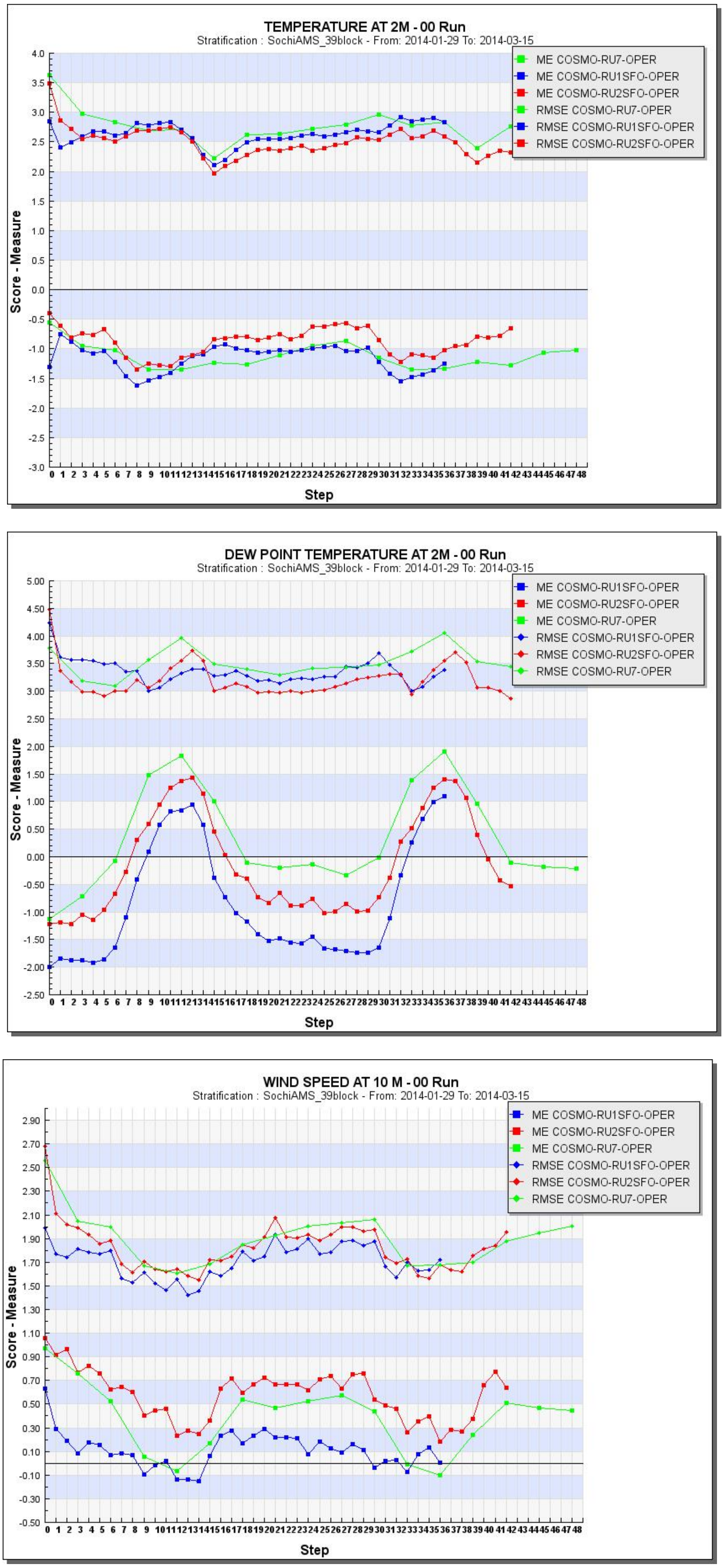


Figure 8: Verification COSMO-Ru1 (blue), COSMO-Ru2 (red) and COSMO-Ru7 (green) results for the 39 stations located at different altitudes in the mountain and coastal clusters for the period 29.01.2014 15.03.2014

4.2.4 Case study

The presence of observation data of different kinds and increasing of AMS numbers in the Sochi region during pre-Olympics period allowed to conduct several case studies. Satellite images, radars and profilers'data, as well as AMS data of high temporal resolution used to investigate COSMO-Ru1 model behavior in different synoptic conditions. List of weather events along with several NWP models behavior in appropriate situations was prepared by forecasters on the basis of their experience obtained during Sochi-2014 Olympics. Two events in the list related to low visibility cases have been studied. Detailed description of these cases is presented in (Shatunova, Rivin, Rozinkina, 2015).

5 Downscalling/post-processing for Sochi area and applications *(I. Rozinkina, E. Kazakova, M. Chumakov, A. Bundel, A. Muravev, D. Blinov, A. Kirsanov, P. Eckert, G. Rivin, A. Euripides, E. Kukanova)*

5.1 T2m correction *(I. Rozinkina, D. Blinov, G. Rivin)*

The goal: To realize the updated software of Fieldextra with inclusion of calculations of subgrid values of T2m based on the forecasts of vertical temperature gradient and to provide the software of 1-D correction of T2m forecasts based on the forecasts of vertical T gradient ("h-correction").

Method:

1. Determine the difference in heights of the model gridpoint and the height at the station Δh.
2. Find the vertical temperature gradient in the planetary boundary layer dT_{pbl}.
3. Find an amendment of temperature to the height as a product of the gradient and the difference in heights. The value of the amendments added to the model temperature at 2 meters. $T2m\_hcorr = T2m + \Delta h \times dT_{pbl}$

Technology: The algorithm was tested in RHM and was operationally used during the Olympic Games in 2014. The vertical profiles of temperature from FieldExtra were used to find the vertical temperature gradients in PBL . As a result, the corrected temperature appears in the text and graphic 1D meteograms.

Outcome: Description of 1-D algorithm of h-correction of T2m.

The examples of results in using the proposed algorithm in COSMO-model are presented in the next sections of this chapter.

5.2 Kalman filtering application for correction of T2m COSMO-Ru-So forecasts *(M. Chumakov, E. Kazakova, I. Rozinkina, P. Eckert)*

It is a commonly acknowleged that Numerical Weather Prediction (NWP) models exhibit systematic errors in the forecasts of near surface weather parameters. This is a result not only of deficiencies of the physical parameterizations, but also of the inability of these models to handle successfully sub-grid phenomena. Furthermore, forecasts for the areas that are not in close proximity to the model grid points are usually based on interpolation of model output parameters, which also increases the 'noise' in the final forecast products.

Well known that the 2m-temperature, is one of the most commonly biased variable, where the magnitude of this bias depends, among other factors, on the geographical location and the season. So for better forecast result some correction algorithm should be used.

One of the most common approache to the above mentioned problems is the use of Kalman filtering (Kalman, 1960). This technique gives excellent results in the correction of systematic errors in any type of prediction, based on the recursive combination of recent forecasts and observations. The main advantage is the easy adaptation to any changes in the data being used (Galanis, Anadranistakis, 2002).

5.2.1 Description of the method

At Hydrometcenter of Russia Kalman filtering and height T2m correction algorithm (through vertical gradient) are implemented in COSMO-Ru2 (the Sochi region) (station locations are shown in the map in Fig.9). The technology works operationally since February 2015.

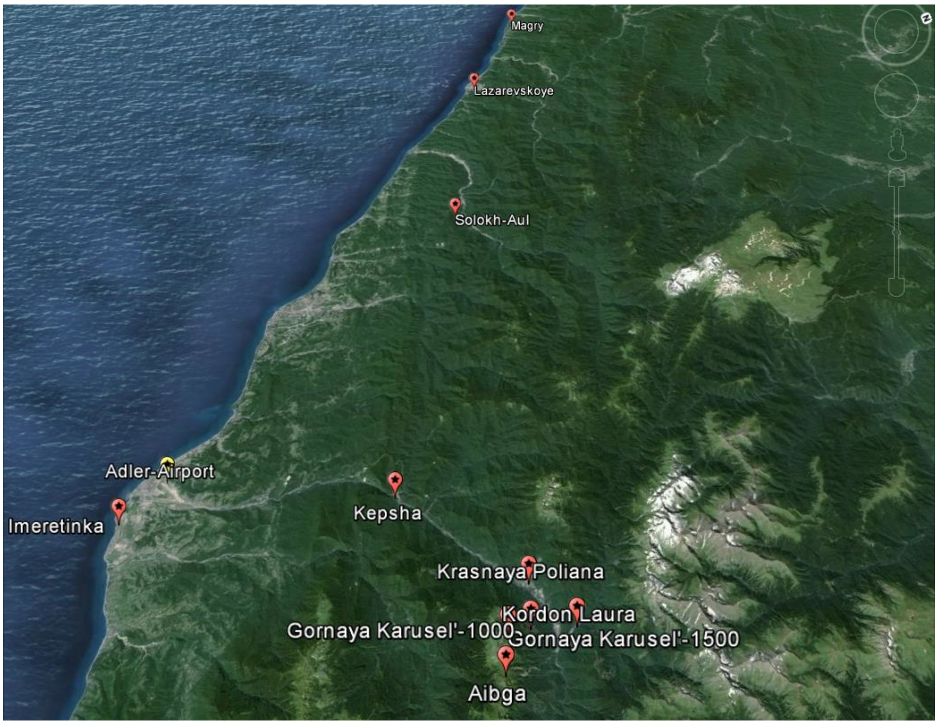


Figure 9: Station locations in the Sochi region

Describe briefly the main features of the implemented Kalman filtering. Suggest that there are two T2m observations T_1 and T_2 which can be represented as:

$T_1 = T_{true} + g_1$

$T_2 = T_{true} + g_2$

where T_{true} — true value of T2m, g_1, g_2 — stochastic variables (connected with measurement or forecast errors). As a rule, it is impossible to know exactly the value of T_{true}. But T_1, T_2 can be specified through reducing noise components g_1, g_2.

Consider that g_1, g_2 obey the normal distribution law and following conditions for mathematical expectation M and variance D are relevant:

$$\begin{aligned} M(g_1) = 0, M(g_2) = 0 \\ D(g_1) = \sigma_1^2, D(g_2) = \sigma_2^2. \end{aligned} \tag{1}$$

At this assumptions the best fit (best estimator), T_{cor}, of the true value of T2m would be written as:

$$T_{cor} = \alpha_1 T_1 + \alpha_2 T_2, \tag{2}$$

where α_1, α_2 are some unknown weight coefficients which has one important feature:

$$\alpha_1 + \alpha_2 = 1. \tag{3}$$

Take into account (3) we may rewrite (2) in following form:

$$T_{cor} = (1-\alpha)T_1 + \alpha T_2, 0 \leq \alpha \leq 1. \tag{4}$$

In general case to assess the quality of it should be introduced some cost function $f(\varepsilon)$. Let the cost function has the form

$$f(\varepsilon) = \varepsilon^2 = (T_{true} - T_{cor})^2. \tag{5}$$

Such form of cost function is convenient for estimation of assessment quality since it has one minimum where derivative exists and equals to zero. This feature gives opportunity to find analytical form of T_{cor}.

Generally speaking function ε is a random variable as errors g_1, g_2 are changing from measurement to measurement, what lead to change of T_{cor} value at the same algorithm of measurements' processing. That's why quality criterion should be chosen in the way that algorithm gives minimum in average function $f(\varepsilon)$, i.e. assessment error variance P must tend to zero:

$$P = M\{(T_{true} - T_{cor})^2\} \longrightarrow 0. \tag{6}$$

Take into account (1) and (4) we obtain analytical formula for P:

$$P = (1-\alpha)^2 D(g_1) + \alpha^2 D(g_2). \tag{7}$$

From the condition

$P = \frac{dP(\alpha)}{d\alpha} = 0$

we find optimal value of α, so Kalman filter is written as:

$$T_{cor1} = T_1 + K \cdot (T_2 - T_1), \tag{8}$$

where $K = \frac{P_1}{\sigma_2^2}$ — amplification factor. P_1 — variance of estimation which is calculated as:

$$P_1 = \frac{D(g_1) \cdot D(g_2)}{D(g_1) + D(g_2)} = 0. \tag{9}$$

This formula is easily extended to the case when there are more than two measurements.

It gives opportunity employ this algorithm for correction current forecast values using results of the preceding forecasts in assumption that variance of current forecast error is equal to value which was calculated using value of error during a few previous days.

Scheme of using COSMO-model (2.2 km) forecast series for the Sochi region is presented in Fig.10. This figure shown, for example, for correction result of 15-hour forecast T2m from 00 UTC of any day may be used forecast result for this time from 00, 06, 12 and 18 UTC of previous day.

Figure 10: Scheme of COSMO-Ru2 forecast series for the Sochi region

Testing of the algorithm was done for station Adler (Sochi) for May 2013 with the use of COSMO-Ru2 version. Results are presented in Table 1. As can be seen, significant reduction of T2m RMSE values was observed for 3-hour, 9-hour and 15-hour lead time model forecasts starting from 06 UTC. It may be supposed that it is related to the quality of forecasted values, which were used in correction or statistical characteristics of forecast errors at this time.

It will be appreciated that only strict implementation of the conditions (1) ensures successful operation of Kalman filtering. Unfortunately forecast's values of T2m not always satisfy these conditions. As a result of studies it was determined that the Fourier coefficients are more relevant.

Thus, modification of Kalman filter algorithm application was done by using discrete Fourier transform. T2m forecast series on particular date can be treated as a real time-dependent function f. Thus suppose that we sample f at N equally spaced time intervals of length Δ seconds starting at moment t_0. Consequently:

$$SEQ_i = f(t_0 + (i-1)\Delta)i = 1, ..., N.$$

Table 5: RMSE values for T2m COSMO-Ru2 forecasts with Kalman filtering application for station Adler for period of May 2013

Forecast, hour	Start 00 h		Start 06 h		Start 12 h		Start 18 h	
	Filtered	Ref.	Filtered	Ref.	Filtered	Ref.	Filtered	Ref.
03	1.3	2.0	1.3	2.3	0.9	1.4	1.1	2.0
06	1.4	1.1	1.4	1.6	1.3	1.3	1.7	1.8
09	1.3	1.3	1.6	2.7	1.1	1.5	1.7	2.1
12	1.5	1.4	1.3	1.5	1.7	1.9	1.6	1.2
15	1.3	1.6	1.1	1.9	1.7	2.1	1.3	1.2
18	1.4	1.3	1.7	1.8	1.1	1.1	1.4	1.4
21	1.1	1.5	1.7	2.0	1.3	1.1	1.2	1.6
24	1.7	1.9	1.1	1.1	1.5	1.3	1.3	1.3

Note. In colors: orange improvement, red significant improvement, blue measurement error.

Discrete Fourier transform of this function can be written as:

$$SEQ_i = \frac{1}{N}[c_1 + 2\sum_{n=2}^{(N+1)/2} c_{2n-2}cos[\frac{2\pi(n-1)(i-1)}{N}] - 2\sum_{n=2}^{(N+1)/2} c_{2n-1}sin[\frac{2\pi(n-1)(i-1)}{N}]]. \tag{10}$$

For obtaining sufficient number of Fourier coefficients synoptic period (7 days) must be used. Each Fourier coefficient (c_i) can be represented as an independent temperature measurement. Accordingly Kalman filtering (KF) algorithm mentioned above can be applied to these coefficients.

5.2.2 Operational results and verification

Since the mid February 2014 Kalman filtering was implemented in operational mode for COSMO-Ru2 Sochi domain at Hydrometcentre of Russia. Meteograms were produced for 11 stations situated in the region, which sent standard regular SYNOP measurements (example is presented in Fig.11). Height corrected temperature forecasts (authors of the algorithm — I. Rozinkina, D. Blinov) were used as T2m COSMO-Ru2 forecasts.

Thus, Kalman filtering was applied to the value of corrected T2m COSMO-Ru2 forecasts and observations at meteorological stations. It could work for other COSMO-Ru domains and when using standard T2m COSMO-Ru forecasts.

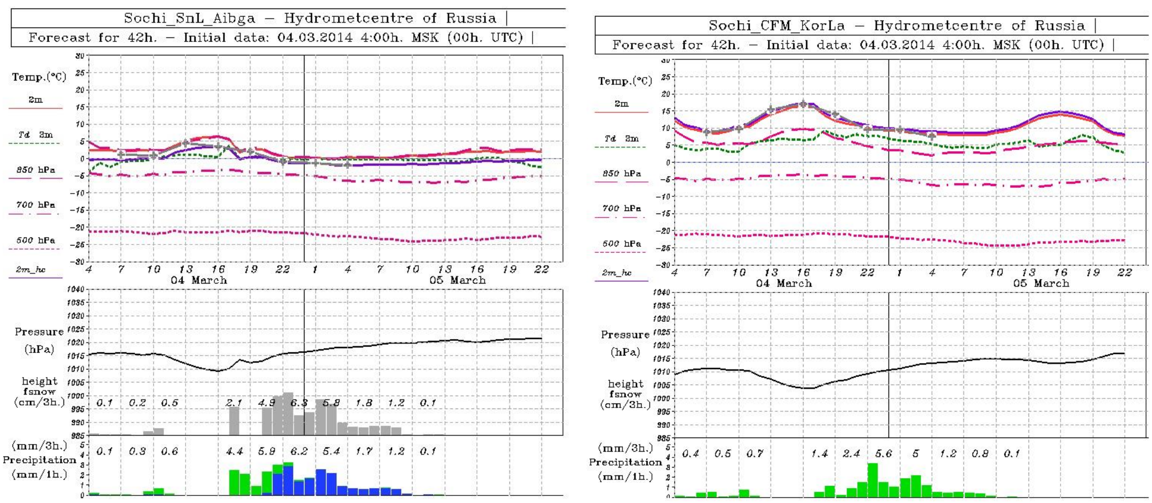


Figure 11: Example of meteograms obtained from integration of COSMO-Ru2 for station Aibga (left) and Kordon Laura (right). Start 00 UTC 4 March 2014. Height corrected temperature is presented by a violet curve, 2m temperature — pink line, result of KF application — gray dots. Grey columns show hourly accumulated depth of fresh snow, numbers above — its 3-hour sums. Blue columns indicate hourly accumulated precipitation in the form of snow, green — in the form of rain

Kalman filtering (with using corrected COSMO-Ru2 T2m forecasts) provides more accurate T2m forecast in mountain region rather than operational version of COSMO-Ru2 (improvement is about 2° C in RMSE) and in most cases — better than using only height correction algorithm for T2m (Fig.12-13). Improvement of T2m forecasts with the use of KF is observed not only for mountain areas, but also for the coastal stations. Comparison between T2m forecasts for the period up to 24 hours was done for these statiuons with start time 00 and 18 UTC — RMSE absolute values were close. The accuracy of KF and T2m corrected algorithm is comparable.

