Creation of a long-term high-resolution hydrometeorological archive for the Russian Arctic: methodology and first results

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Abstract. Taking into account that dangerous phenomena on the Arctic coast are increasing in number, providing the region with detailed hydrometeorological and climatic information with a horizontal resolution of at least several kilometers becomes particularly important. In this work, we obtain for the first time a detailed archive of many hydrometeorological parameters with a spatial resolution of less than 5 km based on long-term simulation experiments. Detailed hydrometeorological fields in the Arctic basin over a long period (1980 – 2016) are derived by a two-step downscaling technology with domains of horizontal resolutions of ~13 km and ~4 km that cover most of the Russian Arctic, by using a regional non-hydrostatic model, COSMO-CLM. First results of verification with hundreds of Russian Arctic stations allow us to select the best configuration of the model and domains, including many turbulent scheme options and starting time of the experiments. The model results for the coast have shown good agreement with observations (with mean errors of 1 - 2 C). The larger temperature biases over the Eastern Siberia inland have been partially reduced by using selected turbulence scheme options (with mean errors of 5 - 6 C to 2 – 3 C). The differences between the ERA-Interim and ERA5 driving conditions are not great. Therefore, the former are chosen as basic reanalysis, taking into account the data volume and limitations on computational resources. A possible future regional reanalysis output would be useful in many applications, e.g. modelling ocean’s characteristics, coastal ecosystems, detailed investigation of individual extreme phenomena in nested domains, analysis of trends in the frequency of occurrence of extreme events and features of their spatial distribution, study of the hydrometeorological regime of coastal areas, the climatology and tracking of polar mesocyclones, etc.

1. Introduction

The Arctic is the region that is most sensitive to climate change on the globe; it concerns both physical feedbacks in the climate system and ecological systems [1]. In particular, abrupt sea ice area depletion in the Arctic Ocean starts an albedo positive feedback mechanism, increasing the temperature growth...
rate [2]. However, the spatial distribution of the climate changes in the region is ambiguous. There are various estimates of the trends of certain meteorological parameters in different water areas and coastal zones of the Russian and foreign Arctic regions [3, 4].

Taking into account the increasing number of dangerous phenomena and outlooks for the Arctic coast and the Northern Sea Route development, the task of providing the region with detailed hydrometeorological and climatic information with a horizontal resolution of at least several kilometers becomes particularly important. As a tool for solving this task, it seems efficient to use regional climate modeling. Long-term detailing of many hydrometeorological fields with a spatial resolution of less than 5 km allows one to obtain more thorough and justified estimates of current regional and mesoscale Arctic climate changes and extreme weather events.

It is necessary to take into account the mesoscale processes to specify and detail the hydrometeorological information in contrast to the current scales resolved in global climate models and reanalyses, including non-hydrostatic effects. This lack could be eliminated by applying mesoscale climate models using global modeling data as input forcing.

2. Data and methods

2.1. Model description

The COSMO-CLM model (ver. 5.0/5.05) is used as the main tool for the creation of this long-term meteorological archive. The COSMO-CLM is a climate version of the well-known mesoscale COSMO model, including some modifications and extensions adapted to the long-term numerical experiments. It was developed by the German Weather Service (DWD) and the CLM-Community (see CLM Community site http://www.clm-community.eu/ [5, 6]). The COSMO-CLM model is based on the primitive Navier-Stokes equations describing the dynamics of compressible fluid in the moist atmosphere. The model equations are solved on the rotational grid ‘latitude-longitude’ (λ, φ) with a pole tilt. It helps to minimize the problem of convergence of the meridians over the pole. The numerical scheme is realized on an Arakawa C-grid [7], and the vertical coordinate is a hybrid Gal-Chen coordinate [8, 9]. The height-based hybrid Gal-Chen coordinate [8] is given as an analog of the σ-coordinate from the surface to Z₀ level and as the Z-coordinate above the Z₀ level. This representation allows avoiding problems associated with the surface heterogeneity.

The standard configuration of the COSMO-CLM model was applied with the Runge-Kutta integration scheme with the 5th advection order. The Ritter and Geleyn radiation scheme [10] is based on the 8 two-stream version of the radiation transfer equation. The precipitation formation is described by a bulk microphysics parameterization, and Tiedtke mass-flux schemes with equilibrium closure based on moisture convergence are used for moist and shallow convection [11]. Turbulence is described by a prognostic TKE-based scheme, with 2.5 order closure [12]; Smagorinsky diffusion is included. There is an option of applying the spectral nudging technique [13]. A full description of the COSMO Model physics, dynamics, and parameterizations is available on (http://www.cosmo-model.org/content/model/documentation/core/default.htm).

