Cyclonic activity in high latitudes as simulated by a regional atmospheric climate model: added value and uncertainties

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Abstract
Decadal long simulations of atmospheric circulation in the high latitudes have been carried out using a multiscale atmospheric modeling system that consists of MGO global and regional atmospheric models with respective resolutions of 200, 50 and 25 km in the horizontal. The detailed analysis of extratropical cyclone activity including activity of polar mesocyclones has been conducted for the winter season using an advanced cyclone identification and tracking scheme. To enhance the applicability of high-resolution regional atmospheric modeling in the context of detailed general atmospheric circulation analysis, an end-to-end approach for cyclone trajectory calculation on a unified global and regional grid has been proposed. It has been shown that increasing modeling resolution in the high latitudes allows one to more realistically simulate the activity of baroclinic waves and the thermal regime of the Arctic troposphere. The statistical structure of cyclonic activity has been investigated depending on the spatial resolution of the modeling system and compared with that in the reanalyses and satellite-derived analyses. The performance of the atmospheric models in the simulation of extreme cyclones is evaluated.

Keywords: baroclinic waves, model resolution, added value, polar low, climate extremes, Arctic, RCM

1. Introduction

Since the publication of the Fourth Assessment Report of the International Panel on Climate Change (IPCC 2007), noticeable progress of climate models associated with improving the quality of global climate system simulations has been documented (e.g., Sillmann et al 2013). However, an increase in the quality of regional climate simulations by up-to-date global climate models (GCMs) is not so evident. Modeling discrepancies with observations at regional scales can to a large extent be connected with an insufficient spatial resolution of the GCMs, which most often falls within the range 100–200 km. A 10^2 km grid step not only imposes constraints on the quality of surface climate simulations due to excessively smoothed orography and underrepresented surface inhomogeneities, but also degrades modeling skills in reproducing the observed atmospheric circulation patterns. Coarse modeling resolution results in oversmoothed spatial structures of the baroclinic Rossby waves (Beguin et al 2012) and an inevitably skewed geometry of simulated cyclones and anticyclones. The number of pressure systems thereby tends to be underestimated, primarily due to dissipation of the kinetic...
energy of mesoscale motions (Jung et al. 2006, Blender and Shubert 2000).

Baroclinic instability activates the mechanism of the meridional heat and moisture transport in the global atmosphere by means of cyclonic activity. Therefore, the underestimation of cyclone numbers and intensities by low resolution models may lead to a weaker, as compared with observational estimates, energy supply from lower latitudes to the Arctic, and affect surface heat fluxes and radiative heating associated with cloud cover. Another consequence of the deficiencies in modeling cyclone activity is the underrepresentation of dangerous weather events connected with cyclones, e.g. gales and high-intensity precipitation. In high latitudes, such events are often associated with polar mesocyclones (polar lows), which belong to the family of maritime mesoscale atmospheric vortices. Such cyclones emerge north of the polar front, mainly during the cold season. Their cyclogenesis is explosive, and their life cycle is relatively short. Caused by polar lows, extreme weather conditions constitute a threat to coastal infrastructure and economic activity in the polar seas. According to the estimates obtained in Zahn et al. (2008), Blechschmidt (2008) and Lutsenko and Lagun (2010), the number of polar lows in the North Atlantic can amount up to 30 per winter season. The investigation of polar lows and connected extreme events may be helped by an integrated approach to calculation and an analysis of atmospheric circulation based on the application of multiscale modeling systems and sophisticated diagnostic tools that allow one to consider the evolution of the individual pressure systems with high spatio-temporal resolution.

As compared to climate models, reanalyses likely provide more realistic information on the cyclone dynamics, notably in regions with dense observational networks. These regions include primarily mid-latitude land areas. Over the oceans, mainly in high latitudes where a great deal of extratropical cyclone trajectories are located, the observations are sparse and the quality of the reanalyses may deteriorate. Thus, the reanalyses, notably at relatively low spatial resolution, significantly underestimate the number of mesocyclones relative to the satellite-derived mesocyclone database (Condron et al. 2006).

An alternative source of information about mesocyclone activity can be provided by regional climate models (RCMs), which typically have resolutions up to 0.1° × 0.1°. Regional models are high-resolution modeling systems embedded into GCMs based on the same numerical solution of the primitive equations and explicit description of physical processes, including radiative transfer in a cloudy atmosphere, convection, horizontal and vertical heat, moisture and momentum exchange, and other processes in the atmosphere and land surface. The Main Geophysical Observatory (MGO) RCM was developed at the end of twentieth century and is of considerable current use for regional climate variability and change studies in the regions of Eurasia and Arctic (Shkolnik et al. 2007, Shkol’nik et al. 2012, Shkolnik et al. 2010). The resolution of the MGO RCM has recently increased to 25 km.