Sochi Adler (0 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.8	1.9	1.5
6	1.8	1.8	1.5
9	2.0	2.0	2.1
12	1.9	1.9	1.9
15	1.6	1.6	1.7
18	1.5	1.5	1.8
21	2.0	2.0	2.2
24	1.4	1.5	1.9

Imeretinka (6 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	3.0	3.1	2.8
6	3.1	3.1	3.0
9	3.8	3.8	3.9
12	3.7	3.7	3.6
15	1.7	1.6	1.6
18	2.0	2.1	2.3
21	2.0	2.0	2.3
24	2.3	2.3	2.6

Lazarevskoe (9 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.0	2.1	1.8
6	2.0	2.0	2.1
9	3.0	3.0	2.6
12	3.1	3.1	2.5
15	2.4	3.3	2.4
18	1.6	1.6	2.0
21	1.6	1.6	1.5
24	2.0	1.9	1.7

Magri (50 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	4.0	3.9	3.4
6	1.9	1.9	2.1
9	2.9	3.0	2.7
12	2.9	2.9	2.5
15	1.9	1.9	1.9
18	3.3	3.2	2.5
21	4.2	4.1	3.2
24	4.1	3.9	3.2

Kepsha (180 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.8	3.1	2.8
6	2.8	3.4	2.8
9	4.2	4.2	4.0
12	5.0	4.7	4.4
15	3.4	3.5	3.6
18	1.5	2.1	1.6
21	1.4	1.6	1.7
24	1.6	1.6	1.9

Kalman filter is better/equal than operational version and T2m correction algorithm

Kalman filter is better than operational version

T2m correction algorithm is better than operational version

Solokh Aul (443 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.8	1.6	1.3
6	1.8	1.7	1.8
9	2.6	2.5	2.5
12	2.9	2.8	2.7
15	2.7	2.6	2.7
18	1.6	1.3	1.3
21	1.7	1.4	1.3
24	2.6	2.5	2.5

Krasnaya Polyana (564 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.7	1.5	1.3
6	1.9	2.0	1.7
9	2.7	2.3	2.3
12	3.3	2.7	2.3
15	2.5	2.0	2.0
18	2.0	1.8	2.1
21	1.7	1.5	1.8
24	1.6	1.5	1.6

Kordon Laura (570 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.9	3.1	2.4
6	3.2	3.4	3.3
9	3.1	3.0	3.0
12	3.7	4.0	3.7
15	2.0	2.8	1.7
18	2.8	3.1	2.4
21	2.1	2.4	1.8
24	2.6	2.9	2.1

Gornaya Karusel (977 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.3	2.3	2.1
6	2.9	2.7	2.7
9	2.3	2.0	2.0
12	3.0	2.6	2.7
15	3.1	2.9	3.1
18	1.7	1.5	1.6
21	1.6	1.5	1.5
24	1.4	1.3	1.6

Gornaya Karusel (1434 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.0	2.1	2.2
6	2.2	2.2	2.2
9	2.4	2.4	2.4
12	3.0	3.0	3.1
15	1.6	1.6	1.8
18	1.3	1.3	1.8
21	1.4	1.4	1.7
24	1.3	1.3	1.6

Aibga (2225 m)

forecast. Hour	RMSE oper	RMSE cor	RMSE KF
3	2.5	1.3	1.4
6	3.0	1.3	1.4
9	3.5	1.7	1.7
12	4.1	2.5	2.3
15	3.0	1.4	1.3
18	3.2	1.4	1.9
21	2.8	1.1	1.1
24	7.4	1.5	2.3

Figure 12: RMSE for T2m COSMO-Ru2 forecasts for stations in the Sochi region. Start 00 UTC. 1 March — 30 June 2014

Sochi Adler (0 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.0	2.0	1.9
6	1.6	1.6	1.5
9	1.5	1.5	1.5
12	1.9	1.9	1.7
15	2.2	2.2	2.3
18	2.0	2.0	2.4
21	1.7	1.7	1.8
24	1.4	1.4	1.7

Imeretinka (6 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.0	2.1	2.0
6	2.4	2.4	2.3
9	2.8	2.9	2.7
12	3.2	3.2	3.0
15	3.0	3.0	3.1
18	3.5	3.5	3.8
21	1.7	1.6	1.7
24	2.2	2.3	2.5

Lazarevskoe (9 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.5	1.5	1.4
6	1.8	1.9	1.6
9	2.2	2.2	1.8
12	2.3	2.2	2.3
15	3.3	3.2	2.7
18	3.4	3.3	2.8
21	2.4	2.4	2.5
24	1.7	1.7	2.1

Magri (50 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	4.3	4.2	3.6
6	4.0	3.9	3.2
9	4.2	4.0	3.3
12	2.1	2.2	2.3
15	3.1	3.2	2.7
18	3.2	3.3	2.9
21	3.6	3.6	3.6
24	3.3	3.2	2.7

Kepsha (180 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.8	1.9	1.5
6	2.1	1.9	1.8
9	2.7	2.8	2.8
12	2.8	3.3	2.7
15	4.2	4.3	3.9
18	4.7	4.5	4.6
21	2.2	2.4	2.4
24	1.5	1.9	1.6

Kalman filter is better/equal than operational version and T2m correction algorithm

Kalman filter is better than operational version

T2m correction algorithm is better than operational version

Solokh Aul (443 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.4	1.2	1.2
6	2.6	2.5	2.3
9	2.8	2.6	2.4
12	3.0	2.8	3.0
15	3.6	3.5	3.6
18	3.8	3.7	4.0
21	1.7	1.6	1.7
24	1.6	1.4	1.5

Krasnaya Polyana (564 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.1	1.8	1.6
6	1.9	1.7	1.5
9	1.7	1.5	1.3
12	1.9	2.0	1.7
15	2.7	2.5	2.7
18	3.2	2.7	2.7
21	2.5	2.1	2.0
24	2.1	1.9	2.2

Kordon Laura (570 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.4	2.6	1.9
6	2.8	3.0	2.1
9	2.7	2.9	2.2
12	2.3	2.4	2.2
15	3.3	3.3	3.2
18	2.5	2.9	2.8
21	2.2	5.1	4.1
24	2.8	3.4	2.3

Gornaya Karusel (977 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.8	2.0	1.6
6	1.8	1.9	1.4
9	1.9	2.0	1.5
12	2.3	2.1	2.1
15	2.5	2.1	2.0
18	3.0	2.6	2.9
21	2.3	2.1	2.2
24	1.8	1.6	1.8

Gornaya Karusel (1434 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	1.5	1.5	1.4
6	1.5	1.5	1.3
9	2.1	2.1	2.2
12	2.1	2.1	2.3
15	2.5	2.5	2.4
18	3.0	2.9	3.4
21	1.7	1.7	1.8
24	1.4	1.4	1.8

Aibga (2225 m)

forecast. hour	RMSE oper	RMSE cor	RMSE KF
3	2.3	1.0	1.0
6	2.5	1.1	1.2
9	2.4	1.2	1.3
12	3.2	1.4	1.4
15	3.8	1.8	1.7
18	4.2	2.4	2.5
21	3.1	1.5	1.3
24	3.3	1.6	2.0

Figure 13: RMSE for T2m COSMO-Ru2 forecasts for stations in the Sochi region. Start 18 UTC. 1 March — 30 June 2014

According to Kalman filtering approach, most T2m picks during spring period in 2014 were predicted in a good correspondence with measurements (Fig.14).

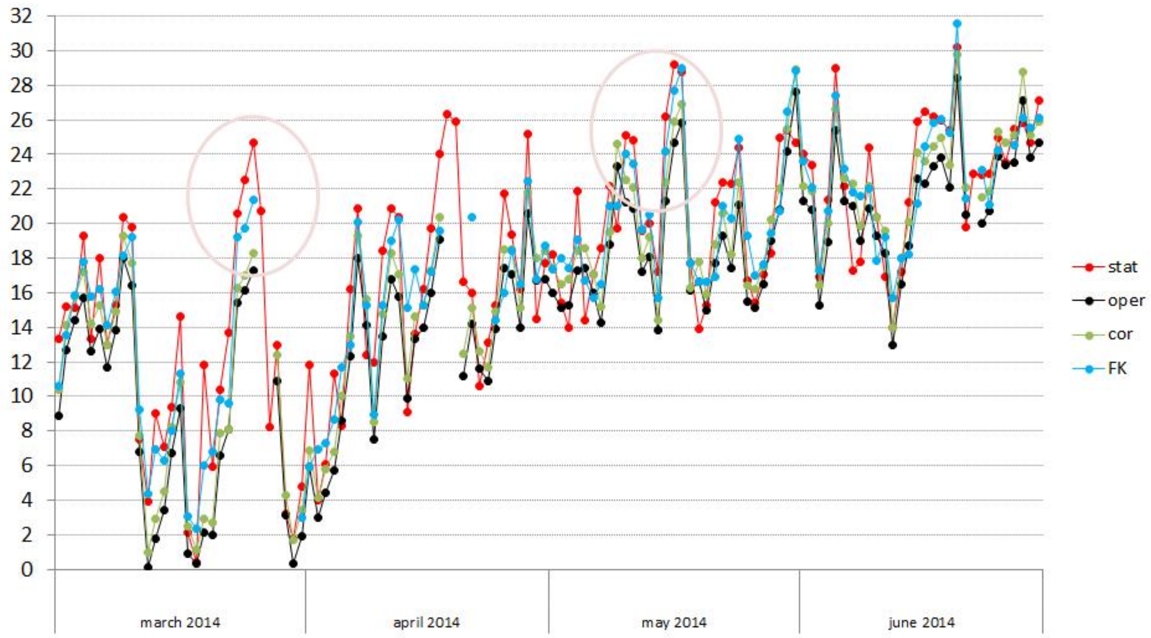


Figure 14: Example of T2m 12h forecasts by COSMO-Ru2 for station Krasnaya Polyana. Start 00 UTC. 1 March — 30 June 2014. Red line observations, black — operational forecast, green — T2m correction algorithm, blue — Kalman filtering

In future we plan to perform a series of experiments to develop the technology of using Kalman filtering in case of the partial absence of forecast data.

5.3 Fresh snow depth postprocessing example for COSMO-Ru-So *(E. Kazakova, M. Chumakov, I. Rozinkina)*

Model precipitation is considered to be a mass of water, which reached earth surface (taking into account its phase state) for given time period, i.e. accumulated water equivalent. According to WMO regulations, information about fallen precipitation is received from synoptic observational network in the same terms as the general-purpose weather forecasts are made.

Due to determined structure "data numerical forecast general-purpose weather forecast", in case of falling of solid or mixed precipitation, users (transportation, electricity supply networks, community facilities, organization of winter sports events, etc.) are not provided with greatly demanded information about depth of snow layer after snowfall which has already taken place or predicted.

As a rule, for fresh snow depth determination simple empirical dependences based on assumption of constant values of its density are used in operational synoptic practice. Use of more valid difficult dependencies should be provided on the basis of automated technology.

Snow depth measurements are held at hydrometeorological stations (HMS) and sent once a day through communication link to international exchange. Such a discreteness of measurements is not satisfactory for exact determination of snow depth in the train of snowfalls, since during this period of time snow cover could experience significant changes (snow could dense, melt, be blown by wind). In some regions there are automated meteorological stations (AMS), for example, in the Sochi region in Russia, which measure snow depth with high time discreteness (once in 10 minutes). Yet, as the practical usefulness of these measurements has been demonstrated, these data should have pass quality control because reliability of these data is very sensitive to accuracy of setting, operation conditions and regularity of technical service of AMS. Thus the information about snow from AMS can't always be directly used in operational practice.

The main goal of the project was to provide users of mesoscale forecasting system COSMO-Ru output with a new type of information snow increment for several hours. In order to achieve this goal a number of algorithmic and technological issues needed to be resolved.

Forming of suggestions and testing of algorithm for fresh snow density calculation (hence, its layer thickness) referred to algorithmic tasks, combination of calculation of this characteristic from existing elements of postprocessing of COSMO-Ru operational system to technology application. Additional task was analyzing a success of fresh snow depth calculation received from direct COSMO-Ru forecasts (with the proposed algorithm included into its postprocessing) versus direct snow observations at AMS and HMS of North-Caucasian region during the period of winter Olympic Games Sochi-2014. Technological aspects consist of combining the calculations according to the proposed module with operationally functioning postprocessing systems of COSMO-Ru.

While forming meteograms, fresh snow depth could be calculated on the basis of elements' values included in the table. The peculiarity of technological changes during present work was the fact that in the framework of preparation of meteorological support for Sochi-2014 at Hydrometcenter of Russia algorithm of model air temperature (2 meters) correction for mountain region based on moving amendments connected with differences between model and actual relief heights (for points for which meteograms are prepared) was proposed and implemented. Its obvious that when big differences occur, such a temperature amendment should be taken into account in calculations of fresh snow depth, especially at temperatures close to zero.

For output processing in grid nodes the program module of universal postprocessing Field-Extra was developed in COSMO consortium. One of the tasks of the present work was to adapt and implement the proposed algorithm of fresh snow depth calculation based on air temperature data in FieldExtra tool, which in future could allow providing users with calculated information in form of maps.

5.3.1 Description of fresh snow depth calculation algorithm and its testing

Calculation of fresh snow depth is based on the formulas which are used in the snow model SMFE (see COSMO Newsletter, Kazakova, Chumakov, Rozinkina, 2013). For fresh snow depth $h_{s,f}$ (mm) calculations of accumulated precipitation (observed or prognostic) p_s (mm) and fresh snow density $\rho_{s,f}$ (kg/m^3) are needed:

$h_{s,f} = \frac{p_s \cdot \rho_w}{\rho_{s,f}}$,

where $\rho_w = 1000\ kg/m^3$ - water density.

For testing of the proposed method it was checked against several assumptions:

- linear dependence on air temperature at 700 hPa from (McGurk, Azuma, Kattelmann, 1988);
- formula for fresh snow density calculation in TERRA of the COSMO-model, depending on temperature of the model lowest atmospheric level (Doms et al., 2011);

– constant density value equal to 100 kg/m^3, which is mostly used in synoptic practice while making weather forecast for conversion of precipitation sums into snow depth.

For quality assessment of unique observations of several snowfalls in January 2013 at the station Gornaya Karusel (1500 m) was conducted (Fig.15). As shown, the proposed fresh snow depth calculation method gives a good approximation to the values measured at the station, which happened to be more accurate in comparison with other algorithms. Thus, RMSE of fresh snow depth in case of the proposed method is 1.1 cm and MAE is 2.9 cm, while relative error is equal to 8.3 %. Linear dependence on T700 could be used only for a limited temperature range. As a rule, use of constant value of 100 kg/m^3 and formula from TERRA lead to fresh snow depth underestimation.

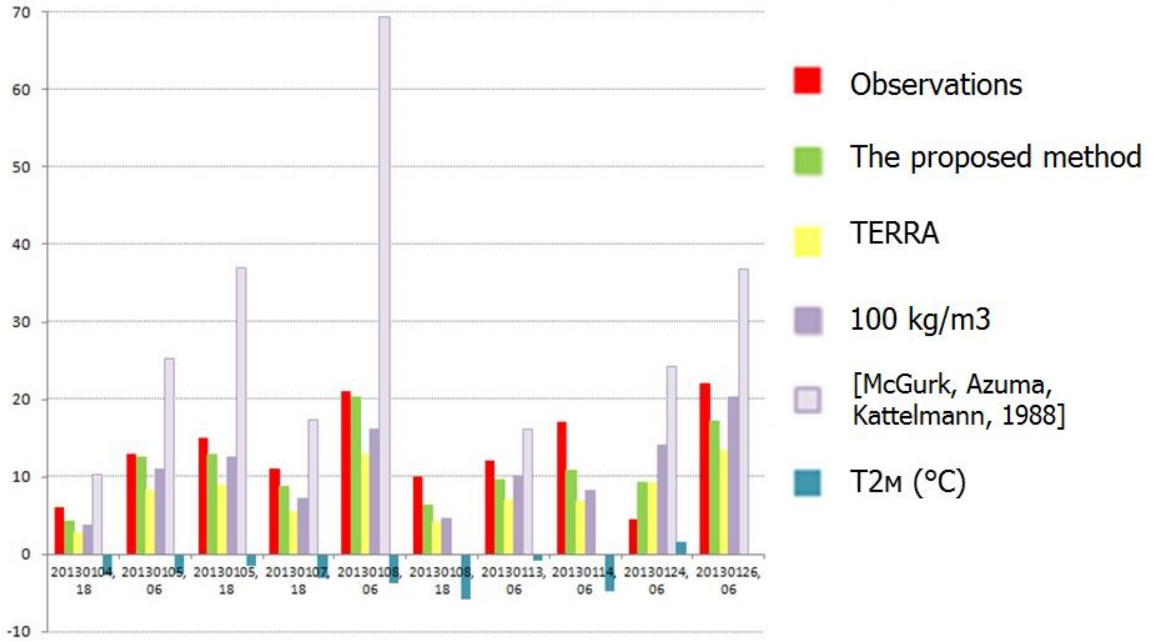


Figure 15: Fresh snow depth (cm) is coloured as: red observations at station Gornaya Karusel, light green results of proposed method using T2m (° C), yellow using formula from TERRA of the COSMO-model, violet under the assumption of the constant fresh snow density value of 100 kg/m^3, light violet according to linear dependency on T700. In blue T2m values (° C) are shown

From a network of observation stations and reports of road services in Moscow numerical experiments an assessment of the proposed method results in case of heavy snowfall in Central Russia at 3-4 February, 2013 was conducted. In particular, information of road services helped to take into account the increment of snow depth up to 25 cm, not recorded in the standard reports in SYNOP code. The latter indicated the snow depth growth only by 13 cm. Standard observations are done once a day, however, during this period snow had compacted. Calculated by COSMO-Ru7 prognostic values of accumulated snow were a little bit less than 12-hour observations (19.2 and 25.0 mm, respectively). According to the proposed method on the basis of observed 12-hour precipitation sums recalculation, fresh snow depth estimations of 25.2 cm were obtained (which corresponded the reports of road services). The research showed applicability of the method and its greater efficiency in case of using of accurate needed initial data of accumulated precipitation and air temperature when they were fallen.

5.3.2 COSMO-model fresh snow depth output

Prior to start of winter Olympic Games Sochi-2014, a prognostic maps of fresh snow depth were being produced since 3 February 2014 at Hydrometcenter of Russia on the basis of forecasts of accumulated precipitation provided by different versions of COSMO-Ru model with grid resolution of 7 km (COSMO-Ru7), 2.2 km (COSMO-Ru2) and 1.1 km (COSMO-Ru1). Maps were formed according to operational forecasts starting at 00, 06, 12 and 18 UTC.

Also values of fresh snow depth were recorded in meteograms for stations situated in North-Caucasian region. Prognostic values were calculated taking height-corrected air temperature into consideration.

The technological branch of fresh snow postprocessing and its output in the framework of COSMO-Ru system postprocessing are shown in Fig.16.