2.2. Description of the experiments and downscaling technology

The general scheme proposed is long-term and, therefore, the test experiments are as follows. Reanalyses from ECMWF (ERA-Interim [14], ERA5 [15]), which are widely known and used in international research, will be used as driving conditions for COSMO-CLM regional model runs over 1980 – 2016. Information about the external parameters (e.g., land-sea mask, roughness length, grid sea-ice cover, sea surface temperature, etc.) is obtained from the program utility EXTPAR v.5.1.1 (https://tools.clm-community.eu/web_pep/gui/web_pep.php). Further, it is interpolated on the model grid of the chosen domain as ‘ready-to-use’. The ‘dynamical downscaling’ (‘nesting domains’) technique will be used to obtain detailed meteorological fields for the last 35 years with an hourly time increment of data. The first model run will be performed over the base raw-resolution domain (grid step: ~13 km) covering most of the area of the Russian Arctic with global reanalysis as forcing. After
that the output data of these experiments will be used as initial and driving conditions for interpolation and model runs over fine-resolution small domains (less than 5 km) for three key regions of the Russian Arctic: the Barents, Kara, and Laptev Seas. A scheme of the model domains is shown in Figure 1. About a hundred of different hydrometeorological parameters would be presented in the output files, including the surface quantities, three-dimensional quantities within the atmosphere and soil. Test and future long-term model runs were made on the MSU Supercomputer Complex “Lomonosov-2” [16]. An example of successful previous implementations by the authors is given in [17].

Figure 1. Scheme of the model domains. The cyan rectangle denotes the basic domain with a grid step of ~13 km; and magenta, yellow, and green ones denote nesting modeling domains with grid steps of ~3.3 km for the Barents, Kara, and Laptev Seas, respectively.

The main goal of the test numerical experiments was to choose the best configuration using many parameterizations, options and taking into account the specificity of the Arctic climate system. An optimal configuration is defined based on the verification procedure, i.e. a comparison of model runs with real observations. The test experiments were performed for the base domain with a ~13-km grid step for August-September 2015 and December-January 2012-13. It is important that the experiments were made for different seasons to examine how the model could reproduce the contrasting atmospheric circulation conditions and surface-atmosphere interactions. For instance, the sea-ice conditions are changing significantly over this region during the summer and winter periods and, therefore, the circulation, heat exchange regimes, and stratification are changing as well on the synoptic scale, as on the mesoscale. It was important to estimate the parameters of model experiments which are capable of reproducing the above differences in the contrast conditions.

The main options changed in the experiments are listed below, and their properties and differences are briefly explained. The full list of experiments, their properties and acronyms are given in Table 2 and Appendix.
1) Different initial and driving conditions: ERA-Interim reanalysis and new reanalysis ERA5.
2) Switching on/off the ‘spectral nudging’ technique. It means assimilation of the large-scale atmospheric circulation components from reanalysis data not only on the boundaries, but also inside the model domain. It ensures that the mesoscale weather and climate features are simulated in realistic atmospheric circulation conditions.
3) Changing of constants affects the vertical turbulence diffusion parameterization: 4 times reduction of the minimal value of the turbulence drag coefficient (from 0.4 to 0.1) and 5 times reduction of the subgrid temperature heterogeneities scale (from 500 m to 100 m) influencing the TKE generation. These parameters affect the simulation results in the boundary layer stable stratification conditions [18].
4) Two different model versions are used: the 5.0 version as a current stable and the official COSMO-CLM version utilized by the CLM-Community; and the last COSMO 5.05 version. Parameterizations of many physical processes are affected in the latter version, unified with the atmospheric model ICON [19, 20].
5) Different start time of experiments – with or without ‘cold start’. ‘Cold start’ was defined as one month.