Despite considerable progress in Arctic climate research using RCMs (Dethloff et al. 2012), the investigation of cyclone activity in high latitudes, including a comprehensive analysis of extreme cyclones and their migration routes, is nonetheless far from complete. This paper aims at the analysis of value added in the cyclone activity (including the activity of polar lows) simulated by a high-resolution RCM with respect to a coarser resolution global atmospheric model. Here the estimates of cyclonic activity are obtained using an advanced scheme of cyclone identification and tracking developed at the University of Melbourne. To increase the efficiency of cyclone tracking in the limited area domain of the RCM we propose a ‘seamless’ approach based on combining numerical solutions of the RCM and the GCM on a single high-resolution global grid. In addition, the paper addresses the issue of temperature biases in the Arctic troposphere depending on the modeling resolution. For comparison with the model estimates the reanalyses and satellite-based observational data analyses of cyclonic activity are used. The paper consists of four parts: introduction, descriptions of the experiments and approaches to the analysis of model calculations, the results of analysis, and a summary.

2. Experimental setup and approach to analysis

To simulate global atmospheric circulation the MGO AGCM T63L25 (Meleshko and Baidin 2013) with a horizontal grid resolution of ~200 km has been used. The RCM domain (figure 1) has been optimized in order to allow the description of a full life cycle of the majority of extratropical cyclones in the Arctic and subarctic regions. The modeling domain is centered at the North Pole with lateral boundaries located at ~50°N. The RCM domain includes 151 × 151 (301 × 301) grid points in the horizontal at 50 (25) km resolution. The RCM incorporates parameterizations of physical processes
and spatial distributions of the land surface characteristics (albedo, soil and vegetation properties) identical to those of the AGCM. Both models include the same 25 $\sigma$-levels in the vertical. Thus the RCM and AGCM differ only in the resolutions of their horizontal grids, provided that the models respectively employ finite-difference and spectral approximations of the advection terms. Global and regional models used the same prescribed evolution of the sea surface temperature (SST) and sea ice concentration (IC) derived from reanalysis NCEP-CFR (Saha et al. 2010). The monthly averaged SST/IC distributions have been linearly interpolated onto modeling grids with 200, 50, and 25 km mesh widths.

Due to highly computer-intensive calculations (this applies primarily to the experiments with the 25 km version of the RCM) all model simulations have been conducted for relatively short ten-yr intervals spanning 1980–1989. Decadal long simulations are sufficient for a satisfactory evaluation of the most prominent systematic errors in modeling. It should be emphasized, however, that more statistically confident results can be obtained in experiments of a longer duration. Three calculations in total have been carried out: one with the AGCM and two with the RCM at resolutions of 50 and 25 km (hereinafter referred to as RCM50 and RCM25, respectively) using the lateral boundary conditions derived from 6-hourly AGCM output. The system of RCM equations is numerically solved on a regular grid in a polar stereographic projection. For analysis purposes all modeling output has been interpolated onto the corresponding spherical grid ($0.5^\circ \times 0.5^\circ$, or $0.25^\circ \times 0.25^\circ$).

Evaluation of baroclinic wave activity is usually performed using either the Eulerian approach (Blackmon 1976, Hoskins and Valdes 1990), based on the filtering of modeling sea level pressure and geopotential fields, or the Lagrangian algorithm, which includes procedures for the identification and tracking of the individual pressure systems (Murray and Simmonds 1991, Gulev et al. 2001). Both approaches are widely used in the analyses of synoptic wave activity. As indicated in Hoskins and Hodges (2002), the latter approach is preferable because it allows one to carry out a comprehensive analysis of the characteristics of individual cyclones, not just generalized statistical properties of their population. It has been noted in section 1 that the identification and tracking of individual cyclones using high-resolution modeling output best suits the consistent assessment of extreme cyclones and related dangerous weather events.

The study employs the cyclone identification and tracking scheme (CITS) developed by Murray and Simmonds (1991) and Simmonds and Murray (1999). In these studies the basic principles and techniques of the CITS are described. As an input the scheme requires the spatial distributions of sea level pressure obtained every 6 h from model simulations and reanalyses. Analysis of cyclone activity has been conducted for the winter season (December–January–February) in the Northern Hemisphere considering that there is large dynamic instability of the atmosphere. In order to filter out noise and the influence of different methods of reducing pressure to the mean sea level in the models and reanalyses, some restrictions on the calculated cyclone trajectories have been imposed. Cyclones with lifetimes below 12 h and surface wind velocities (available at 6-hourly intervals from model simulations and reanalyses) exceeding 30 m s$^{-1}$, as well as cyclones generated over land and having trajectories shorter than 10$^3$ km, have been excluded from the analysis.

Using the CITS, model simulations, ERA-40 (Uppala et al. 2005) and NCEP-CFR reanalyses (hereinafter referred to as ERA and CFS, respectively) a set of characteristics of cyclones has been calculated and an intercomparison of cyclone properties in the AGCM, RCM and reanalyses has been conducted. It is appropriate to note at this point that a range of in-depth investigations of cyclonic activity in the reanalyses has been conducted over the past decade (Zolina and Gulev 2002, Rudeva and Gulev 2007, Hodges et al. 2011).