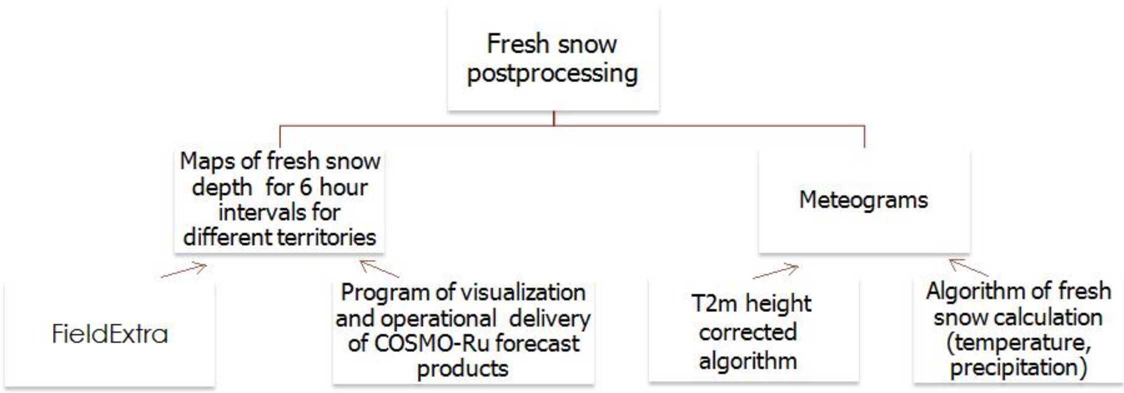


Figure 16: The scheme of fresh snow depth calculation at Hydrometcenter of Russia (based on mesoscale model COSMO-Ru)

Output in form of meteograms for stations and maps of fresh snow depth for 6-hour intervals prepared for versions COSMO-Ru7, COSMO-Ru2 and COSMO-Ru1 four times a day with the use of FieldExtra.

Fig.17 shows that there are significant differences in calculations using different COSMO-model versions.

The fact that relief detailing and its model heights for this region turned to be principle for precipitation phase prediction, large elevation and temperature extremes are observed. The relief is smoothed for coarser model resolution (COSMO-Ru7) and larger area with negative air temperatures occurred in comparison with more detailed modeling (COSMO-Ru2, COSMO-Ru1), where definition of relief led to more accurate description of extended valleys and relatively small highlands regions, for which snow falling was typical. In addition testing done in (Shatunova, Rivin, 2013) indicated to lower precipitation sums formed by COSMO-Ru1 in comparison with COSMO-Ru2.

5.3.3 Results of fresh snow depth calculation implemented into COSMO-Ru system postprocessing

Maps of fresh snow depth and meteograms were used for initial quality estimation of work of the proposed system as well as hourly measurements from AMS situated at different levels on the mountain resort Roza Khutor and daily measurements from three HMS (Aibga, Kordon Laura, Gornaya Karusel-1500) located in the region of winter Olympic Games Sochi-2014.

Complexity of testing realization was determined by several factors: firstly, snowfalls were observed only several times during winter season 2013/2014; secondly, model data could be compared with measurements only at some stations.

During winter Olympic Games Sochi-2014 there were three cases with significant snowfalls: 17-19 February, 21 February and 26-28 February. The main peculiarities in fresh snow depth reproduced by COSMO-Ru in the region of winter Olympic Games Sochi-2014 are described below.

Preliminary results demonstrated significant variability of snowfall forecasts for the same period started at different time and the latest forecast was not always the best in comparison with forecasts started before. Based on quite detailed analysis of time-distribution intensities inside snowfall period its turned out to be impossible to conclude which forecast with what lead time is more successful, and which forecast is more accurate: obtained by model versions with resolution of 2.2 km or 1.1 km. Yet in general the best agreement with snowfall measurements was observed in case of all realizations averaging.

Comparison with similar calculations found at website www.snow-forecast.com (www.snow-forecast.com) showed systematic underestimation of represented fresh snow values and results are more close to reality calculated by COSMO-Ru1 and COSMO-Ru2 systems. Example of analysis of one snowfall case according to observations at Roza Khutor is shown in table 6.

Table 6: Fresh snow depth (cm) according to observations at AMS Roza Khutor 4, forecasts from COSMO-Ru2 and COSMO-Ru1 and data from publically available website, produced by WRF model, www.snow-forecast.com. 18 February 2014

Observations	Forecast start (day hour)						Website data
	mean	17 00	17 06	17 12	17 18	18 00	
	COSMO-Ru2						
28.2	27.6	30.0	39.5	22.1	25.4	21.3	12.0
	COSMO-Ru1						
28.2	23.8	17.0	24.9	40.8	19.9	16.8	12.0

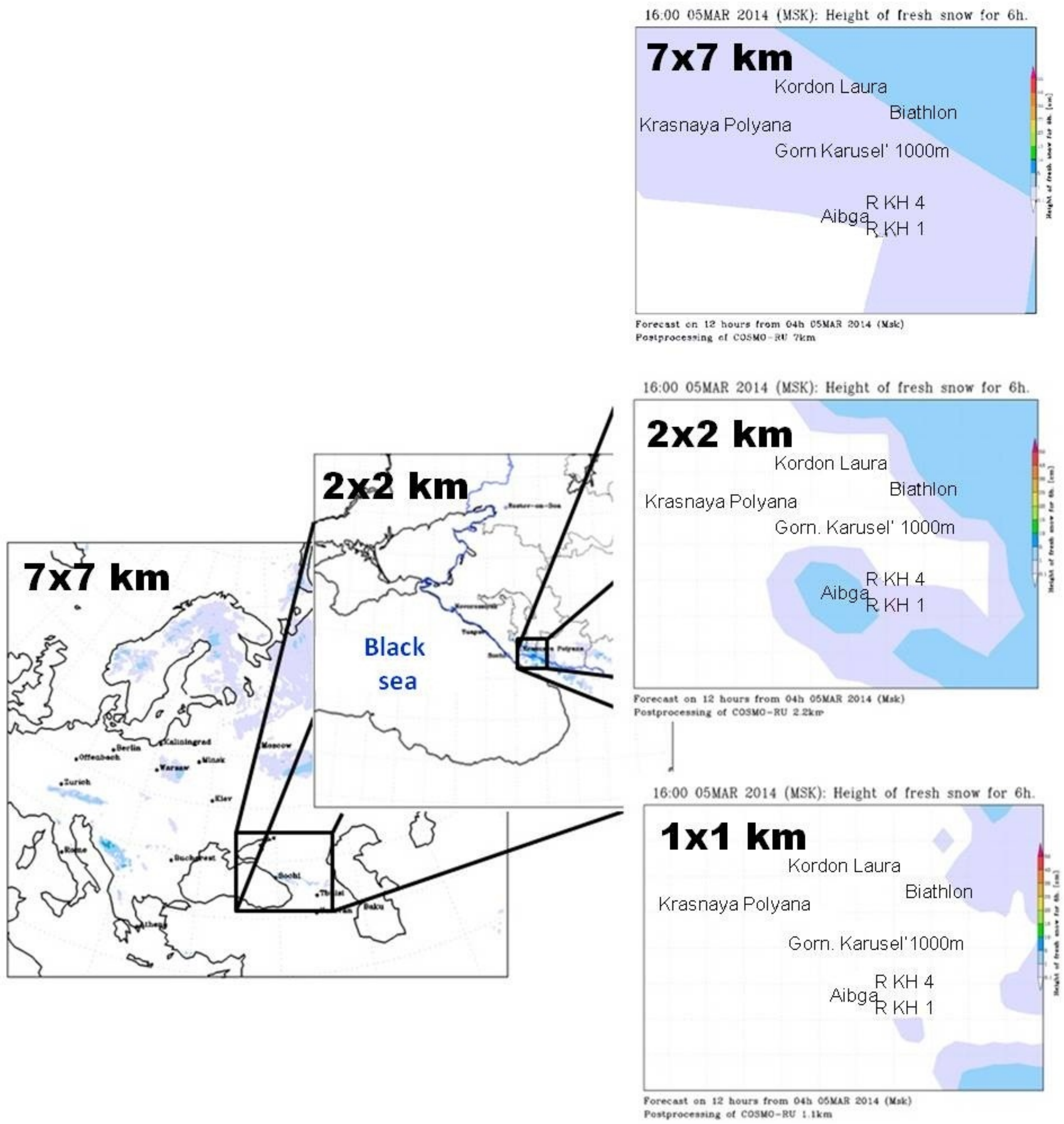


Figure 17: 12h-forecasts of fresh snow fallen for the last 6 hours according to COSMO-Ru7, COSMO-Ru2 and COSMO-Ru1. Start — 00 UTC 5 March 2014)

The proposed system gives more successful fresh snow depth forecast with account of height-corrected air temperature against the case of using air temperature received from standard version of COSMO-Ru model (the example is shown in Fig.11 (see Section 5.2.2 for station Aibga).

Maps of fresh snow depth can be created for any territory which coincides with the calculated grids of COSMO-Ru model versions (Fig.17). For example, it is true for the region, which include most part of the European territory of Russia. Meteograms containing fresh snow depth forecasts were prepared in January-March 2014 for North-Caucasian region for the purpose of specifying this meteorological element at points (stations). Analogous meteograms with fresh snow depth data can be obtained for stations located in other regions.

The testing showed that the developed system reproduces fresh snow depth quite realistically.

Note that COSMO-Ru provides the fact of precipitation falling in form of snow reliably, but quantitative estimations depend on forecast interval.

5.3.4 Conclusions

Thus, the system of prediction of fresh snow depth in the framework of COSMO-Ru post-processing is developed and realized at Hydrometcenter of Russia. The system includes preparation of fresh snow depth maps for 6-hour intervals four times a day according to model versions with the resolutions of 7, 2.2 and 1.1 km. Additionally, the fresh snow forecasts for stations are provided as meteodrams. Preliminary analysis of snowfalls occurred in North-Caucasian region in February 2014 showed that COSMO-Ru output connected with fresh snow characteristics could be used in weather forecasting. This output was used by weather forecasters in the framework of meteorological support of winter Olympic Games Sochi-2014, in particular for completion of daily bulletins and competitions planning.

5.4 Verification of COSMO forecasts for the Sochi-2014 region *(A. Bundel, A. Muravev, D. Blinov, A. Kirsanov)*

Verification of weather forecasts was one of the most important components of Sochi-2014 Winter Olympics and Paralympics meteorological support. The Sochi region has complex terrain with the Black Sea in close proximity. Information of high spatial and temporal resolution was required for competitions. These factors made more challenging both forecasting itself and verification and required development of new approaches.

5.4.1 Verification tools

Most of the scores were calculated in VERSUS (VERification System Unified Survey), an official COSMO verification tool. Several FROST online verification tools were used: FROST online monitoring of forecast quality only for stations, and FROST Point forecast and diagnostic data viewer. For some tasks, MET tool was used.

5.4.2 Verification problems

A dense observational network is needed for reliable verification. A number of automatic weather stations were installed in the regions of Games. However, their number was not sufficient for application of some verification methods. The stations are clustered. Even several 1-km grid points could be the nearest to certain station (Fig.18). For statistically reliable conclusions, long time series of data are necessary, while some models and verification tools became available just before the Games (for example, COSMO-Ru1 only at the end of January).

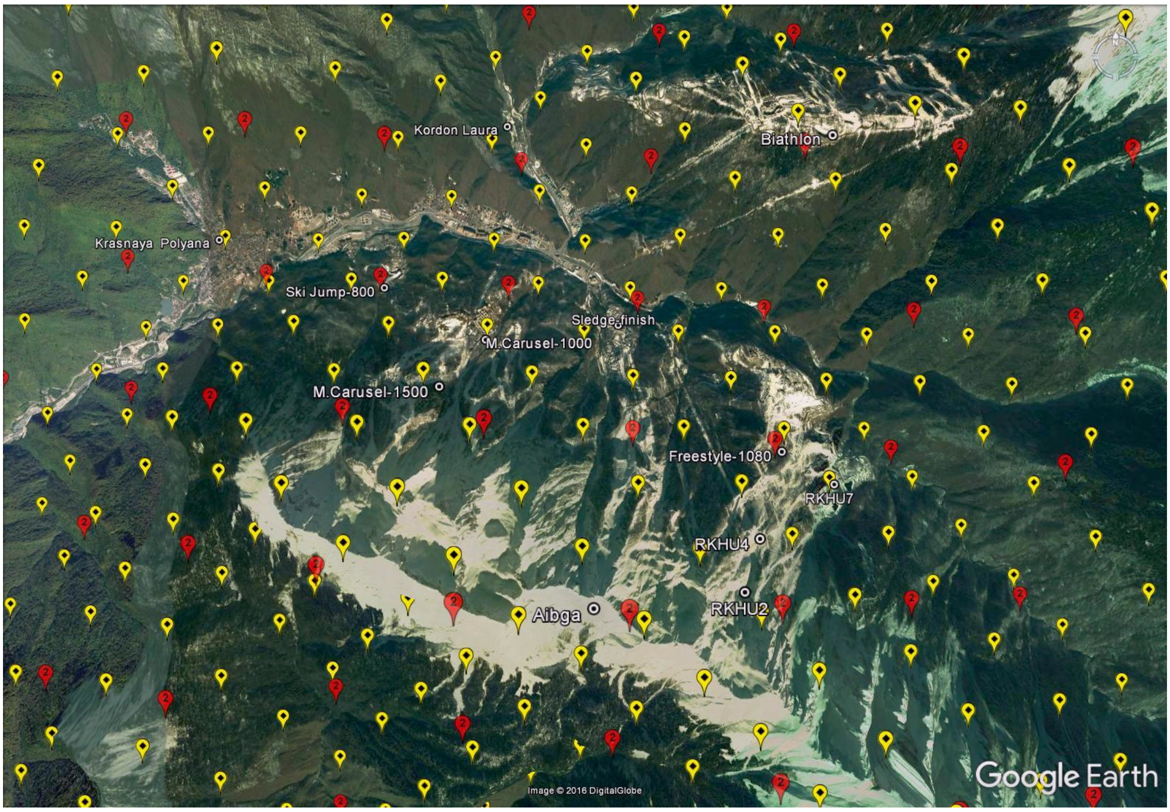


Figure 18: Nearest point approach: COSMO-RU2 (red lamps) and COSMO-Ru1 (yellow points) — models grid points and weather stations (superscripted)

5.4.3 Verification over the test periods and during the official evaluation period of the Games of 2014

Deterministic verification

Deterministic forecasts of COSMO-Ru7, COSMO-Ru2, COSMO-Ru1 systems were verified. The evaluation period was 15 January — 15 March, 2014. Various continuous and categorical metrics were applied to near-surface temperature, dew point temperature, relative humidity, wind speed, wind direction, wind gusts, and 3-hour accumulated precipitation.

Period of the Games was anomalously warm, the COSMO models, like most models providing forecasts for Sochi-2014, underestimated surface air temperature (in particular, during the daytime). The underestimation is more pronounced during the clear sky conditions compared to overcast ones. The likely cause of this behavior is insufficient soil warming in the sunny weather.

For the COSMO model family, the effect of resolution enhancement was especially notable for wind speed and gusts (Fig.19, Fig.20). COSMO-Ru7 is worse overall. T2m and dew point temperature were better in COSMO-RU2. Traditional scores aggregated over the Sochi region show overall prevalence of COSMO-Ru2 with relation to COSMO-Ru7 and COSMO-Ru1. However, some cases of intense precipitation and visibility were better predicted by COSMO-Ru1 during the period of Games. That coincides overall with subjective forecasters' opinion that among the five COSMO based models/ensembles, COSMO-Ru2 is perhaps the best.

The best precipitation forecasts were made during the late afternoon (16–19 h local time) according to the Pierce Skill score.

The spatial methods are needed to better analyze the effect of high resolution of precipitation (and some other variables, e.g., wind characteristics). These methods applied to the Sochi-2014 archive are explored within the relevant PP INSPECT tasks.