3. Results and discussion
Data from 466 meteorological stations over Russia, Norway, Finland, and Sweden covered by the base domain and located north of 60 N were used for the verification of the tests experiments. The data were accessed from the www.rp5.ru site for 2005 – 2017. Each station archive was verified for less than 25 % lacks for 2 m temperature, 10 m wind speed, and sea level pressure separately. Model grids for comparison were defined for each station based on the least RMSE among the 4 nearest grid points. This technique takes into account that mesoscale models tend to reproduce many atmospheric features in the vicinity of the point, but not at the point exactly. The main statistical metrics of verification for each variable were the mean error (ME), the root mean square error (RMSE), and the correlation coefficient. These estimates were made for all stations and for coastal and inland stations separately. The coastal stations were defined by the distance of 20 km or less from the nearest ‘sea’ grid point. The main results of the verification are listed in Tables 1a-b and Figures 2 – 4. its detailed description is given below.
1) The model reproduces synoptic-scale dynamics almost perfectly within the base domain, which is confirmed by sea level pressure correlation coefficients above 0.98 – 0.99.
2) ‘Spectral nudging’ (‘sn’ experiments) significantly reduces the model biases for the temperature and for the wind speed, and increases the correlation between the observations and modeling data compared with experiments without ‘spectral nudging’. This result is first obtained for the pan-Arctic spatial scale, in contrast to previous case studies over the Arctic region [21].
3) Correction of the vertical turbulence diffusion parameters (‘_turb sn’ experiments) decreases systematic temperature model biases for inland areas, especially for Eastern Siberia and Scandinavia (Figures 2 and 3). The standard configuration of the model significantly overestimates the temperature (up to 5 – 10 C) during calm, clear winter weather conditions. It is a well-known problem of reproduction of stable boundary layers in mesoscale models. However, the sensitivity of the model to the parameters of the turbulence scheme is small for the coastal stations, both for the summer period and for wind speed estimates.
4) Using the new model version (‘_v505’ experiments) has almost the same effect as the turbulence scheme correction in the old model version. It is associated with the implementation of new physical parameterizations from the ICON model, especially affecting the reproduction of intense mixing in stable stratification conditions. Furthermore, the new model version decreases biases not only for the winter season, but also for the summer season.
5) No significant differences were revealed in biases between the driving conditions (ERA-Interim reanalysis - ‘_interim’ experiments, and ERA5 reanalysis - ‘_era5’ experiments). This allows
one to utilize ERA-Interim reanalysis for the initialization of long-term experiments, because it requires less memory resources and preparation time with almost the same verification results.

6) Experiments with ‘cold start’ (‘_long’) have shown some small and multidirected differences. For the wintertime ‘cold start’ increases model biases for the temperature, and for the summertime the situation is opposite. It is probably associated with differences in the behavior of the inertial components of the model system, the active soil layer in the summertime, and the snow cover in wintertime. Therefore, there are not a certain choice for an optimal model configuration.

| Experiment name | T_2M (all) | T_2M (coast) | T_2M (inland) | VEL_10M (all) | VEL_10M (coast) | VEL_10M (inland) | PMSL (all) |
|-----------------|------------|--------------|---------------|---------------|----------------|-----------------|------------|
| interim         | 4.22       | 0.76         | 3.12          | 0.78          | 4.80           | 0.75            | 2.30       | 0.55       | 3.12           | 0.59       | 1.83          | 0.53       | 2.98       | 0.96       |
| era5_sn         | 4.19       | 0.76         | 3.07          | 0.79          | 4.77           | 0.74            | 2.30       | 0.57       | 3.11           | 0.62       | 1.84          | 0.55       | 2.77       | 0.97       |
| interim         | 3.69       | 0.83         | 2.61          | 0.85          | 4.25           | 0.82            | 2.12       | 0.65       | 2.78           | 0.70       | 1.74          | 0.62       | 2.01       | 0.99       |
| era5_sn         | 3.70       | 0.83         | 2.62          | 0.86          | 4.27           | 0.81            | 2.10       | 0.66       | 2.76           | 0.71       | 1.73          | 0.63       | 2.13       | 0.99       |
| interm          | 4.10       | 0.76         | 3.29          | 0.78          | 4.53           | 0.76            | 2.30       | 0.55       | 3.12           | 0.59       | 1.84          | 0.53       | 3.24       | 0.96       |
| turb_sn         | 4.16       | 0.76         | 3.32          | 0.78          | 4.60           | 0.75            | 2.32       | 0.57       | 3.17           | 0.61       | 1.84          | 0.54       | 3.25       | 0.96       |
| interm          | 3.38       | 0.84         | 2.65          | 0.85          | 3.77           | 0.83            | 2.12       | 0.65       | 2.79           | 0.69       | 1.74          | 0.63       | 2.08       | 0.99       |
| turb_sn         | 3.57       | 0.83         | 2.74          | 0.85          | 4.00           | 0.83            | 2.11       | 0.65       | 2.79           | 0.70       | 1.72          | 0.62       | 2.14       | 0.99       |
| interm          | 3.37       | 0.85         | 2.67          | 0.86          | 3.74           | 0.84            | 2.09       | 0.66       | 2.77           | 0.71       | 1.71          | 0.64       | 2.18       | 0.99       |
| interm          | 3.34       | 0.85         | 2.37          | 0.88          | 3.85           | 0.84            | 2.22       | 0.67       | 2.90           | 0.71       | 1.84          | 0.64       | 1.69       | 0.99       |
| v505_sn         | 3.94       | 0.78         | 2.99          | 0.79          | 4.44           | 0.78            | 2.47       | 0.54       | 3.30           | 0.57       | 2.00          | 0.53       | 2.83       | 0.96       |
| interm          | 3.33       | 0.85         | 2.45          | 0.87          | 3.80           | 0.84            | 2.24       | 0.65       | 2.92           | 0.70       | 1.86          | 0.63       | 1.63       | 0.99       |
| ERA-Interim     | 3.10       | 0.88         | 2.52          | 0.89          | 3.41           | 0.88            | 2.31       | 0.66       | 2.65           | 0.72       | 2.11          | 0.64       | 1.10       | 0.99       |