The ERA and CFS reanalyses belong to different generations: the older lower resolution ERA (80 km resolution) was developed in 2005, while the CFS (38 km resolution), which is based on the coupled atmosphere and ocean models, was created in 2010. The 6-hourly ERA and CFS sea level pressure fields have been obtained at $2.5^\circ \times 2.5^\circ$ and $0.5^\circ \times 0.5^\circ$ ($2.5^\circ \times 2.5^\circ$) resolutions, respectively. Despite the different resolutions of the forecast models both reanalyses include for the period 1980–1989 the same observational database, which should bring together their estimates and to some degree overcome possible effects associated with different resolutions (Hodges et al. 2003). In addition to the resolution, one should specify other sources of the uncertainty in estimates of cyclone activity in the reanalyses, such as different methods of observational data assimilation and numerical implementations of the forecast models. For instance, as noticed above, the CFS incorporates a numerical model of the ocean dynamics, while the ERA includes prescribed SST/IC distributions derived from observations (this imposes limitations on the feedback between atmosphere and ocean dynamics and thermodynamics). The above should be taken into account when comparing reanalyses to each other and to model simulations which have been conducted here in the framework of a single strategy.

It is known that tracking cyclones in a limited area is difficult since part of the information on atmospheric variables is presented on an AGCM grid, i.e. outside the RCM domain. As a result of this, the calculated trajectories of cyclones crossing the lateral boundaries of the RCM domain appear to be discontinuous. This implies that the use of high-resolution RCM data within the general context of the detailed evaluation of global cyclonic activity requires optimization. In this paper we propose an approach to ‘seamless’ cyclone tracking on a global grid, accounting for both the AGCM and RCM solutions. The implementation of this approach consists of the following steps. First, the global 6-hourly distributions of sea level pressure simulated by the AGCM at $1.8^\circ$ resolution are interpolated to a high-resolution global grid that corresponds to the grid of the embedded RCM version (either $0.5^\circ \times 0.5^\circ$ or $0.25^\circ \times 0.25^\circ$). Next, the AGCM solution at the grid points with coordinates that coincide with coordinates of the RCM grid points is replaced by the RCM solution for the corresponding 6-hourly
interval. Thus, the resulting global grid includes a combined solution of the global and regional models for the sea level pressure. The procedure is repeated for all 6-hourly intervals for the entire period of the simulation. Then, the resulting combined global data is used as input to the CITS. Given the smooth transition from the AGCM-simulated pressure to that of the RCM near the lateral boundaries, the approach allows one to build the full cyclone trajectory without significant distortion, to evaluate the complete life cycle of cyclones that enter a limited area, and to study their transformations due to mesoscale forcings in the interior of the RCM domain.

It should be emphasized, however, that assuming one-way interactions between the AGCM and the RCM (the numerical solution of the RCM does not feed back into the driving global model), there are still limitations on the description of the cyclone trajectories that are directed outwards from the RCM domain. This issue can emerge for cyclones that are (1) generated outside the region, enter the RCM domain and have lifetimes greater than the time of passage through an area with a linear size of 7500 km, and (2) generated inside the region and move near the lateral boundary (∼50°N) southwards. Preliminary analysis of the cyclone trajectories has shown that such systems constitute less than 1% of the total number of cyclones whose life cycle is satisfactorily described by the modeling system owing to the optimum location and size of the RCM domain.

3. Analysis of the simulations

Adveective transport of heat from low latitudes provides more than 50% of the annual heat influx to the Arctic climate system (Przybylak 2003). Most of the heat (95%) is transported to the high latitudes by atmospheric circulation, and only a small part (5%) by the ocean currents. In winter, when the solar radiation in the Arctic is close to zero, the transfer of heat to high latitudes by synoptic and low-frequency eddies is the key mechanism for ‘heating up’ the Arctic atmosphere, which loses heat at its top. An important role in the transport of heat and moisture to the pole is played by large cyclones with sizes of 10⁵ km, trajectory lengths of several thousands of kilometers and characteristic lifetimes of a few days. It is possible that insufficient intensity of such cyclones in climate models can lead to significant errors in the calculation of the thermal regime of the Arctic troposphere. Let us consider the broad outlines of cyclonic activity as inferred from model simulations and reanalysis.