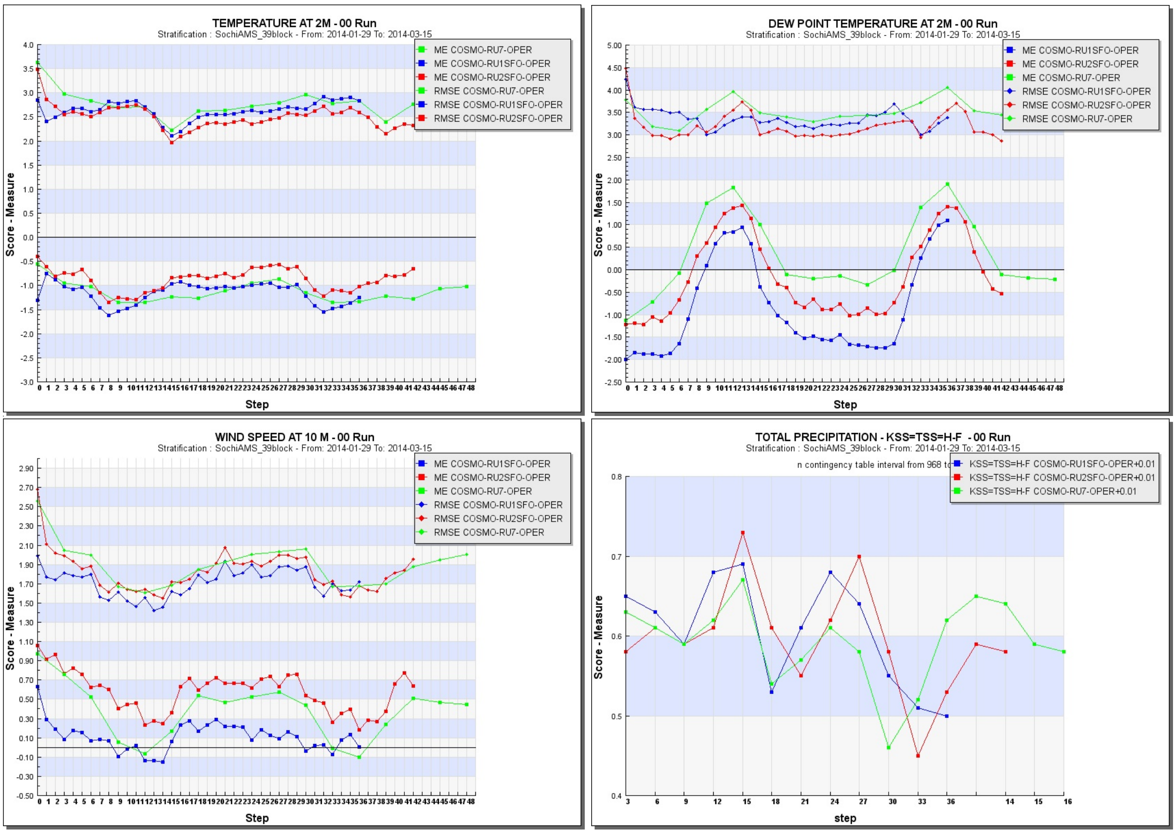


Figure 19: Scores for COSMO-Ru1, COSMO-Ru2, and COSMO-Ru7, 29 Jan–15 March 2014

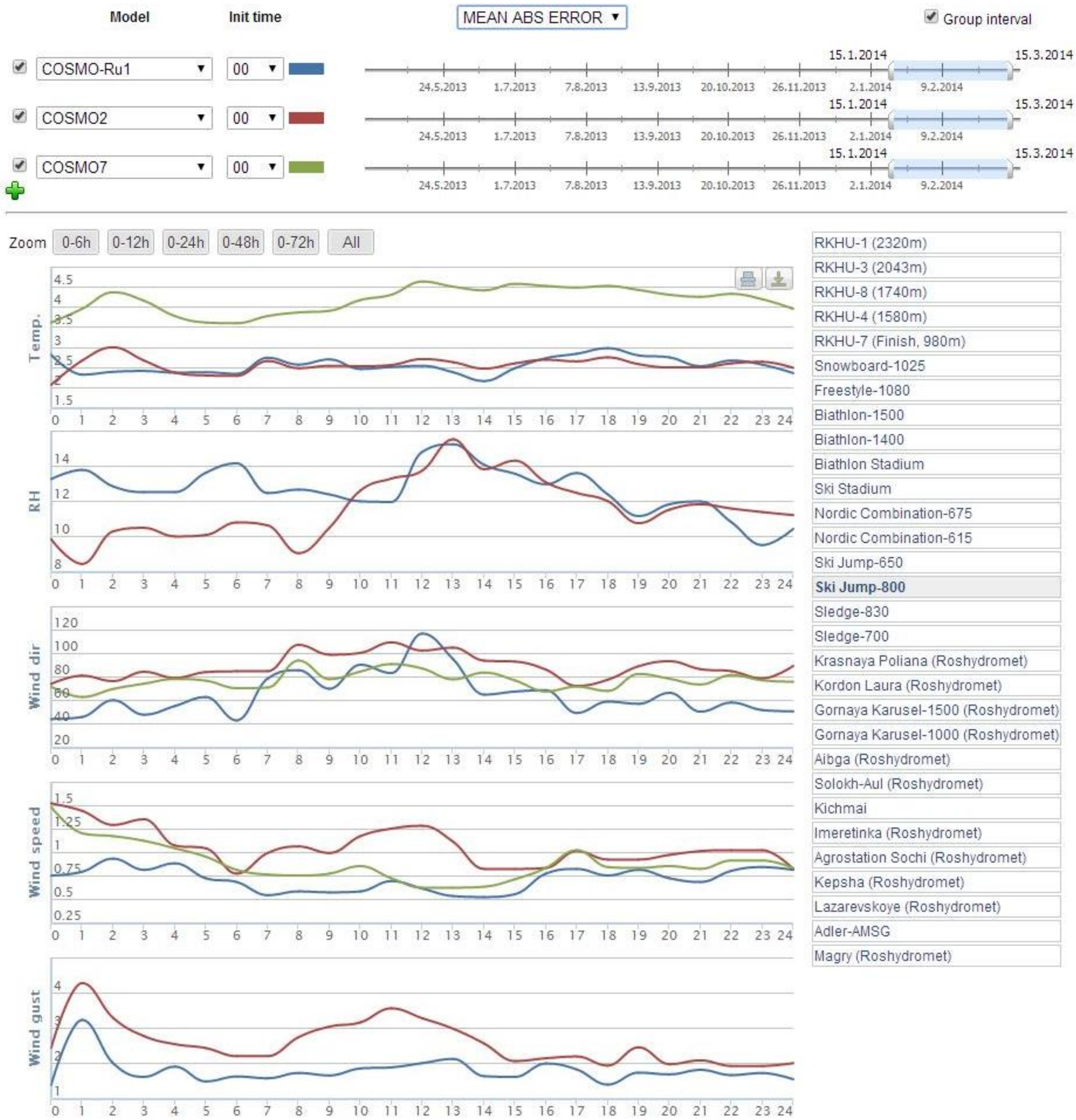


Figure 20: Effect of resolution, COSMO-Ru1, COSMO-Ru2, and COSMO-Ru7, 15 Jan–15 Mar 2014. Ski Jump-800 station

The dependence of COSMO forecast skill on the driving model (either ECMWF-IFS or DWD-GME) was found limited (study of Andrea Montani).

Analysis of test periods

Thorough verification of past seasons is important for the development of models and new methods. Analysis of COSMO-Ru performance during the previous test seasons revealed that the model bias could change its sign from one cold season to another depending on the prevailing weather regimes (Fig.21). It is still unclear, is it due to 2013 warm anomaly, or observation data distribution, amount, and quality? Therefore, it was found difficult to make model calibration.

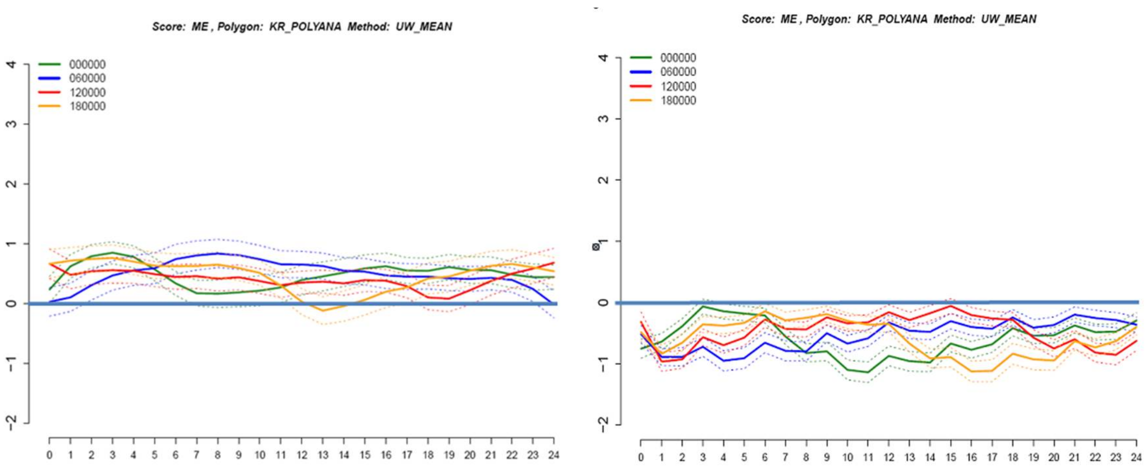


Figure 21: COSMO2Ru T2m mean error during the first test period (winter 2012–2013) (left panel) and the second test period (Jan–Feb 2014) (right panel) (all initial times) at Krasnaya Polyana station

Diagnostic verification

"It is advisable in verification projects to examine the data before computing the scores. This can be done by means of scatter plots and quantile-quantile plots, or, for categorical data, by histograms" (Recommendations of **"Suggested methods for the verification of precipitation forecasts against high resolution limited area observations"** by the JWGFVR for the WGNE (Laurie Wilson, Beth Ebert et al.)

A station-based diagnostic verification tool for thorough diagnostic analysis was created for the Sochi-2014 project. It is "diagnostic"in the sense that it focuses on the fundamental characteristics of the forecasts, the corresponding observations, and their relationships (A. Murphy, B. Brown, Y. Chen, 1989). Figure 22 shows an example of diagnostic verification plots. On the right-hand bottom plot, the red lines denote maximum, mean, and minimum observed value for each forecast bin. Green lines denote 75, 50, and 25 % quantiles for the bin sample volume of no less than 10 pairs (sample stability). Such plots were made for each variable, station, lead time, and method. They show the forecast errors in the whole variable range including the distribution tails, that is, extreme values important for decision making about the competitions; show the sample size in different categories and outliers. The interquantile range values are inversely related to forecast accuracy.

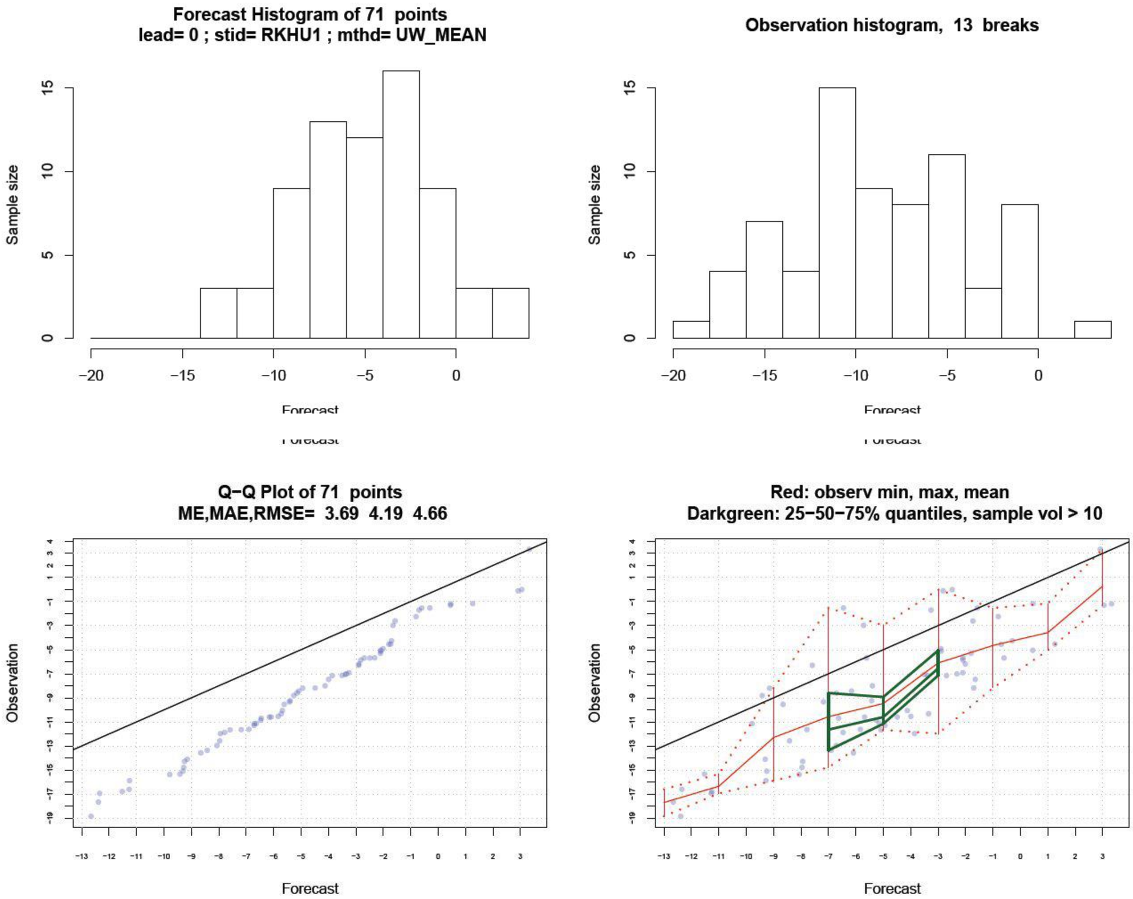


Figure 22: An example of diagnostic verification plots

High Impact Weather (HIW) verification

HIW definitions can be prescribed by value thresholds given by authorities or statistically determined by extreme values or distribution tail statistics.

Traditional scores become insensitive to changes in accuracy for low base rates (rare events) (base rate is the frequency of occurrence of the event in the verification sample). For example, the PSS becomes 0 with the base rate diminishing. There is increasing uncertainty about the quality (sample effect, jumping score values) *(J.Jolliffe, D.Stephenson)*. It was shown (Ferro and Stephenson 2011) that the extremal dependency index (EDI) and symmetric extremal dependency index (SEDI) are insensitive to base rate; they also are both formulated to use the hit rate (H) and false alarm rate (F) only, which links these scores to the Pierce Skill score (H-F) and the ROC curve frequently used in verification of probability forecasts.

$EDI = (logF - logH)/(logF + logH)$

The EDI is especially recommended for low base-rate thresholds, but it will give a good comparative estimate of accuracy for all thresholds. These scores were applied to the Sochi-2014 data. The dependence of EDI, PSS, and base rate on precipitation threshold is shown in Fig.23.

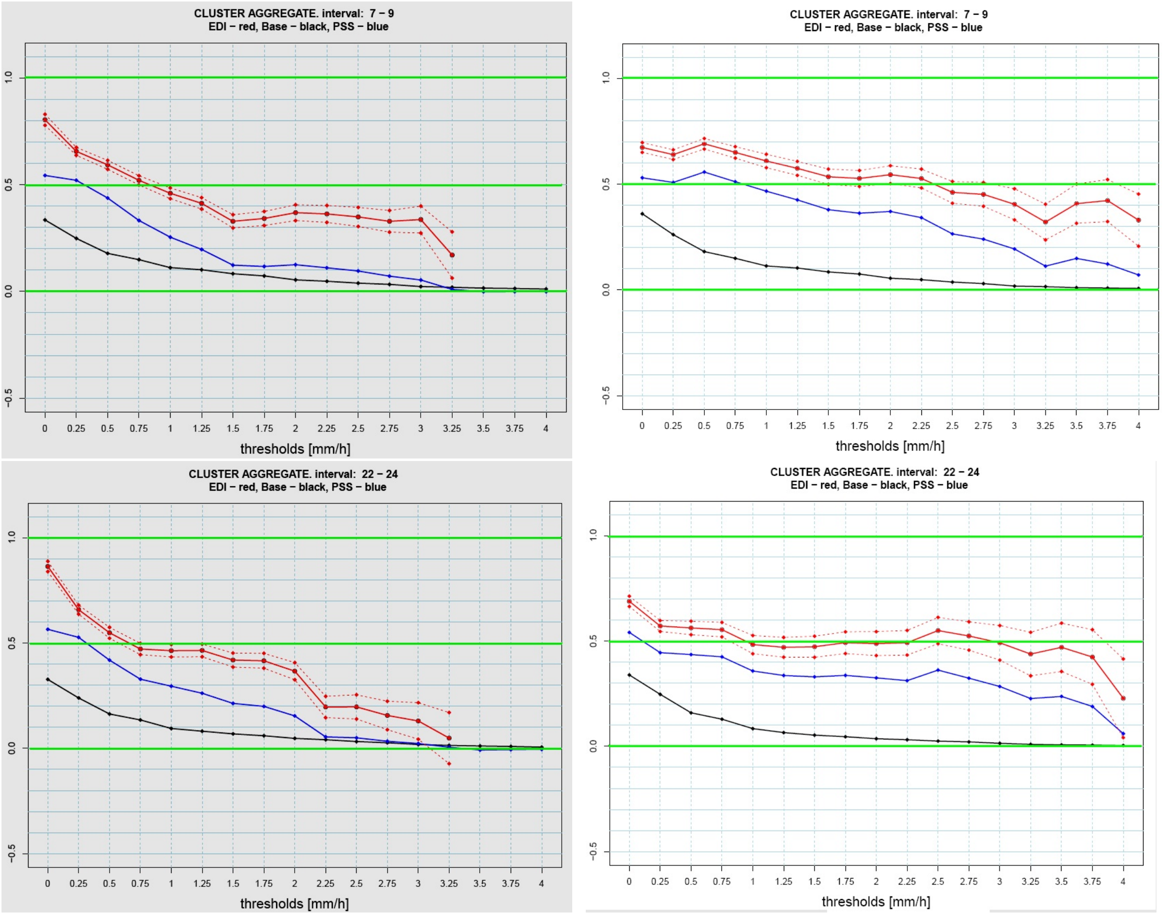


Figure 23: EDI (red), PSS (blue), and base rate (black) for COSMO-Ru2 (left panel, shaded) and NMMB (right panel) 3h precipitation, nearest point, Jan–March 2013, Mountain cluster

Figure 23 shows that:

- There are 10 % of events higher than 1 mm and 5 % , higher than 2 mm;
- $EDI > PSS$ (Pierce Skill Score);
- COSMO predicts better precipitation fact, NMMB predicts better more intense precipitation.

The similar graphs were made for temperature and wind speed.

The study on EDI application showed that:

- EDI is appropriate but not universally applicable (failure with wind speed);
- EDI does not always converge, often it reflects a combination of model, observation and sampling errors;
- EDI is generally not monotonic with relation to PSS (Fig.24);
- EDI is always greater than PSS for positive PSS (Fig.25).

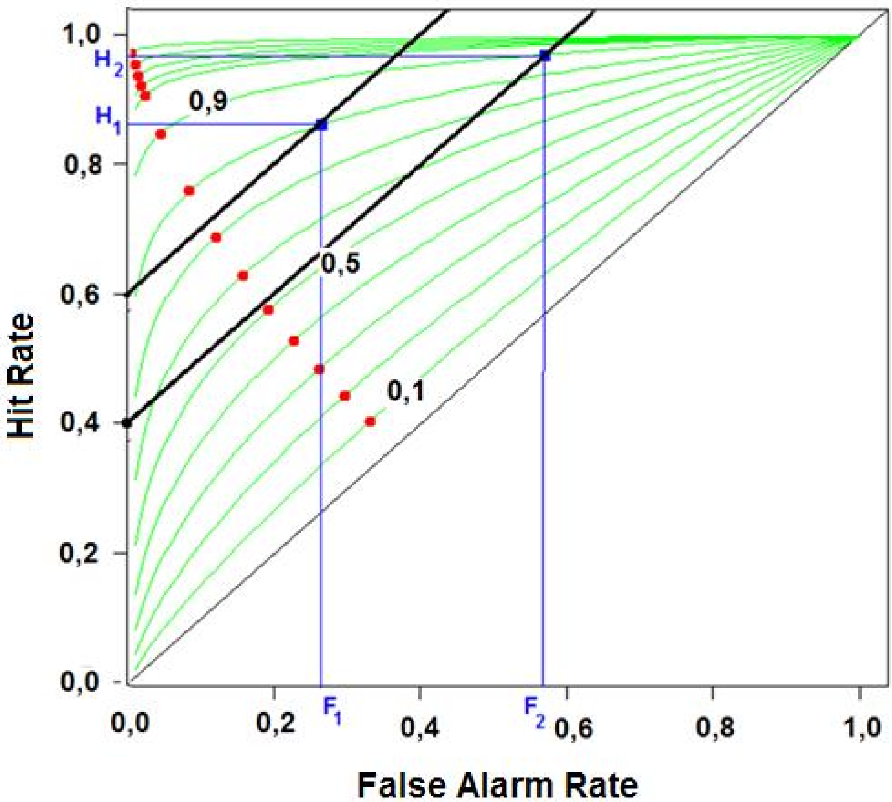


Figure 24: EDI (green) and PSS (black) isopleths; EDI for 0.1 – 0.9 and 0.95 – 0.99 with intervals 0.1 and 0.01; $PSS = H - F$ for 0.4 and 0.6 values; $H = F$ diagonal corresponds to $EDI = PSS = 0.$; Red points: EDI curves tangent to straight PSS lines (strict formulas). Blue squares at (F,H): the monotonic EDI and PSS relation breaks down: Nonlinear dependence — not STRICTLY monotonic: for $(F1, H1)$ and $(F2, H2)$ $PSS1 > PSS2$, but $EDI1 < EDI2$

Figure 25: Relation between EDI minimum value and PSS

5.4.4 Conclusions and prospect for the future

- Nearest point approach in the complex terrain
- Different seasons and model changes calibration difficulties
- Weather dependent verification much effort, but it turned out difficult to give exact instructions to forecasters because of insufficient data and calibration difficulties
- More Conditional verifications are needed

The spatial methods are needed to better analyze the effect of high resolution of precipitation (and some other variables, e.g., wind characteristics). These methods applied to the Sochi-2014 archive are explored within the relevant PP INSPECT tasks.