**Table 1b. RMSE and correlation, for September 2015, all experiments.**

| Experiment name | T_2M (all) | T_2M (coast) | T_2M (inland) | VEL_10M (all) | VEL_10M (coast) | VEL_10M (inland) | PMSL (all) |
|-----------------|------------|--------------|---------------|---------------|----------------|-----------------|------------|
| COSMO_interim   | 2.38       | 0.77         | 1.83          | 0.75          | 2.69           | 0.78            | 2.02       | 0.65       | 2.63           | 0.67       | 1.65          | 0.64       | 1.87       | 0.99       |
| COSMO_interim_long | 2.41  | 0.76         | 1.85          | 0.75          | 2.72           | 0.77            | 2.06       | 0.64       | 2.68           | 0.66       | 1.68          | 0.63       | 1.96       | 0.99       |
| COSMO_era5      | 2.34       | 0.79         | 1.78          | 0.78          | 2.65           | 0.80            | 2.00       | 0.67       | 2.59           | 0.69       | 1.65          | 0.65       | 1.70       | 0.99       |
| COSMO_interim_sn| 2.29       | 0.79         | 1.72          | 0.78          | 2.60           | 0.79            | 1.89       | 0.70       | 2.41           | 0.73       | 1.58          | 0.68       | 1.53       | 1.00       |
### Verification plots for 2 m temperature, January 2013, ‘COSMO_interim’ experiment

Map of modelled (color background) and observed (round markers) mean monthly temperature (top left). The marker size is proportional to the RMSE value for the given station. Map of mean errors (bottom left). Modified Taylor diagrams show the correlation coefficient and RMSE values normalized on the observed standard deviation for each station (top right); correlation coefficients and ratio between the modelled and observed standard deviations for each station (bottom right). Green triangles show an ideal accordance case. The table (top right) shows mean statistics for the given experiment over the domain: the bias and RMSE for all, inland, and coastal stations.

| Experiment                  | Mean | Bias  | Bias Inland | Bias Coastal | RMSE  | RMSE Inland | RMSE Coastal |
|-----------------------------|------|-------|-------------|--------------|-------|-------------|--------------|
| COSMO_era5_sn               | 2.29 | 0.81  | 1.71        | 0.80         | 2.61  | 0.81        | 1.87         |
| COSMO_interim_turb          | 2.43 | 0.77  | 1.87        | 0.76         | 2.74  | 0.78        | 2.03         |
| COSMO_era5_turb             | 2.41 | 0.80  | 1.82        | 0.79         | 2.73  | 0.80        | 1.98         |
| COSMO_interim_turb_sn       | 2.35 | 0.79  | 1.78        | 0.79         | 2.67  | 0.80        | 1.89         |
| COSMO_interim_turb_sn_long | 2.25 | 0.80  | 1.71        | 0.80         | 2.54  | 0.80        | 1.90         |
| COSMO_era5_turb_sn          | 2.35 | 0.81  | 1.76        | 0.81         | 2.67  | 0.81        | 1.88         |
| COSMO_era5_sn_v505          | 2.16 | 0.82  | 1.60        | 0.81         | 2.47  | 0.83        | 1.97         |
| COSMO_interim_v505_long     | 2.25 | 0.78  | 1.75        | 0.76         | 2.53  | 0.80        | 2.15         |
| COSMO_interim_sn_v505_long  | 2.10 | 0.81  | 1.58        | 0.80         | 2.39  | 0.82        | 1.97         |
| ERA-Interim                 | 1.83 | 0.87  | 1.60        | 0.84         | 1.96  | 0.89        | 1.95         |
Figure 3. The same as Figure 2, but for 2-m temperature, January 2013, ‘COSMO_interim_turb_sn’ experiment.