Table 1 contains the number of cyclones for ten winters generated in the 50°–90°N area. As can be seen in the table, there are significant differences between reanalyses in the cyclone count. The number of cyclones in the CFS reanalysis is larger than that in ERA by 1627 cyclones (47%). Such differences may be either due to the different degrees of physical comprehensiveness of the forecast models and their spatial resolutions discussed in section 2 or due to the resolutions of the pressure fields used (respective resolutions are two and five times higher in CFS relative to ERA). We have assessed the influence of the spatial resolution of the pressure fields on the calculated cyclone statistics in the CFS reanalysis. The calculated cyclone quantity for resolutions 0.5° × 0.5° and 2.5° × 2.5° (the latter corresponds to the resolution of ERA) implies that the five-fold decrease in pressure field resolution results in a reduction of the cyclone number by 478 systems (9%). This difference is 3.5 times smaller than the above difference between CFS and ERA, suggesting that the most significant uncertainties of the estimates of cyclone activity in the reanalyses are caused by the underlying formulations of the forecast models and the observational data assimilation methods. The AGCM results are close to those of ERA; the use of the RCM leads to an increase in cyclone number that is in agreement with higher resolution CFS estimates. Note that by doubling the resolution of the regional model (from 50 to 25 km) the number of cyclones increases by 11%. The results of RCM50, in which the model resolution over the Arctic is four times higher than that of the AGCM, give the number of cyclones larger by 34% as compared to the global model. Therefore, the relative increase in the number of cyclones associated with doubling the resolution in the range of 50–200 km grid spacing is ∼17%. Such an increase is 1.5 times larger than the above-mentioned relative increase in the number of cyclones for the range of finer resolutions. The absolute increase in the number of pressure systems by doubling the resolution in the two resolution ranges is equal to 543 and 636 cyclones, respectively. The cyclone count dependence on grid resolution in the models is generally consistent with estimates previously obtained (Jung et al 2006), where the sensitivity of extratropical cyclone count to horizontal grid resolution in the ECMWF forecast model was investigated.

Table 2 contains the winter mean area averaged cyclone track density (cyclone days/winter) in the latitude ranges 50°–90°N, 60°–90°N and 70°–90°N.

Table 1. Total number of cyclones in the latitude range 50°–90°N during ten winter seasons (DJF).

| Resolution | CFS | ERA | RCM25 | RCM50 | AGCM |
|------------|-----|-----|-------|-------|------|
| 0.5° × 0.5° | 5100 (4622) | 3473 | 5517 | 4974 | 3703 |

Table 2. Ten-winter mean area averaged cyclone track density (cyclone days/winter) in the latitude ranges 50°–90°N, 60°–90°N and 70°–90°N.

| Resolution | >50°N | >60°N | >70°N |
|------------|-------|-------|-------|
| CFS        | 30.2  | 27.5  | 28.3  |
| RCM25      | 27.2  | 25.1  | 29.9  |
| RCM50      | 25.8  | 23.3  | 27.1  |
| AGCM       | 21.5  | 16.9  | 17.4  |
| ERA        | 25.6  | 24.2  | 25.7  |
Figure 2. Ten-year winter mean density of cyclone tracks (cyclone days/winter) in ERA (a), CFS (b), AGCM simulation (c), RCM50 (d) and RCM25 (e). The RCM simulation domain is denoted by a black square. Regions with high orography (above 1000 m) are masked in black.

per unit area equivalent to a 5° spherical cap, ∼10⁶ km²) in the reanalyses and model simulations. The table includes estimates for different areas (50°–90°N, 60°–90°N and 70°–90°N). The largest track density can be found in the reanalysis CFS, and the least in the AGCM. It should be noted that despite the small difference in the number of cyclones between the AGCM and ERA (the cyclone count in the former is larger than that in ERA by 7%), the values of density between them differ considerably. The density in the AGCM is underestimated by 30% relative to ERA and CFS. The RCM application tends to ameliorate the above deficiency in the AGCM, as both the RCM50 and RCM25 experiments reveal better agreement with reanalyses.

Figure 2 shows the spatial distribution of the cyclone track density. It can be seen that the qualitative picture of the cyclonic activity is in satisfactory agreement across reanalyses; however, there is a somewhat greater density of trajectories in CFS over the North Atlantic and Barents Sea as compared to ERA. The reason for the area mean track density underestimation in the AGCM is the spatial mismatch of cyclone tracks in the global model and reanalyses. The AGCM-simulated patterns over the Arctic and north-western Eurasia, as well as over Siberia, appear to be half the size of those in the reanalyses. Over the Pacific the density of trajectories in the AGCM turns out to be higher than that in ERA by 20%, and in some areas of the Atlantic and southern mid-latitudes of the Eurasia model the simulated density is 1.5–2 times larger. As can be seen in figure 2, the above disagreement in the track density distributions between global model simulations and reanalyses can in a large part be eliminated in the 50°–90°N area when the trajectory calculation takes into account a high-resolution RCM simulation. The most noticeable differences between the RCM and AGCM are pronounced over the Arctic Ocean, where during the winter season there is a two to three times larger cyclone track density in the RCM as compared to that in the driving global model.