Overall, the findings of objective verification agree with subjective opinion of Sochi forecasters.

6 Development and adaptation of COSMO EPSs for the Sochi region *(D. Alferov, E. Astakhova, C. Marsigli, A. Montani, T. Paccagnella, G. Rivin, A. Shcherbakov)*

The Sochi region belongs to the moderately humid subtropical zone and is influenced by the non-freezing Black Sea and by the spurs of the Main Caucasus Range. The necessity of weather forecasting at Olympic venues located both in the coast and in the mountains, quite steep and intersected by multiple shallow canyons, made meteorological support of the Sochi-2014 Olympics rather complicated effort. A state-of-the-art approach to mountain weather forecasting implies the application of high-resolution modeling, nowcasting and ensemble technologies. Reasoning from this, the ensemble component was included to the CORSO project as task 3.

The goal of task 3 was to demonstrate the capabilities of ensemble systems in numerical weather prediction in a mountainous region with complex orography and to assess the effect of practical use of ensemble products during Sochi-2014 Olympic Games. To achieve this goal, two activities were planned:

- adaptation of COSMO-LEPS 7 km to the Sochi region and to specific requirements of winter Olympics; operational ensemble forecasts during the Olympics;
- development and verification of a convective-resolving EPS for the Sochi region (with ICs and BCs from the 7-km EPS).

As a result, the two ensemble prediction systems based on COSMO model were developed: COSMO-S14-EPS with a 7-km resolution (a relocation of COSMO-LEPS to the Sochi region) and COSMO-Ru2-EPS with a 2.2 km resolution (nested to COSMO-S14-EPS). Both systems ran in operational mode during the Olympics; the probabilistic products were regularly delivered to Sochi forecasters. Analysis of regular runs, their application, and case studies demonstrated that ensembles gave a valuable support to forecasters and the higher-resolution ensemble gave more detailed and precise forecasts.

The following sections give the description of the systems, survey their application during the Olympics and present the analysis of EPS performance.

6.1 Ensemble prediction system with a 7-km resolution

A system with a 7-km grid size named COSMO-S14-EPS (S14 stands for Sochi-2014) was created at ARPA-SIMC (Montani et al., 2013, 2014) and is a version of the COSMO-LEPS system displaced from the European area to the Sochi region. COSMO-LEPS has been operationally running for more than 10 years and demonstrated good results, in particular, for regions with complex orography (Marsigli et al, 2003; Montani et al., 2011).

Methods and approaches used in COSMO-LEPS and COSMO-S14-EPS are similar. The boundary and initial conditions came from the global ensemble system of the European Centre for Medium Range Forecasting (ECMWF-EPS, (Molteni et al, 1996)). The facts that the horizontal resolution should be higher in limited-area forecasts and the time for preparing operational forecasts should be minimal combined with usually limited computer resources lead to the necessity to reduce the ensemble size. It was done by selecting the most representative prognostic realizations of the global ECMWF-EPS via clustering (48-72 hour forecasts of geopotential, wind components, and humidity at 500, 700, and 850 hPa were considered) (Molteni et al, 2001; Montani et al, 2013). The prognostic realizations of the global EPS chosen by this procedure were then interpolated to the grid of the mesoscale model COSMO (see http://www.cosmo-model.org) and served as initial and boundary conditions for limited-area forecasts. No additional regional perturbations were introduced. The most essential differences between the COSMO-S14-EPS and COSMO-LEPS systems were integration domains (the Sochi region or Europe) and ensemble sizes (10 or 16 members, respectively).

The lower boundary condition for all COSMO-S14-EPS members was taken from COSMO model runs in hindcast mode (short-range forecast nested on ECMWF analyses).

The model-related uncertainty was taken into account in COSMO-S14-EPS by using two different convection parameterization schemes (Tiedtke or Kain-Fritsch, random choice) in different members and also by varying tuning coefficients in parameterizations of sub-grid scale processes (in particular, turbulent).

The main characteristics of COSMO-S14-EPS are summarized in Table 7, which also reports some details relative to the global ensemble ECMWF-EPS.

Table 7: Main features of the present implementations of ECMWF-EPS, COSMO-S14-EPS, and COSMO-Ru2-EPS

	ECMWF-EPS	COSMO-S14-EPS	COSMO-Ru2-EPS
Hor. res. Vert. res.	$\sim 31\ km$ 62 ML	7 km 40 ML	2.2 km 50 ML
Forecast length	240h	72h	48h
Ensemble size	50+1	10	10
Initial time	00/12 UTC	00/12 UTC	00/12 UTC
Convection	Parameterized	Parameterized	Resolved
Running at	ECMWF	ECMWF	Roshydromet
ICs and BCs	SV ini pert + EDA	from selected ECMWF-EPS members	from COSMO-S14-EPS members
Model perturbations	Stochastic physical tendencies + backscatter	Physical parameterizations	

COSMO-S14-EPS was implemented on ECMWF supercomputers in November 2011 and ran on a regular basis from 19 December 2011 till mid-May 2014 thanks to the billing units provided by the ECMWF Special Project SPCOFROST.

6.2 Ensemble prediction system with a 2.2-km resolution

The experience of projects initiated by WWRP before the Olympic Games in Beijing in 2008 and Vancouver in 2010 (B08RDP and SNOW-V10) (Duan Y. et al, 2012; Isaac G. A., 2012), as well as of the MAP D-PHASE project (Rotach M. W. et al, 2009) demonstrated that good descriptions of meteorological processes and forecasts of severe events in the regions with complex mountainous relief can be achieved only with high-resolution models (with resolution not coarser than 2–3 km). This is because of more accurate orography data used in such models, fine resolution enabling to simulate local events, and switched off convective parameterization. It is worth to note that development of convection-permitting ensemble prediction systems (with a grid size of 2–3 km) is in the mainstream now.

The ensemble prediction system COSMO-Ru2-EPS was created as a research tool and is based on the COSMO-Ru2 model version (Rivin et al, 2015) with a resolution of 2.2 km. The initial and boundary conditions were interpolated from COSMO-S14-EPS forecasts. The boundary conditions were refreshed every hour.

COSMO-Ru2-EPS and COSMO-S14-EPS had the same ensemble size. No additional model perturbations were introduced. Thus, COSMO-Ru2-EPS performed a dynamical downscaling of COSMO-S14-EPS increasing the forecast resolution both in horizontal (from 7 to 2.2 km) and in vertical (from 40 to 50 levels). The COSMO-Ru2-EPS system was implemented on a Roshydromet computer SGI Altix 4700.

The main features of COSMO-Ru2-EPS are summarized in Table 7 along with the features of ECMWF-EPS and COSMO-S14-EPS. The organization of COSMO-based ensemble forecasting for the Sochi region is sketched in Fig.26.

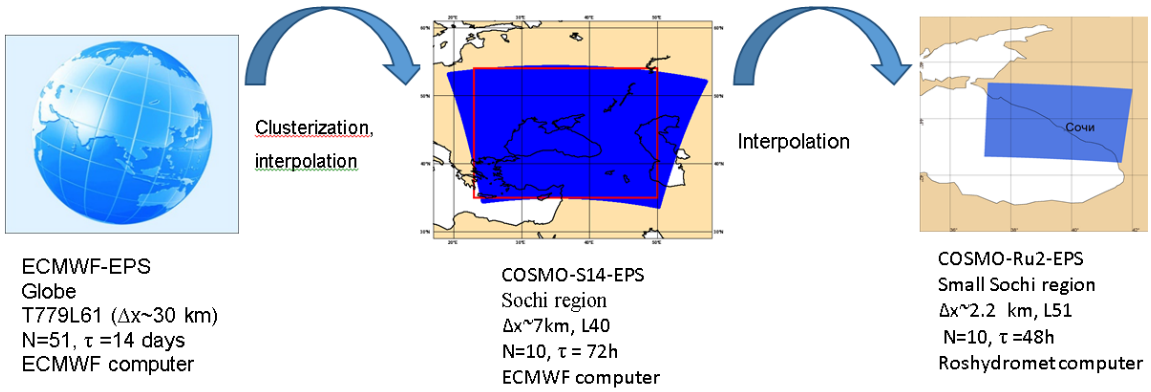


Figure 26: Organization of COSMO ensemble forecasting for the Sochi region. N is the ensemble size, τ is the forecast length, and L is the number of vertical levels

Figure 27 reports the orography for three systems of Table 7 and is meant to indicate the potential impact of increased horizontal resolution in the description of orographic and mesoscale-related processes.

The ECMWF-EPS orography (top-left panel) shows almost no evidence of the valley running for about 40 kilometres from Sochi-Adler, the coastal cluster of the winter Olympics 2014, where ice-sport competitions took place, towards Krasnaya Polyana, located in the mountain Olympic cluster where snow-sport competitions were held. COSMO-S14-EPS (top-right panel of Fig.27) already offers a better description of the complex topography of the area, although it has to be pointed out that only with the 2.2 km grid-size of COSMO-RU2-EPS (bottom panel) some important details of the geography (e.g. the eastward turn of the valley after Krasnaya Polyana) can emerge.

6.3 Providing ensemble forecasts for the Sochi Olympics and preceding trial competition

The COSMO-S14-EPS products were accessed by the Hydrometcenter of Russia since the end of 2011. These mesoscale ensemble forecasts for the Sochi region were the first for Russian forecasters. During the following three pre-Olympic years all technology problems were solved (in particular, the earlier time of forecast accessibility was achieved) and tools for presenting the COSMO-S14-EPS probabilistic information were developed. The most important was that forecasters got a valuable experience of working with this information. Therefore, it is not surprising that COSMO-S14-EPS probabilistic forecasts were most widely applied among all ensemble forecasts prepared within the FROST-2014 project (the blended RDP/FDP project devoted to the Olympics 2014) and available to forecasters during the Olympic Games in Sochi.

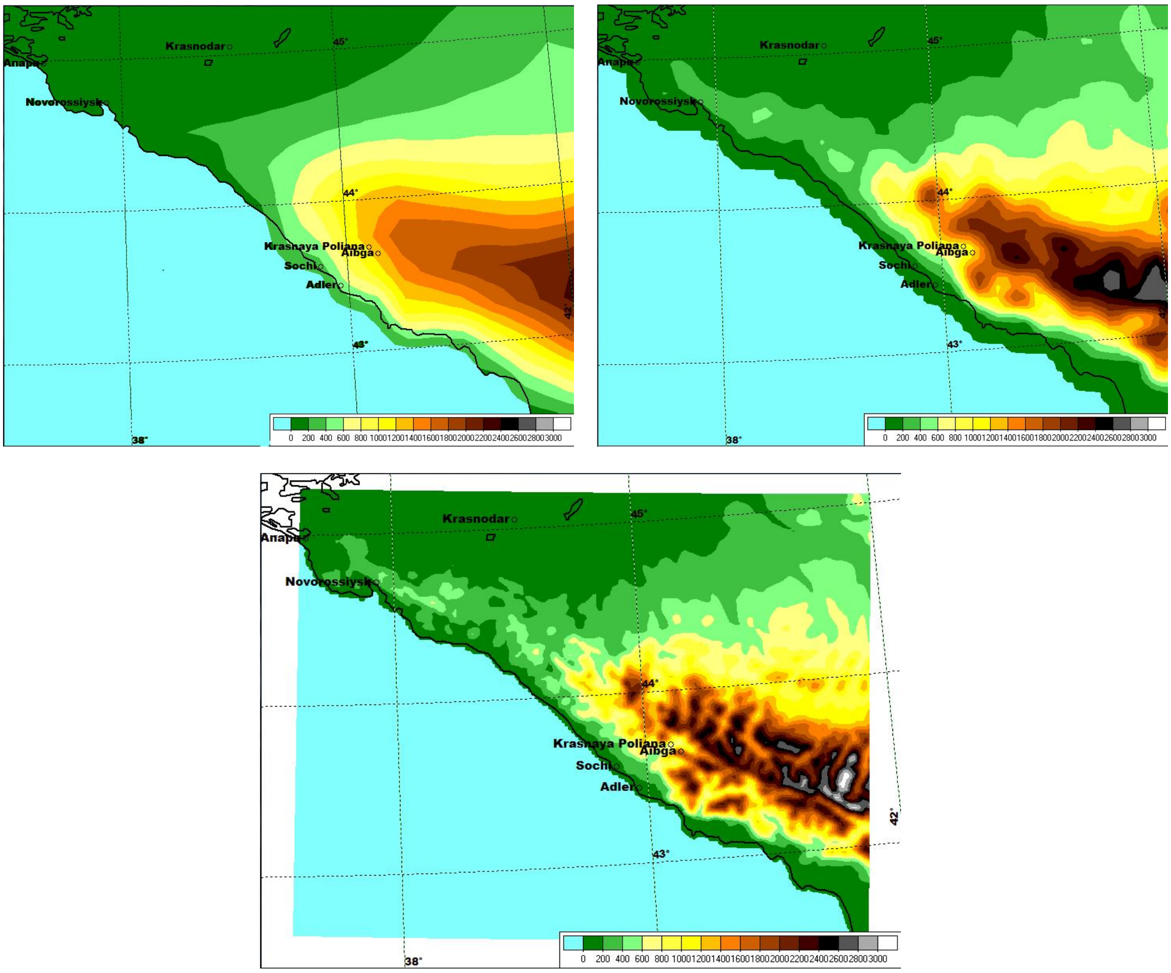


Figure 27: Model orography (in m) for ECMWF-EPS ($\Delta x = 31\ km$, top-left panel), COSMO-S14-EPS ($\Delta x = 7\ km$, top-right panel) and COSMO-RU2-EPS ($\Delta x = 2.2\ km$, bottom panel) in the Olympic region

COSMO-S14-EPS generated a set of standard probabilistic products, including probability of surpassing a threshold, ensemble mean and ensemble standard deviation for several surface and upper-air variables. These products were delivered in real time to the Hydrometcenter of Russia (Roshydromet), further disseminated to Sochi forecasters and presented at the FROST-2014 Web-site (http://frost2014.meteoinfo.ru, authorization required)). In addition to this, all forecast members for a specially defined area were transferred to Roshydromet where the epsgrams for predetermined points were prepared (see http://frost2014.meteoinfo.ru/forecast/arpa-new). Generation of different types of non-graphical products made use of Fieldextra, the official COSMO post-processing software (for information about Fieldextra, please refer to http://www.cosmo-model.org). The graphical products were prepared using the GRADS package.

In addition to the ensemble products, initial and hourly-boundary conditions (up to t+48h) were provided to Roshydromet for the experimentation with the convection-resolving ensemble COSMO-Ru2-EPS (see below). Some examples of COSMO-S14-EPS products provided to Sochi forecasters during the Olympics are presented in figs.28 and 29. (Note that initially the system was named COSMO-FROST-EPS and this title was kept in the operational plots to avoid confusion).

In addition to the ensemble products, initial and hourly-boundary conditions (up to t+48h) were provided to Roshydromet for the experimentation with the convection-resolving ensemble COSMO-Ru2-EPS.

First it was not planned to use COSMO-Ru2-EPS for the meteorological support of the Olympics. However, the analysis of COSMO-Ru2-EPS skill during the winter of 2012/13 demonstrated the usefulness of the system and confirmed that the high resolution enables more detailed information (without loss of quality) to be achieved about the future state of the atmosphere. Thus it was decided to run COSMO-Ru2-EPS operationally in winter-spring 2014 and disseminate the prognostic results to the Olympic forecasters. COSMO-Ru2-EPS ensemble meteograms and plume diagrams were regularly posted at the FROST-2014 site and refreshed twice a day. A 2m temperature was corrected for the difference between the heights of model gridpoints and the real heights of the stations using the prognostic temperature lapse rate (see the description of CORSO task 2 for more details).