Figure 4. The same as Figure 2, but for 10-m wind speed, January 2013, ‘COSMO_interim_turb_sn’ experiment.
Generally, the first verification over hundreds of stations of the Russian Arctic has shown the best configuration of the model and domains, including different model versions, spectral nudging, turbulent scheme options, and starting times of the experiments. Many test experiments for summer and winter months were conducted. The default version without spectral nudging has shown the worst results: temperature biases are about 1°C, RMSE 3.5 – 4°C. There are specific large errors over the inland Eastern Siberia stations, because the model has strongly underestimated winter boundary layer freezing. Switch on the spectral nudging reduced the RMSE slightly, while many corrections in the turbulent scheme options decreased the RMSE significantly (up to 2.5°C for the coastal stations and 3°C for inlands), and slightly negative biases (approx. -0.5°C) were obtained. The model version 5.05 has also shown a reduction of biases. The same estimates are for the wind speed but, in general, the biases are smaller.

According to the results of the comparison, it could be concluded that an optimal model configuration has to use the ‘spectral nudging’ technique and correction of the turbulence scheme parameters for the base model version or rely on the new model version. It is also reasonable to use ERA-Interim reanalysis as driving conditions for the main long-term experiments. It is worth noting that this investigation of the sensitivity of the model parameters for such a large Arctic region was carried out at the first time; particularly, a comparison of ERA-Interim and ERA5 driving conditions. A good agreement of these results with many previous case studies confirms relevance and significance of the identified patterns.

4. Conclusions and perspectives

The detailed hydrometeorological fields in the Arctic obtained over a long period (1980 – 2016) can give new, more thorough and justified estimates of current regional climate changes, as well as extreme weather events. This can provide broad opportunities for detailed climate assessments of the Russian Arctic region, research analysis of a large number of climate parameters during the recent decades. In particular, the data can be used in studies on modern environmental changes, e.g., for the construction of various buildings, infrastructure facilities on the coast and the sea shelf, long-term planning of maritime operations, safe navigation along the Northern Sea Route, and many others.

The scientific significance of this regional reanalysis is a possibility of using this information as input data in modeling ocean's characteristics (wind waves and dynamics), coastal ecosystems (turbulent heat and moisture fluxes, greenhouse gases) for a more detailed research of individual phenomena in nested domains (extreme situations, hazardous weather events, etc.), analysis of trends in the frequency of occurrence of extreme events and features of their spatial distributions, hydrometeorological regime in coastal areas, climatology and tracking of polar mesocyclones, etc.

The scientific and applied importance of the above methodology is also in the fact that it can be used for downscaling of the global CMIP5 (or CMIP6) project climate projections and for detailed assessments of climate and environmental changes on a regional scale in the Arctic in the 21st century.

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Appendix

| Table 2. List of all test experiments with its properties and acronyms. |
|---------------------------------------------------------------|
| Experiment’s acronym | model version | reanalysis | ‘cold start’ | ‘spectral nudging’ | turbulence scheme correction |
| COSMO_interim        | 5.0           | ERA-Interim | No           | No               | Standard                      |

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| Dataset                  | Version | Model   | Initialisation | Downscaling | Resolution |
|-------------------------|---------|---------|----------------|-------------|------------|
| COSMO_interim_long      | 5.0     | ERA-Interim | Yes            | No          | Standard   |
| COSMO_interim_turb_sn   | 5.0     | ERA-Interim | No             | Yes         | Corrected  |
| COSMO_era5_turb         | 5.05    | ERA5    | No             | Yes         | Corrected  |
| COSMO_interim_v505_long | 5.05    | ERA-Interim | Yes            | No          | Standard   |

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