Along the Arctic coast of eastern Eurasia (∼70°N) the regional model simulates a density of trajectories greater by 20–30% with respect to the reanalyses. It is noted in section 1 that Arctic regions include a sparse observational network and therefore cyclone activity in the reanalyses over these regions may be underestimated. On the other hand, the RCM and AGCM use the same description of physical processes, generalized in order to minimize errors in global climate simulations. This description needs adaptation to climate calculations on a regional scale. Thus, the use of the same parameterization of vertical turbulent exchange of heat and moisture for mid- and high-latitudes may lead to an underestimation of the stability of the Arctic atmosphere in winter (Dethloff et al 2001, Grachev et al 2013). A weaker stability of the atmosphere, and hence its greater baroclinity,
can maintain higher cyclonic activity in the RCM with respect to reanalysis over the Arctic.

The estimated cyclone travel velocity in the reanalyses falls in the range 20–60 km h\(^{-1}\) (the figure is not shown). Lower velocities of cyclones are typically found in high latitudes due to the frequent occurrence of slow cyclones undergoing cycolysis in the Arctic. The spatial structure of the velocity distributions simulated by global and regional models is in good agreement with both CFS and ERA. However, the AGCM underestimates cyclone velocity in the areas of very low track density in the Arctic shown in figure 2. In this region the cyclones in the AGCM are two to three times slower compared to cyclones in the reanalyses and the RCM. In table 3 are shown the corresponding area averaged velocities in the range of latitudes north of 50\(^\circ\), 60\(^\circ\) and 70\(^\circ\) N.

Figure 3 demonstrates the spatial distribution of the mean radius of cyclones (weighted mean angular distance from the cyclone center to the points at which the Laplacian of pressure is equal to zero). The cyclone size in GCM, CFS and ERA are generally in good agreement (the respective area mean radius averaged over 50°–90°N area is 5.4°, 4.7° and 5.2° latitude) with a slightly smaller cyclone radius in the CFS reanalysis. In the experiments RCM25 and RCM50, the values of radii are 4.5° and 4.6°, respectively. The relationship of cyclone sizes in models and reanalyses reflect the dependence of the mean cyclone size on the modeling resolution. The smaller sizes of cyclones in RCM50, RCM25 and CFS compared to those in ERA and AGCM can be explained by the better description of mesoscale cyclogenesis in the former, resulting in a more significant contribution of small size systems to the overall cyclone statistics.

The mean cyclone lifetime (~2 days) agrees well across models and reanalyses (the figure is not shown). More substantial differences can be found for the average depth of cyclones (the difference between the central pressure and the value of pressure averaged over the points at which the Laplacian of pressure turns to zero). The mean cyclone depths (the figure is not shown) in CFS and ERA in the area 50°–90°N are 6.5 and 7.3 hPa, respectively. The models tend to simulate relatively shallow depressions with mean depths

| Table 3. Ten-winter mean area averaged cyclone travel velocity (km h\(^{-1}\)) in the latitude ranges 50°–90°N, 60°–90°N and 70°–90°N. |
|---------------------------------|--------|--------|--------|
|                                | >50°N  | >60°N  | >70°N  |
| CFS                            | 34     | 31     | 29     |
| RCM25                          | 31     | 29     | 29     |
| RCM50                          | 32     | 29     | 29     |
| AGCM                           | 31     | 27     | 23     |
| ERA                            | 34     | 32     | 30     |
In the Arctic the cyclone depths in RCM and CFS are mostly in the range 5–6 hPa, while in the global model and ERA the depths are lower (3–5 hPa) and higher (5–7 hPa), respectively.

As discussed above, during winter the heat balance of the Arctic atmosphere depends substantially on heat and moisture transport provided by synoptic scale circulation (Newman et al. 2012, Wu et al. 2011). Let us evaluate to what extent the modeling performance in the simulation of the tropospheric thermal regime and cyclonic activity can be reconciled. For the evaluation we compare the modeling temperature of the troposphere with that in the reanalysis. Figure 4 shows the ten-year mean latitude–altitude cross-section of differences between the AGCM (both alone and combined with the RCM) simulated winter temperature and the CFS reanalysis. It can be seen that the zonal mean temperature biases in the northern mid-latitudes and in the Arctic clearly depend on the spatial resolution of the modeling system. Thus, in the stand-alone AGCM simulation the winter temperature is underestimated relative to the reanalysis up to 7°C over the pole (in the area of 50°–80°N, the cooling is 2–4°C relative to CFS). The use of the RCM at 50 km resolution (figure 4(b)) leads to reducing modeling temperature bias by a factor of two. By doubling the RCM resolution the systematic cooling in the middle and lower troposphere of the Arctic is almost eliminated (figure 4(c)). It should be pointed out that there is some increase in the temperature error near the tropopause in RCM50 (cooling by 2–4°C) and RCM25 (cooling by 4–6°C).