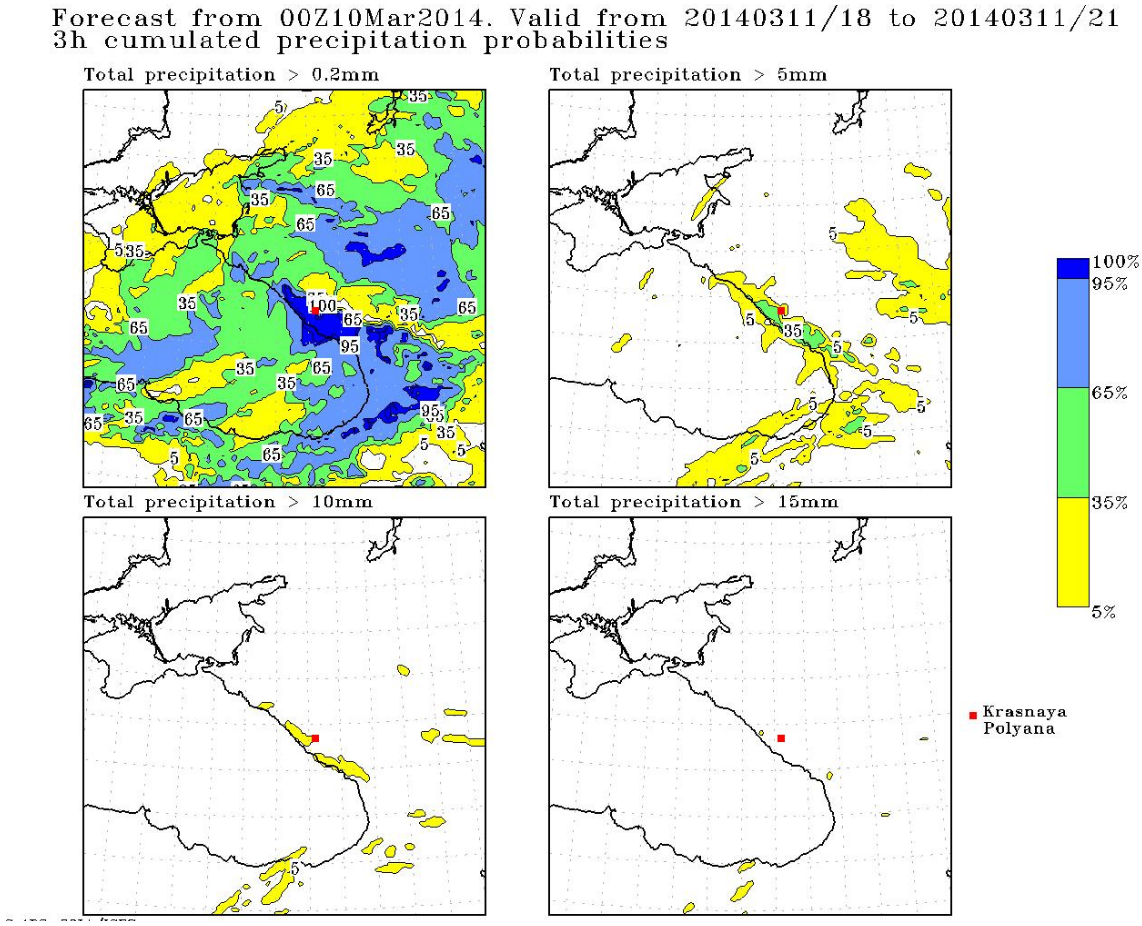


Figure 28: An example of COSMO-S14-EPS products operationally provided to the Olympic forecasters: probabilities of the events "3-h cumulated precipitation is more than 0.2 (upper left panel), 5 (upper right panel), 10 (lower left panel), and 15 mm (lower right panel)". COSMO-S14-EPS 45-h forecast starting from 10 March 2014, 00 UTC. A red square indicates the location of Krasnaya Polyana

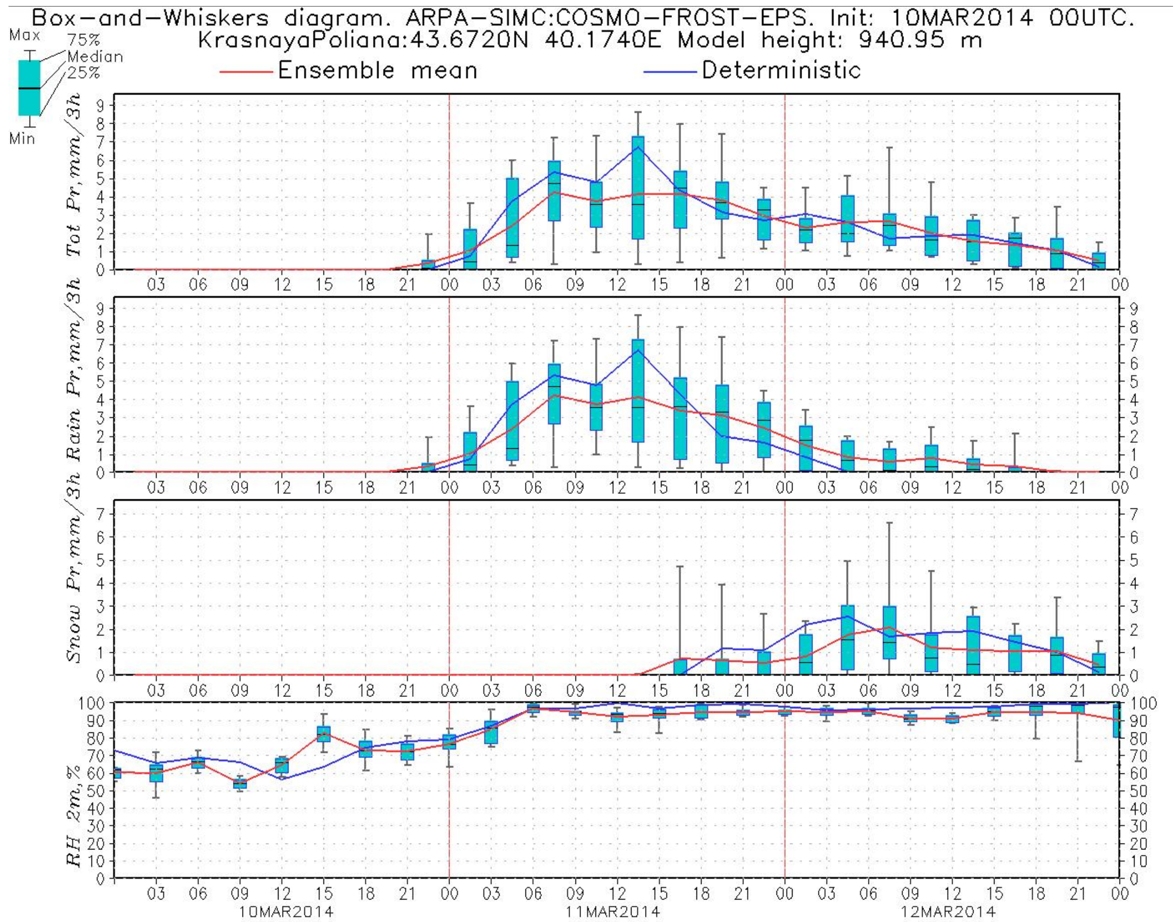


Figure 29: An example of COSMO-S14-EPS products operationally provided to the Olympic forecasters: the ensemble meteograms for total precipitation, rain, snow, and 2-m relative humidity for the Krasnaya Polyana station

6.4 Skill of ensemble forecasts *(E. Astakhova, A. Bundel, A. Muravev)*

The skill of the ensemble systems developed was analyzed step by step in several ways. First, the skill of COSMO-S14-EPS was compared to that of the driving ECMWF-EPS system and it was demonstrated that the mesoscale EPS outperforms the global system. Then several case studies with mesoscale EPSs of both resolutions were made showing the correct representation of near-surface temperature and precipitation patterns including the precipitation phase. Finally, probabilistic verification scores were calculated for month or longer periods. The details are given hereafter.

6.4.1 Verification of COSMO-S14-EPS compared to ECMWF-EPS

The skill of the mesoscale ensemble COSMO-S14-EPS was assessed over the period JanuaryMarch 2012 and compared to that of ECMWF EPS. For both systems, the probabilistic prediction of 12hour accumulated precipitation exceeding a number of thresholds for several forecast ranges was considered. Only forecasts starting at 12 UTC were examined.

As for observations, it was decided to use the data obtained from the SYNOP reports available on the Global Telecommunication System (GTS), since this was recognized to be a homogeneous and stable dataset throughout the verification period. In order to quantify the skill of the system over complex topography, the verification was performed over the domain 40N50N, 35E45E. Within this domain, a xed list of 60 SYNOP stations was considered and the relative reports in terms of total precipitation were used to evaluate the COSMOS14EPS and ECMWF-EPS skill.

As for the comparison of model forecasts against SYNOP reports, the gridpoint closest to the observation was selected. Little sensitivity to the results was found when, instead of the nearest gridpoint, a bi-linear interpolation using the 4 nearest points to the station location, was used to generate the model forecasts. Therefore, the results shown hereafter will be relative only to the nearest gridpoint method. The performance of both systems was examined for 6 different thresholds: 1, 5, 10, 15, 25, and 50 mm/12 h.

The following probabilistic scores were computed over the verication period: the Brier Skill Score (BSS), the Ranked Probability Skill Score (RPSS), the Relative Operating Characteristic Curve (ROC) area and the Percentage of Outliers (OUTL). For a description of these scores, the reader is referred to Wilks (1995) and to Marsigli et al. (2008). The main features of the verification exercise are summarized in Table 8.

Table 8: Main features of the verification configuration

variable	12hour accumulated precipitation (18-06, 06-18 UTC)
period	from 1 January to 31 March 2012
region	40-50N, 35E-45E
method	nearest grid-point
observations	SYNOP reports
fcst ranges (h)	6-18, 18-30, 30-42, 42-54, 54-66
thresholds	1, 5, 10, 15, 25, 50 mm/12h
scores	ROC area, BSS, RPSS, OUTL

The skill of the two systems in terms of prediction of 12hour accumulated precipitation is summarized in Fig.30, where the Ranked Probability Skill Score (RPSS) is plotted against the forecast range for both COSMOS14EPS and ECMWF EPS. It can be noticed that COSMO-S14EPS has higher RPSS for all forecast ranges. The difference between the two systems is consistent throughout the full forecast range, with a larger gap for the first day of integration. This implies that, despite the larger ensemble size of ECMWF EPS, the higher resolution of COSMO-S14EPS contributes to provide more accurate probabilistic predictions of precipitation.

If the attention is now focused on the performance of both systems for a specic event, most of the above comments still hold. As an example, Fig.31 shows the scores of COSMO-S14-EPS and ECMWF EPS in terms of ROC area for the event “12hour accumulated precipitation exceeding 10 mm”. COSMO-S14EPS outperforms ECMWF EPS for all forecast ranges, although both systems exhibit a semidiurnal cycle in the score and tend to provide better guidance for “night-time” precipitation, that is occurring between 18UTC and 6UTC (and corresponding to the ranges 6–18 h, 30–42 h and 54–66 h). As for COSMO, this is linked with a too rapid onset of convection, as pointed out by Oberto and Turco (2008) for runs of COSMO in “deterministic mode”.

Finally, the attention is focused on the ability of COSMOS14EPS to reduce the number of outliers with respect to ECMWF EPS, thanks to the higher resolution and the better description of mesoscale and orographicrelated processes. Fig.32 shows that COSMOS14EPS has fewer outliers than the global ensemble, with a clear added value of the mesoscale ensemble for short forecast ranges.

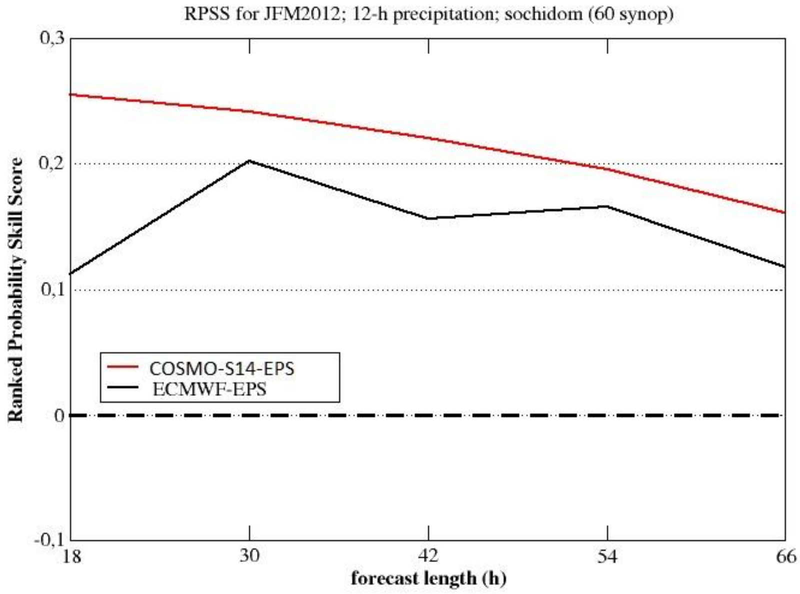


Figure 30: Ranked Probability Skill Score as a function of forecast length for COSMO-S14-EPS

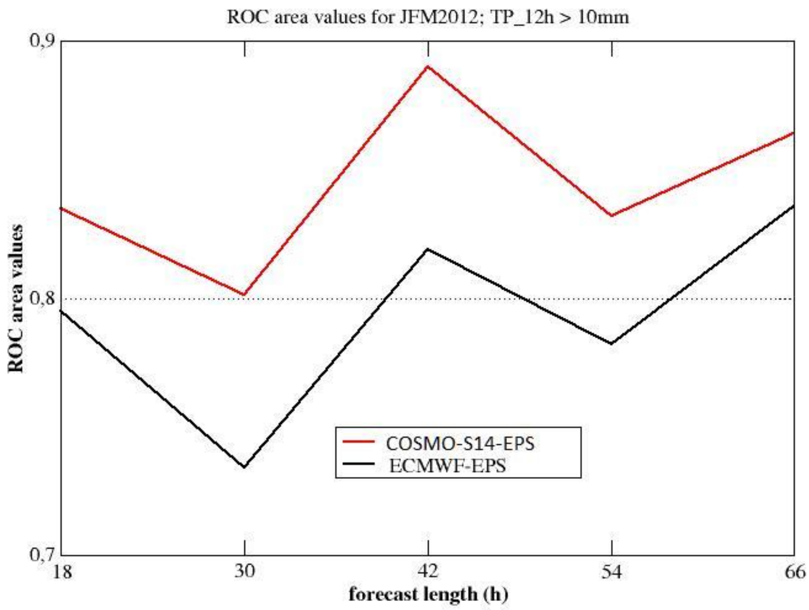


Figure 31: ROC area values for COSMO-S14-EPS (red) and ECMWF EPS (black) relative to the event "precipitation exceeding 10mm in 12 hours"for the forecast ranges of Table 8. Both scores are calculated over the 3-month period from January to March 2012

According to Talagrand et al. (1999), the value of outliers for a reliable ensemble of size N is given by $2/(N+1)$. These values should not be exceeded. The dashed lines of Fig.32 indicate these limits for both COSMO-S14-EPS (red, 18 %) and ECMWF EPS (black, 4 %). Therefore, it looks as if COSMO-S14-EPS approaches the theoretical value to larger extent than ECMWF EPS, which seems to have too many outliers in the short range.

Generally, it was concluded that the mesoscale COSMO-S14-EPS system, based on a relocation of COSMO-LEPS, provided added value with respect to the driving global ensemble

ECMWF EPS as for the probabilistic prediction of precipitation events.

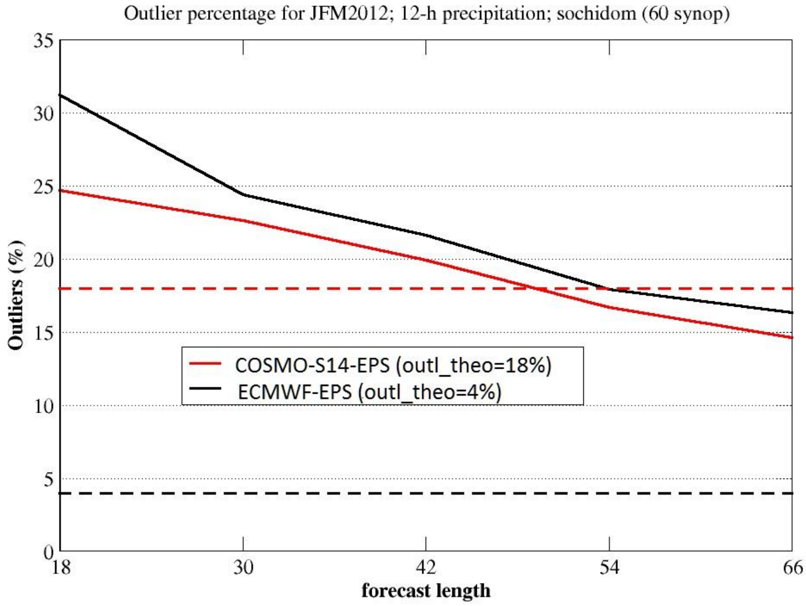


Figure 32: Percentage of Outliers for COSMO-S14-EPS (red) and ECMWF EPS (black), calculated over the 3-month period from January to March 2012. The red (black) dashed line indicates the theoretical limit of outliers for COSMO-S14-EPS (ECMWF EPS)

6.4.2 Case studies

The performance of COSMO-S14-EPS and COSMO-Ru2-EPS was analyzed in detail for several cases.

Hereafter, the attention is focused on two highimpact weather events:

- heavy precipitation event on 13 January 2013 with 21 mm of rain during the day on the coast (Sochi/Adler) and 33 mm of snow-water equivalent in the mountains (Krasnaya Polyana);
- Foehn event on 14-15 February 2013 with a sudden 14-degree warming.

Heavy precipitation event

Heavy precipitation was observed on the 13th of January 2013 in the Sochi region with mainly rain in the coastal cluster and snow in the mountain cluster. The corresponding SYNOP data are presented in Table 9.

Figure 33 reports the performance of COSMO-S14-EPS in terms of probabilistic prediction for two variables: probability of 12hourly accumulated rainfall exceeding 20 mm (left panel) and probability of 12hourly simulated snowfall exceeding 15 mm of equivalent water (right panel).

The ensemble runs start at 00 UTC of 11 January 2013 and the attention is focused on the 48-60 hour forecast range: it can be noticed that COSMO-S14-EPS provides quite accurate forecasts giving large probability of heavy precipitation. Despite the steepness of the orography and the length of the forecast range, the system is able to distinguish between the area more likely affected by rainfall (along the coast, left panel) and the region mainly affected by snowfall (in the mountains, right panel). This is an interesting result, as the knowledge of the possibility of this weather event, with an advance of about 2 days, gives organizers the chance of taking counter measures and relieving the weather-related problems.

Table 9: 12-h accumulated precipitation observed in the Sochi region on January 11-14, 2013

Period (DDMM/HH UTC)	12-h prec, mm Sochi	12-h prec, mm Krasnaya Polyana
11.01/03 - 11.01/15	4	–
11.01/15 - 12.01/03	0	0
12.01/03 - 12.01/15	0	0.9
12.01/15 - 13.01/03	5	10
13.01/03 - 13.01/15	21	33
13.01/15 - 14.01/03	10	9
14.01/03 - 14.01/15	0	–

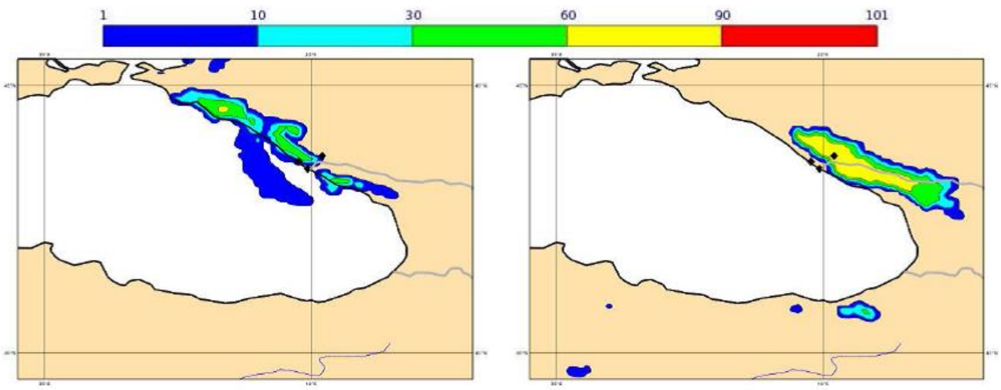


Figure 33: COSMO-S14-EPS run starting at 00UTC of 11 January 2013 (48-60 hour forecast range): probability of 12-hour rainfall exceeding 20 mm (left panel) and of 12-hour snowfall exceeding 15 mm of water equivalent (right panel). The black squares on the coast denote Sochi and Adler; the black square inland denotes Krasnaya Polyana

Let us compare the COSMO-S14-EPS forecasts to COSMO-Ru2-EPS ones. The attention is fixed on the ability of both systems to predict the possible occurrence of heavy snowfall inland. More precisely, we consider the predictability of the following event: "probability of 12h snowfall exceeding 15 mm of equivalent water". In Fig.34, the left column (right column) panels report the performance of COSMO-S14-EPS (COSMO-Ru2-EPS) for the forecast ranges 36-48 hour and 24-36 hour (top-row and bottom-row panels, respectively). It can be noticed that the signal by COSMO-S14-EPS forecasts (left column) is consistent for the different prediction ranges, with a probability of snowfall above 90 % in the area actually affected by the weather event. It is also worth pointing out that no snowfall is predicted along the coast at any forecast range (probabilities below 1 %), consistently with observations.

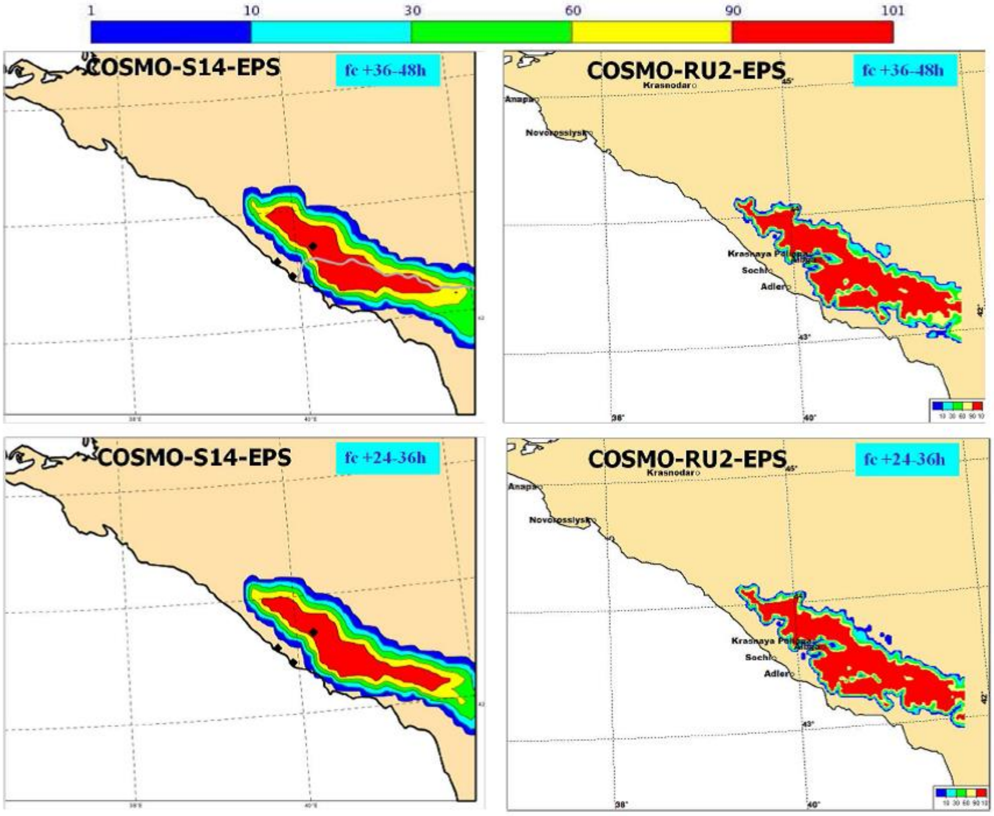


Figure 34: Probability of 12-hour snowfall exceeding 15 mm of equivalent water: COSMO-S14-EPS runs starting at 12 UTC of 11 January (top-left panel, t+36-48h) and at 00 UTC of 12 January (bottom-left panel, t+24-36h) and COSMO-Ru2-EPS runs starting at 12 UTC of 11 January (top-right panel, t+36-48h) and at 00 UTC of 12 January (bottom-right panel, t+24-36h). All forecasts verify at 12 UTC of 13 January 2013. As in Fig.33, the black squares in the left panels denote Sochi, Adler and Krasnaya Polyana.

A straight comparison of COSMO-S14-EPS against COSMO-Ru2-EPS forecasts indicates that the higher resolution ensemble (right column panels of Fig.34) provides more detailed information in terms of location of the regions affected or not by heavy snowfall. In the convective-resolving ensemble, the extent of the coastal region not interested by snowfall turns out to be more evident. At the same time, the higher-resolution ensemble is more confident in giving larger probabilities of snow in the mountainous region. Since more and more spatial and time details are usually required to the forecasts for shorter time ranges, COSMO-Ru2-EPS seems to have, on the basis of this case study, the potential to provide a larger amount of information to local forecasters and event organizers.

Foehn event

Sudden temperature changes in the Olympic areas are considered highimpact weather events possibly affecting outdoor competitions. Therefore, the prediction of this type of event is an important benchmark for the usefulness of ensemble prediction systems. Note that the event considered below was regarded as hardly predictable by local forecasters.

Table 10 shows the evolution of surface temperature in Krasnaya Polyana from 13 to 16 February 2013 (SYNOP data). Linked to the onset of Foehn winds, a marked increase took place between 13 and 15 February, affecting mainly daytime temperatures. On 14 and 15 February, the observed peaks amounted to 13 and 16.2° C, respectively. Ten-minute observations of the automatic meteorological station located at the same point demonstrate even higher values (see Fig.35).

Table 10: Near-surface temperature (SYNOP T2m data) for Krasnaya Polyana during the Foehn event in February 2013

12.02/00	7.1
12.02/06	5.5
12.02/12	6.3
12.02/18	5.1
13.02/00	4.2
13.02/06	4.6
13.02/12	11.3
13.02/18	3.9
14.02/00	1
14.02/06	3.2
14.02/12	13
14.02/18	6.2
15.02/00	2.4
15.02/06	3.7
15.02/12	16.2
15.02/18	9.7
16.02/00	5.4

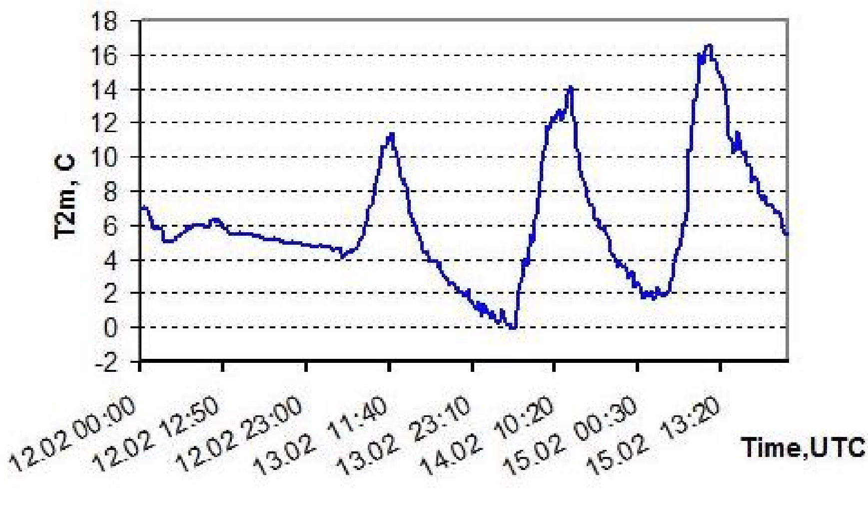


Figure 35: Behavior of 2-metre temperature in Krasnaya Polyana (10-min data of the automatic meteorological station)

As for the ability of COSMO-S14-EPS to predict this temperature increase, Fig.36 reports the meteograms computed over the station point of Krasnaya Polyana, in terms of 2-metre temperature, for different starting times. The top panel of the figure indicates that, already at the 72-hour range (forecasts starting at 12UTC of 12 February), the COSMO-S14-EPS members predict the temperature increase of 14 and 15 February, with peaks close to, or above, 10° C. In this panel, as well as in the others, some discrepancies between observed and predicted temperature are evident, but the differences are partly related to the model orography, which locate Krasnaya Polyana at about 941 m, instead of 564 m.

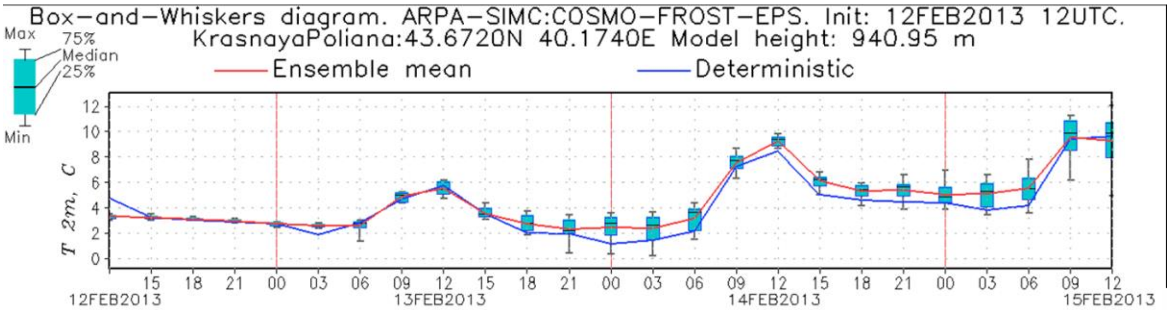
According to COSMO-Ru2-EPS orography, the model gridpoint nearest to Krasnaya Polyana lies at about 734 m above the sea level. This enables the higher-resolution system to describe the temperature peak on February 14 better giving about 12° C (see Fig.36e). However, similarly to COSMO-S14-EPS it fails to give strong enough increase in 2m temperature on February 15. Note that the ECMWF deterministic forecast presented in blue in the epsgrams shows even lower maximum on this date thus indicating that the mistake is possibly related to the weakness of the driving global system in this case.

Fig.37 demonstrates the ability of COSMO-Ru2-EPS to give reasonable probability fields. The probabilities of the event "3-h maximum of 2m temperature exceeds 5° C" are presented in the right panels and the temperature variations at two mountain stations, Aibga (upper curve) and Krasnaya Polyana (lower curve) are shown in the left panels. The vertical red bars in the left figures show two 3-h periods for which the probability fields are given on the right. The COSMO-Ru2-EPS forecast starts at 00 UTC on February 13, 2013 and the probability fields are valid for two 3-h intervals, 03-06 and 09-12 UTC on February 14. The figure obviously demonstrates the coincidence of the periods when 2m temperatures really exceeded 5° C in Krasnaya Polyana and the probability of this event was predicted as high. The temperature was less than 5° C during the entire period 12-16 February in Aibga. Note that the probabilities there are close to zero all the time considered.

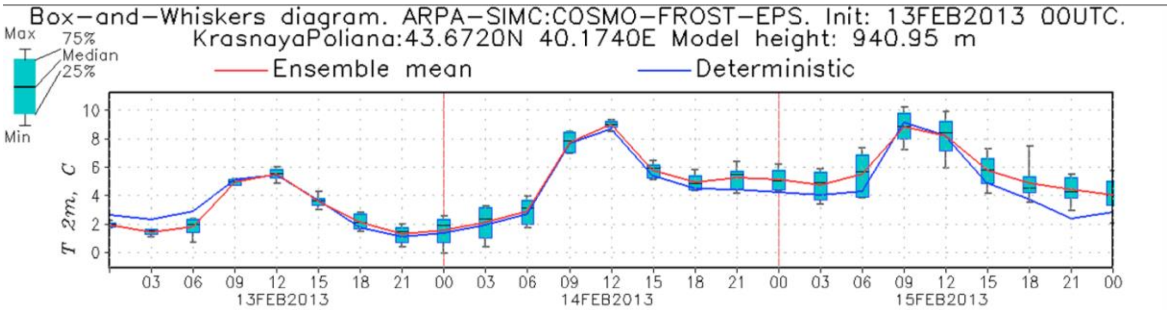
The ensemble forecasts were analyzed in detail for many other cases, mainly characterized by heavy precipitation, sudden temperature changes, or strong wind gusts. As a result of such case studies it was concluded that both COSMO mesoscale ensemble prediction systems (COSMO-S14-EPS and COSMO-Ru2-EPS) were good in simulating 2m temperature and precipitation (precipitation phase was predicted correctly as well) and that much more details can be found in COSMO-Ru2-EPS prognostic charts.

6.4.3 Verification of COSMO-S14-EPS and COSMO-Ru2-EPS for the Olympic and pre-Olympic periods

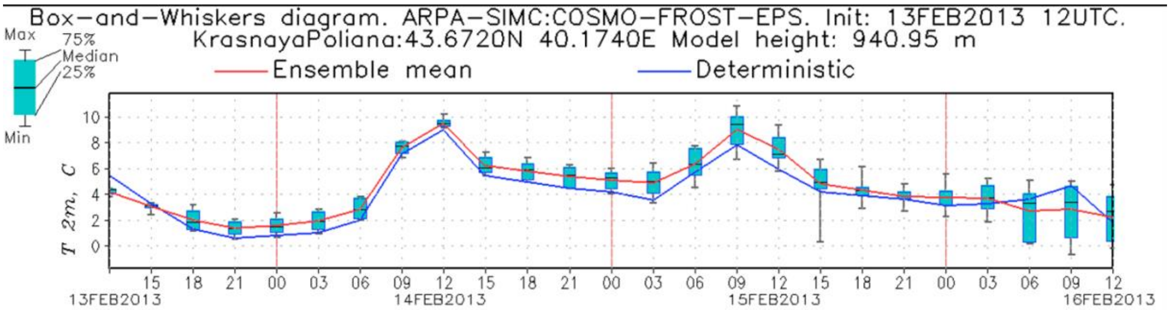
In this section, some verification results are presented; the skills of COSMO-S14-EPS and COSMO-Ru2-EPS are assessed over the period January-February 2013. For both systems, we considered the probabilistic prediction of 2-metre temperature exceeding a number of thresholds for several forecast ranges. As for observations, it was decided to use the data obtained from the SYNOP reports available on the Global Telecommunication System (GTS) as well as from all non-GTS stations in the region.



a)



b)



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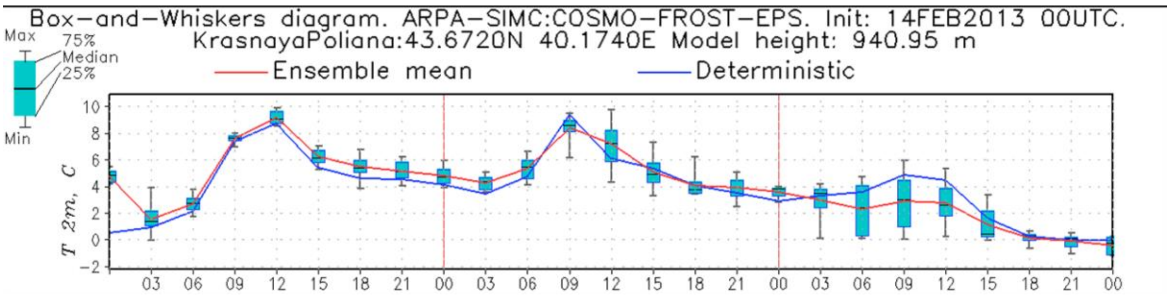

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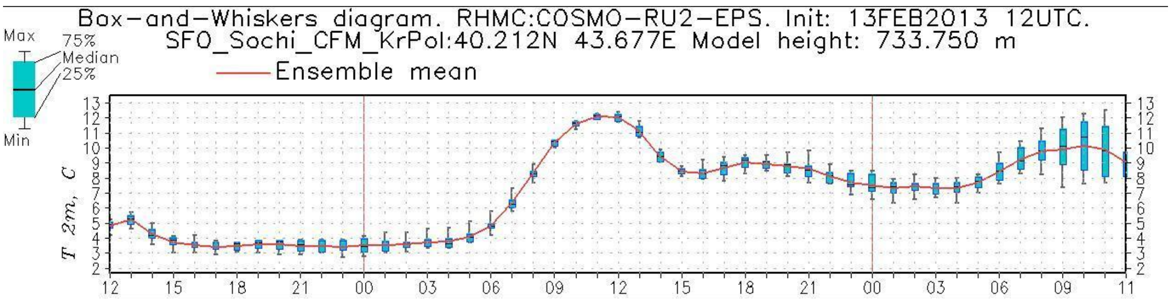

e)

Figure 36: Point meteograms in terms of 2-metre temperature over Krasnaya Polyana based on COSMO-S14-EPS and starting at: (a) 12 UTC of 12 February, (b) 00 UTC of 13 February, (c) 12 UTC of 13 February and (d) 00 UTC of 14 February; and based on COSMO-Ru2-EPS and starting at 12 UTC of 13 February (e)

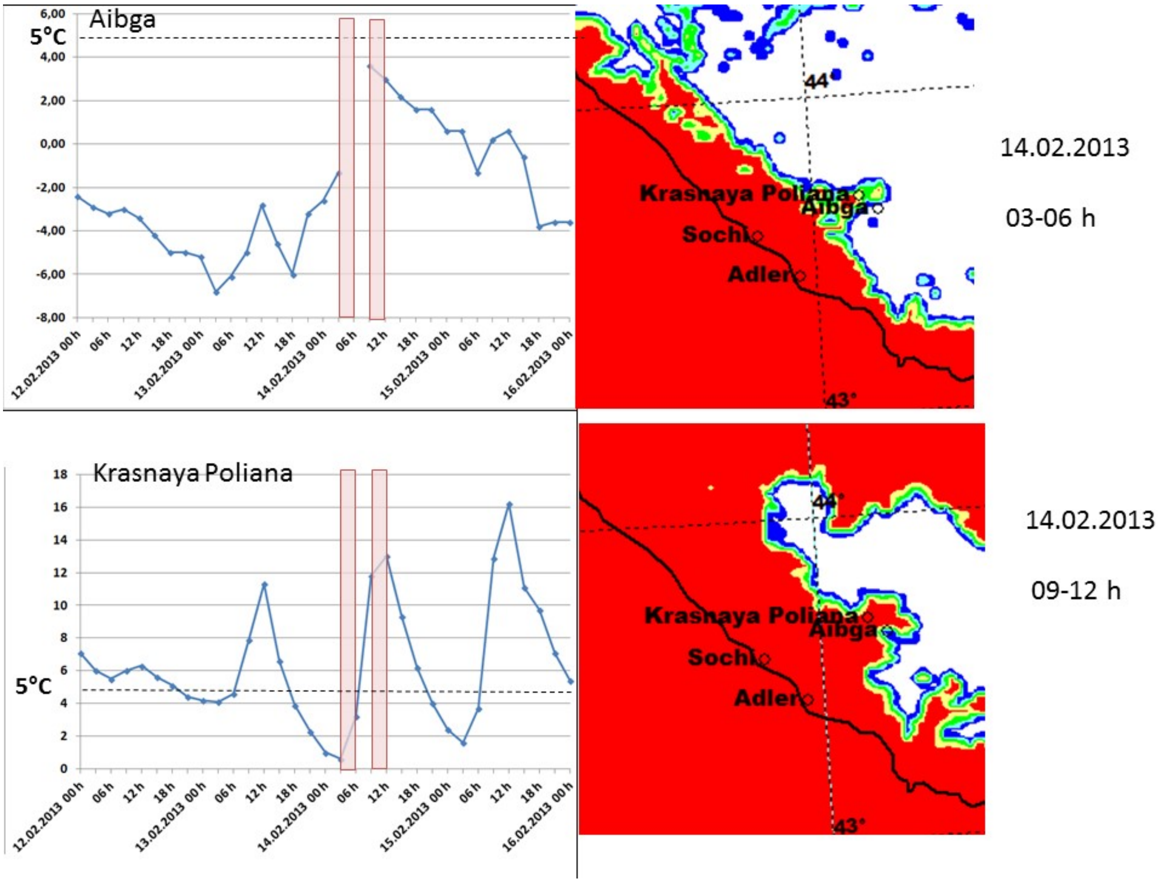

Figure 37: The probabilities of the event "3-h maximum of 2m temperature exceeds 50° C" (right panels) as predicted by COSMO-Ru2-EPS for two 3-h periods on February 14, 2013 and the observed temperature variations (left panels) at two mountain stations, Aibga (upper curve) and Krasnaya Polyana (lower curve). Red: 90-100 %, yellow: 60-90 %, green: 30-60 %, light blue: 10-30 %; blue: 0.1-10 %. See text for details

Table 11: Main features of the verification configuration

variable	2-metre temperature
starting time	12 UTC
period	from 1 January to 28 February 2013
region	42.5-45 N, 37.5-41.5 E
method	nearest 3D optimized grid-point; observations
observations	SYNOP reports + local stations (69 in total); fcst
fcst ranges (h)	from fc+3h to fc+72h every 3h
thresholds	-5, 0, +5, +10 ° C
scores	ROC area, BSS

This enabled the possibility to assess the performance of the systems over a relatively dense observation dataset (69 stations), since the verification domain was restricted to an area centered over the Olympic venue (42.5-45N, 37.5-41.5E). As for the comparison of model forecasts against observations, we selected the gridpoint closest (in 3D) to the observation. The performance of both systems was examined for 4 different thresholds: -5, 0, +5 and 10 ° C. Verification was performed using COSMO software VERSUS. The following probabilistic scores were computed: the Brier Skill Score (BSS) and the Relative Operating Characteristic Curve (ROC) area. For a description of these scores, the reader is referred to Wilks (1995). The main features of the verification exercise are also summarized in Table 11.