The causes of these biases may be as follows. Above a level of 200 hPa the state of atmosphere is close to barotropic and the positive effect of the RCM resolution is not evident. Numerical solution of the RCM at levels aloft is stronger dependent on the lateral boundary conditions as compared with the lower modeling levels. The errors in driving fields in the upper atmosphere can further develop in the interior of the RCM domain (Giorgi and Mearns 1999). As can be seen in figure 4(a), near the lateral boundary of the RCM domain at the 150 hPa level the global model underestimates the air temperature by 3–5°C relative to the reanalysis. Such biases can lead to the above understimation of the temperature in the RCM since AGCM data is used at the lateral boundaries of the RCM domain. The added value of the RCM is pronounced in the middle and low troposphere, where the atmosphere is baroclinic and temperature contrasts are significant. Shown in

![Figure 4](image.png)
Let us evaluate the influence of modeling resolution on the quality of simulating polar lows. As indicated in section 1, polar lows are relatively small short-lived atmospheric vortices accompanied by extreme weather conditions near the surface. The basic features of the polar lows are as follows: the lifetime is 4–48 h (typically 12–36 h), the size is 100–600 km (rarely 800–1000 km), the surface wind velocity and precipitation rate in the cyclone exceed 15 m s\(^{-1}\) and 20 mm h\(^{-1}\), respectively. Virtually the entire life cycle of polar lows proceeds over oceans, since they are subjected to intense cycloysis over land. To separate polar lows from the total number of extratropical cyclones whose characteristics are discussed above, the following selection criteria have been used: (1) the cyclone radius at each stage of its life cycle does not exceed 3.5° latitude (corresponds to the diameter of a cyclone just below 800 km), (2) the initial point of the cyclone trajectory is located over the ocean, (3) the surface wind velocity at one or more modeling grid points within the cyclone is in the range 15–30 m s\(^{-1}\) in each 6-hourly stage of the life cycle, and (4) the minimum lifetime of the cyclone is assumed to be 12 h. The intensity of precipitation within cyclones in this study has not been considered. A surface wind in the North Atlantic polar lows in the range of 15–17 m s\(^{-1}\) is observed for 26% of cyclones, the range of 17–19 m s\(^{-1}\) falls on 36% of cases, and winds of 19–21 m s\(^{-1}\) are observed in approximately 29% of polar lows (Blechschmidt 2008). Higher velocities (21–23 m s\(^{-1}\)) are detected for 9% of the polar lows. It should be noted that the use of the last criterion allows us to assess only the lower bound of the quantity of polar lows, since up to 20% of their population have lifetimes well below 12 h according to satellite-derived estimates (Blechschmidt 2008). Calculation of the cyclone trajectories whose lifetime is less than 12 h can be carried out using the pressure fields at higher temporal resolution (1–3 h) compared to the 6-hourly data used in this study.

Figure 5 shows the trajectories of mesocyclones in the CFS reanalysis and atmospheric models. The ERA reanalysis has been excluded from the analysis because of its low output resolution. It can be seen that the RCM50 and...
RCM25 simulations provide a significantly larger number of mesocyclones as compared to CFS and AGCM. The areas of the intensive mesoscale cyclogenesis in winter are reproduced satisfactorily by the RCM. Such areas include the North Atlantic, Barents Sea basin, Canadian Arctic and northern Pacific (Lagun and Yazev 1994, Lutsenko and Lagun 2010, Turner et al. 1993). Table 4 contains the total number of trajectories of mesocyclones and their mean maximum surface wind velocity. A reasonable agreement can be found between modeling winds and observational estimates (Blechschmidt 2008); however, one should note that the RCM tends to overestimate the maximum surface wind velocity in the mesocyclones by 1–2 m s\(^{-1}\) relative to the reanalysis, AGCM and observational estimates.

We have evaluated the agreement of the intensity of mesoscale cyclogenesis in the models with that derived from observations. It should be noted that at present a homogeneous global climatology of mesocyclones does not exist. For some areas, such as the North Atlantic and, particularly, its North-European basin, where the activity of polar lows is one of the most intensive, there is abundant satellite imagery with information on mesoscale cloud patterns that are a starting point for mesoscale eddy identification. In this study the coordinates of the polar lows based on the analysis of satellite images for the period 1981–1990 over the North-European basin and the Kara Sea (Lutsenko and Lagun 2010) have been used for the comparison with model simulations.

Figure 6 displays locations of the polar lows found in the observations, obtained from CFS reanalysis and simulated by atmospheric models for the ten winter seasons. The total number of polar lows in the region is shown in table 5. One can see that the frequency of polar lows in the reanalysis and AGCM corresponds to ~1 cyclone per two years. According to RCM simulations the number of polar lows, regardless of the RCM resolution, appears to be much larger compared to the reanalysis and AGCM, but still underestimates observations. As can be seen in figure 6, the RCM satisfactorily reproduces spatial patterns of mesoscale cyclogenesis in the region. Some discrepancies between the model and observation analysis occur over the Barents Sea, where the majority of polar lows is observed. The area of polar low activity in the RCM is shifted to the west and includes northern parts of the Norwegian Sea and the Greenland Sea basin.

The mean simulated diameter of polar lows in the models and reanalysis is close to 640 km. The mean polar low size in the observations as estimated by Lutsenko and Lagun (2010) to be 3–3.5 times smaller (~200 km). The two cyclones in their analysis have diameters of 50 km. In 33 observed cases the mesocyclone size is ~100 km. The mean diameter of polar lows over the Nordic Seas according to another observational analysis (Blechschmidt 2008) is estimated to be twice as large (~400 km), suggesting considerable uncertainty in the evaluation of the observed polar lows. The minimum diameters of the polar lows in the RCM25 experiment, global model and reanalysis are 380, 530 and 480 km, respectively. The differences in polar low size between the RCM and observations indicate that increasing the modeling grid resolution to 25 km leads, as shown above, to a noticeable improvement in the description of the mesoscale structure of baroclinic waves; however, it does not allow one to assess the full range of atmospheric disturbances near the lower bound of the mesoscale. In order to better describe the characteristics of polar lows, models with mesh widths less than 25 km are clearly needed.

### 4. Summary

Ten-year climate simulations have been carried out using a multiscale atmospheric model system that consists of a 200 km resolution global model and a 50 (25) km resolution RCM focused on high and northern mid-latitudes. The size of the RCM domain has been optimized in order to include the areas of the most intense activity of extratropical cyclones in the Arctic and subarctic regions. The statistical structure of cyclonic activity, depending on the spatial resolution of the modeling system, has been investigated and compared with that in the reanalyses and observational analyses. The performance of atmospheric models in the simulation of extreme cyclones is evaluated. The key findings of the study are as follows:

1. A ‘seamless’ approach for the calculation of cyclone trajectories on a single global grid that includes both the AGCM and RCM numerical solutions has been implemented. The approach aims at wider application of up-to-date regional climate models for cyclone tracking studies in the broad context of general atmospheric circulation analyses. This is essential in cases when available computing resources limit the mass–volume application of high-resolution global models.

2. It has been shown that the increase in modeling resolution allows one to simulate cyclone activity closer to that in high-resolution reanalysis and leads to a reduction in the modeling errors in the thermal regime of the polar troposphere.
Figure 6. Spatial distribution of polar lows based on satellite imagery analysis (a), simulated by RCM25 (b), RCM50 (c), AGCM (d) and in the CFS reanalysis (e). Observational data (OBS) is presented on a $0.5^\circ \times 1.0^\circ$ grid (Lutsenko and Lagun 2010). The symbol size corresponds to the polar low count in a grid cell during ten winter seasons spanning 1981–1990.

(3) It has been found that a spatial resolution of 25–50 km enables one to obtain estimates of polar mesocyclones that are in qualitative agreement with observational estimates for the North-European basin. However, the RCM tends to simulate larger polar lows as compared to observations.
(4) Since gales have been used to identify the polar lows, the agreement between the RCM-simulated number of polar lows and that observed implies the significant potential of the regional model in assessing the frequency and intensity of extreme wind events in the region.

The added value in cyclone activity due to increasing the modeling grid resolution can be adequately investigated in the framework of global and regional models that share the same vertical structure of the atmosphere and description of physical processes, but differ in their horizontal resolutions. This is the reason why in this study the lateral boundary conditions for the RCM simulations have been obtained from the ‘parent’ global atmospheric model, not from other global climate models or reanalyses.

Further studies of cyclone activity using systems of global and regional atmospheric models may include longer simulations and build ensembles of independent regional and global models. The polar low statistics obtained with such ensembles will provide an opportunity to assess the intermodel uncertainty in the simulation of polar lows, to better reconstruct the spatio-temporal variability of mesoscale cyclones and to classify them according to the intensity and duration of the accompanying extreme weather events. Along with that, future efforts should be focused on improving the validation of polar lows in the modern reanalyses.