The skill of two systems in terms of probabilistic prediction of 2-metre temperature is summarized in Fig.38, where the values of the ROC area are plotted against the forecast range for 4 different weather events: temperature below -5° C (top-left), above 0° C (top- right), above +5° C (bottom-left) and above +10° C (bottom-right). It can be noticed that the ROC area values are well above 0.8 for three out of the four thresholds, indicating that both COSMO-S14-EPS and COSMO-Ru2-EPS manage to discriminate these events. The performance of two systems is quite similar, with a slight predominance of COSMO-Ru2-EPS that has higher scores for most of the thresholds/forecast ranges. Worse scores are obtained by both systems for the highest threshold (bottom-right panel), where COSMO-S14-EPS outperforms COSMO-Ru2-EPS. It is worth pointing out that this is the rarest event with few observations; therefore, the statistical significance of this result needs to be confirmed by a more detailed investigation over a longer verification period.

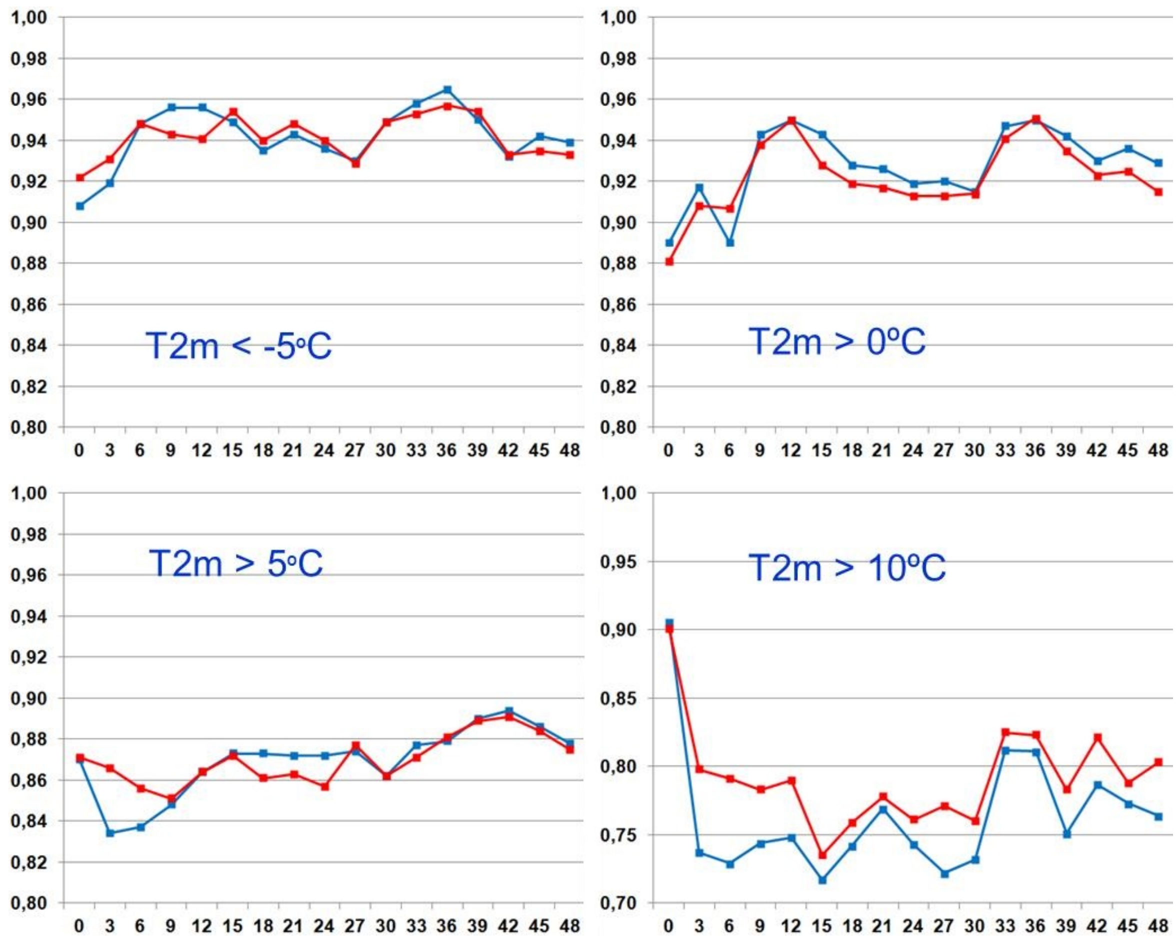

Figure 38: ROC area values as a function of forecast range for four different weather events: 2-metre temperature below -5° C (top-left panel), above 0° C (top right), above +5° C (bottom left) and above +10° C (bottom-right with different vertical scales). The scores are calculated over the period January-February 2013. Red (blue) lines refer to COSMO-S14-EPS (COSMO-Ru2-EPS)

Similar results are obtained when the attention is focused on the Brier Skill Score (BSS), shown in Fig.39. Also with this score, the satisfactory performance of both systems is confirmed: the BSS is always positive for COSMO-S14-EPS and COSMO-Ru2-EPS, indicating a benefit of both systems with respect to climatology as regards the probabilistic prediction of 2-metre temperature for the thresholds of Table 11. Similarly to Fig.38, it can be noticed that COSMO-Ru2-EPS usually outperforms the lower-resolution ensemble, although the difference is not very marked. As for the +10° C threshold (bottom-left panel of Fig.38), the skill of the two ensembles is almost identical, with slightly higher scores for COSMO-S14-EPS.

Precipitation verification for January-February 2014 demonstrated rather high skill of both systems but only slight differences in ROCA and BSS (not shown).

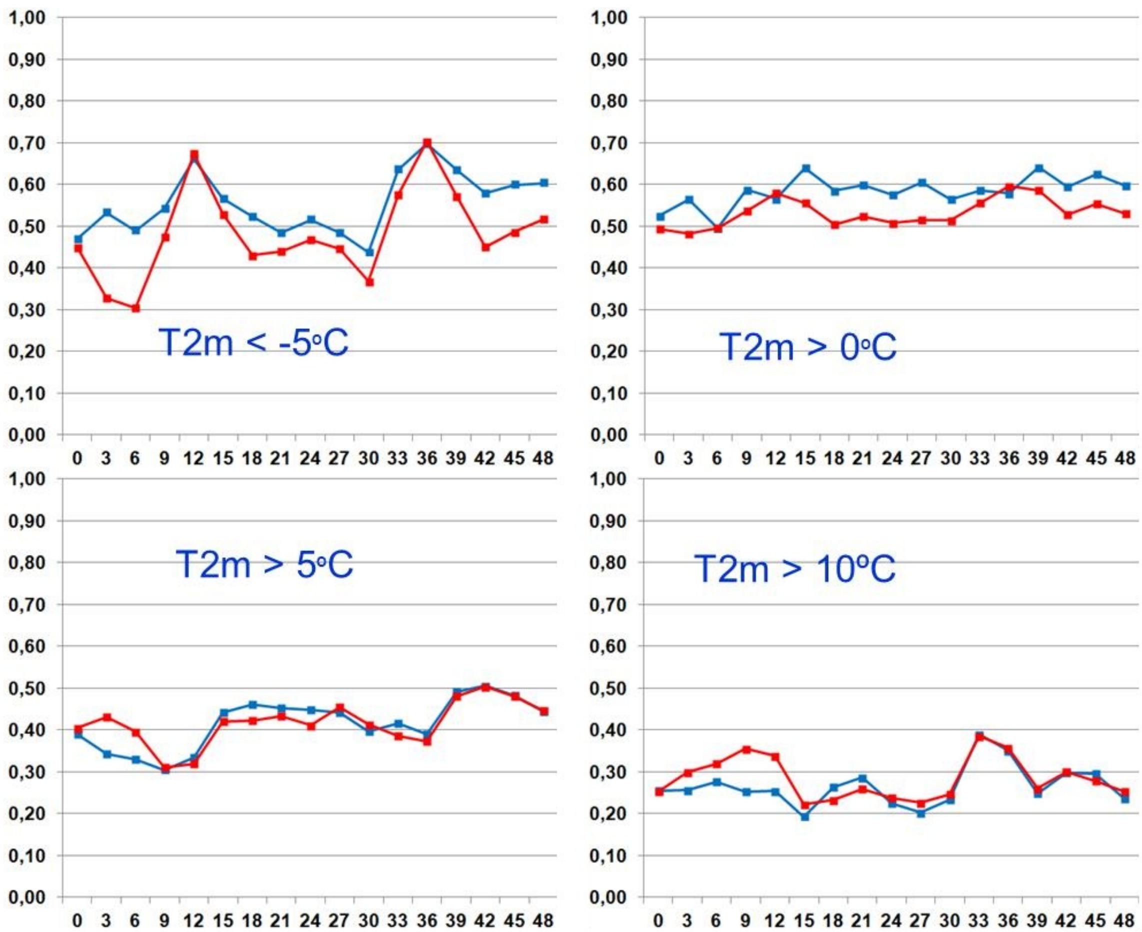

Figure 39: The same as Fig.38 but for the Brier Skill Score. The vertical scale is the same in all panels.

It is important to note that the scores strongly depend on the set of stations applied for verification. Unfortunately, the observation stations are very irregularly distributed over the Sochi region with their highest concentration in the Olympics mountain cluster. In this area, a model gridpoint is often matched (found to be the nearest) to several observation stations. The number of such gridpoints varies for different model resolutions. Additional difficulties are introduced by deviations of the model gridpoint heights from the real heights of meteorological stations. Figures 40a-f demonstrate the ensemble mean 2m temperature at 6 stations of the mountain cluster predicted by COSMO-S14-EPS and COSMO-Ru2-EPS starting from 00UTC February 18, 2014 analysis. The higher-resolution system obviously outperforms. In Fig.40g-h the quantile-quantile plots are presented for 24-h forecasts of two systems from January 15 to March 15, 2014 and the corresponding observations at RKHU7 station. The COSMO-Ru2-EPS forecasts are clearly distributed more like observations for the entire two-month period (the blue line in Fig.40g almost coincides with the forecast-observation diagonal line). However, probably the advantage of high-resolution system mostly comes from a better gridpoint location: the RKHU7 station is 980 m above the sea level while the height of the nearest gridpoint of the COSMO model with resolutions of 7 and 2.2 km is 1460 and 941 m, respectively. This confirms the analysis of ROCA behavior in Fig.38. The scores presented there were calculated involving all stations in the Sochi region, located both in the coastal and mountain clusters. Though the COSMO-Ru2-EPS curves mainly lie higher thus indicating better forecast skill, the benefits from high-resolution are not great. Note that ROCA is not bias-sensitive.

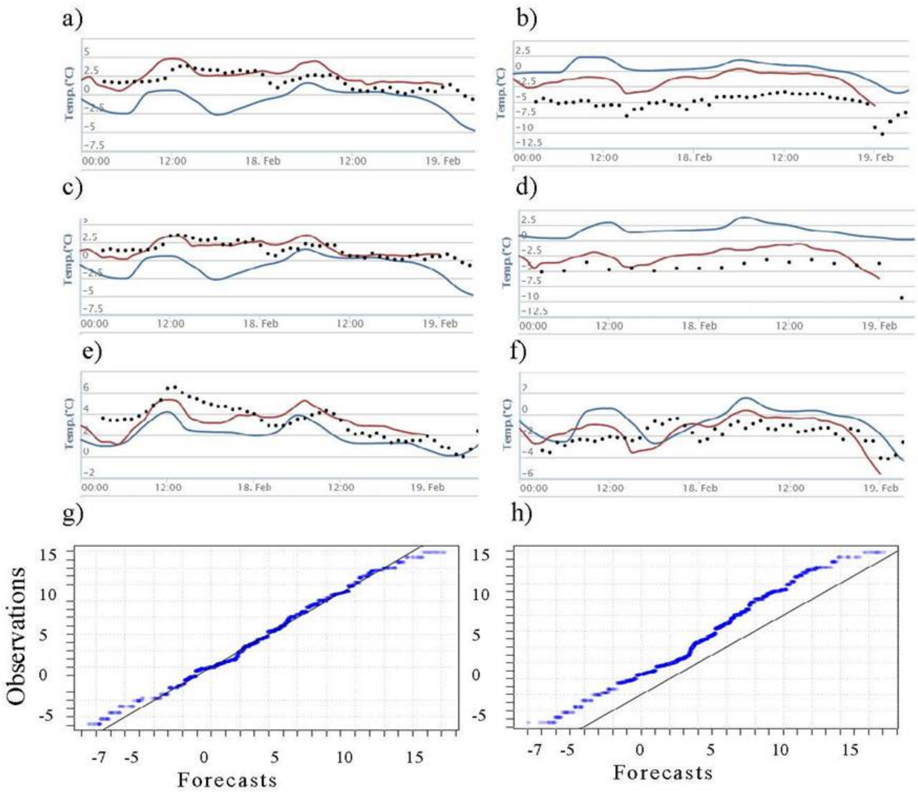

Figure 40: Ensemble mean 2-m temperature predicted by COSMO-Ru2-EPS (in red) and COSMO-S14-EPS (in blue) and observed (black dotted line) at mountain stations RKHU-7 (980 m) (a), RKHU-1 (2320 m) (b), Snowboard-1025 (1027 m) (c), Aibga (2225 m) (d), Sledge-700 (701 m) (e), Gornaya Karusel-1500 (1434 m) (f) using the analysis on 18 February 2014, 00 UTC; quantile-quantile plots for 24-h forecasts of COSMO-Ru2-EPS (g) and COSMO-S14-EPS (h) and observations at RKHU-7 station for the period from January 15 to March 15, 2014

On the whole, both EPS systems demonstrated good skill for 2m temperature, precipitation and wind. Higher-resolution system was slightly more skilful for temperature, but worse for wind. The verification exercises demonstrated the necessity of observations at high temporal and spatial resolution and application of spatial verification methods.

6.5 Conclusions

Two limited-area ensemble prediction systems, based on COSMO-model and referred to as COSMO-S14-EPS (convection-parameterized, 7-km resolution) and COSMO-Ru2-EPS (convection-permitting, 2.2 km resolution), were implemented and run on operational/quasi-operational basis during the pre-Olympic and Olympic seasons. The ensemble systems provided a good support to Sochi forecasters and their probabilistic products were highly appreciated.

The ensemble forecasts were verified by assessing the probabilistic skill of both systems in terms of 2-metre temperature and precipitation during the Olympic and pre-Olympic season (January- February 2013, 2014) over a region centered around Sochi.

Both COSMO-S14-EPS and COSMO-Ru2-EPS turned out to have an overall good performance with ability to discriminate different weather events. The added value of the higher resolution in COSMO-Ru2-EPS was confirmed for 2m temperature by the better probabilistic scores obtained by this system. Verification activity should be continued, including application of new approaches and observations, comparison with other FROST-2014 ensembles.

The forecasts and meteograms prepared during the Olympics were saved in a special archive along with the results of other ensemble systems that participated in FROST-2014 project. The archived information on forecasts, initial and boundary conditions for the higher-resolution system, and observations are valuable and new experiments can be performed within the Sochi testbed.

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COSMO Technical Reports

Issues of the COSMO Technical Reports series are published by the *COnsortium for Small-scale MOdelling* at non-regular intervals. COSMO is a European group for numerical weather prediction with participating meteorological services from Germany (DWD, AWGeophys), Greece (HNMS), Italy (USAM, ARPA-SIMC, ARPA Piemonte), Switzerland (MeteoSwiss), Poland (IMGW), Romania (NMA) and Russia (RHM). The general goal is to develop, improve and maintain a non-hydrostatic limited area modelling system to be used for both operational and research applications by the members of COSMO. This system is initially based on the COSMO-Model (previously known as LM) of DWD with its corresponding data assimilation system.

The Technical Reports are intended

- for scientific contributions and a documentation of research activities,
- to present and discuss results obtained from the model system,
- to present and discuss verification results and interpretation methods,
- for a documentation of technical changes to the model system,
- to give an overview of new components of the model system.

The purpose of these reports is to communicate results, changes and progress related to the LM model system relatively fast within the COSMO consortium, and also to inform other NWP groups on our current research activities. In this way the discussion on a specific topic can be stimulated at an early stage. In order to publish a report very soon after the completion of the manuscript, we have decided to omit a thorough reviewing procedure and only a rough check is done by the editors and a third reviewer. We apologize for typographical and other errors or inconsistencies which may still be present.

At present, the Technical Reports are available for download from the COSMO web site (www.cosmo-model.org). If required, the member meteorological centres can produce hard-copies by their own for distribution within their service. All members of the consortium will be informed about new issues by email.

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