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References

Beguin A, Martius O, Sprenger M, Spichtinger P, Folini D and Wernli H 2012 Tropopause level Rossby wave breaking in the Northern Hemisphere: a feature-based validation of the ECHAMS-HAM climate model Int. J. Climatol. at press (doi:10.1002/joc.3631)
Blackmon M L 1976 A climatological spectral study of the 500 mb geopotential height of the Northern Hemisphere J. Atmos. Sci. 33 1607–23
Blechschmidt A-M 2008 A 2-year climatology of polar low events over the Nordic Seas from satellite remote sensing Geophys. Res. Lett. 35 L09815
Blender R and Shubert M 2000 Cyclone tracking in different spatial and temporal resolutions Mon. Weather Rev. 128 377–84
Condron A, Bigg G R and Renfrew I A 2006 Polar mesoscale cyclones in the Northeast Atlantic: comparing climatologies from ERA and satellite imagery Mon. Weather Rev. 134 1518–33
Dethloff K, Ababeng C, Rinke A, Hebestadt I and Romanov V 2001 Sensitivity of Arctic climate simulations to different boundary layer parameterizations in a regional climate model Tellus A 53 1–26
Dethloff K, Rinke A, Lynch A, Dorn W, Saha S and Handorf D 2012 Arctic regional climate models Arctic Climate Change (Atmospheric and Oceanographic Sciences Library vol 43) (Dordrecht: Springer) pp 325–56
Giorgi F and Mearns L 1999 Introduction to special section: regional climate modeling revisited J. Geophys. Res. 104 6335–52
Grachev A A, Andresen E L, Fairall C W, Guest P S and Persson P O G 2013 The critical Richardson number and limits of applicability of local similarity theory in the stable boundary layer Bound.-Layer Meteorol. 147 51–82
Gulev S K, Zolina O and Grigoriev S 2001 Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data Clim. Dyn. 17 795–809
Hodges K I, Hoskins B J, Boyle J and Thornicroft C 2003 A comparison of recent reanalysis datasets using objective feature tracking: storm tracks and tropical easterly waves Mon. Weather Rev. 131 2012–37
Hodges K I, Lee R W and Bengtsson L 2011 A comparison of extratropical cyclones in recent reanalyses ERA-Interim, NASA MERRA, NCEP CFSR, and JRA–25 J. Clim. 24 4888–906
Hoskins B J and Hodges K I 2002 New perspectives on the Northern Hemisphere winter storm tracks J. Atmos. Sci. 59 1041–61
Hoskins B J and Valdes D J 1990 On the existence of storm-tracks J. Atmos. Sci. 47 1854–64
IPCC 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon (Cambridge: Cambridge University Press)
Jung T, Gulev S K, Rudeva I and Soloviov V 2006 Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model Q. J. R. Meteorol. Soc. 132 1839–57
Lagun V E and Yazev A I 1994 The global distribution and time variability of the synoptic disturbances in the atmosphere USSR Acad. Sci. Rep. 334 642–5 (in Russian)
Lutsenko E and Lagun V 2010 Polar meso-scale cyclonic eddies in the Arctic atmosphere Handbook, Arctic and Antarctic Environmental Monitoring (Atmospheric and Oceanographic Sciences Library vol 43) (Dordrecht: Springer) pp 325–56
Meleshko V P and Baidin A V 2013 Response of atmospheric climate to reduction of sea ice and other external forcings during the recent decades MGO Proc. 56 80–117 (in Russian)
Murray R J and Simmonds I 1991 A numerical scheme for tracking cyclone centres from digital data: part I. Development and operation of the scheme Aust. Meteorol. Mag. 39 155–66
Newman M, Kildalis G N, Weickmann K M, Ralph F M and Sardeshmukh P D 2012 Relative contributions of synoptic and low-frequency eddies to time-mean atmospheric moisture transport, including the role of atmospheric rivers J. Clim. 25 7341–61
Przybylak R 2003 The Climate of the Arctic (Dordrecht: Kluwer Academic)
Rudeva I and Gulev S K 2007 Climatology of cyclone size characteristics and their changes during the cyclone life cycle Mon. Weather Rev. 135 2568–87
Saha S et al 2010 The NCEP climate forecast system reanalysis Bull. Am. Meteorol. Soc. 91 1015–57
Shkol’nik I M, Meleshko V P, Efimov S V and Stafeeva E N 2012 Changes in climate extremes on the territory of Siberia by the middle of the 21st century: an ensemble forecast based on the MGO regional climate model Russ. Meteorol. Hydrol. 37 73–84
Shkolnik I M, Meleshko V P and Kattsov V M 2007 The MGO climate model for Siberia Russ. Meteorol. Hydrol. 32 351–9
Shkolnik I M, Nadyozhina E D, Pavlova T V, Molkentin E K and Semioshina A A 2010 Snow cover and permafrost evolution in Siberia as simulated by the MGO regional climate model in the 20th and 21st centuries Environ. Res. Lett. 5 015005
Sillmann J, Kharin V V, Zhang X, Zwiers F W and Bronaugh D 2013 Climate extremes indices in the CMIP5 multimodel ensemble: part 1. Model evaluation in the present climate J. Geophys. Res. Atmos. 118 1716–33
Simmonds I and Murray R J 1999 Southern extratropical cyclone behaviour in ECMWF analyses during the FROST special observing periods Weather Forecast. 14 878–91
Turner J, Lachlan-Cope T A and Thomas J P 1993 A comparison of Arctic and Antarctic mesoscale vortices J. Geophys. Res. 98 13019–34

Uppala S et al 2005 The ERA re-analysis Q. J. R. Meteorol. Soc. 131 2961–3012
Wu Y, Ting M, Seager R, Huang H-P and Cane M A 2011 Changes in storm tracks and energy transports in a warmer climate simulated by the GFDL CM2.1 model Clim. Dyn. 37 53–72
Zahn M, von Storch H and Bakan S 2008 Climate mode simulation of North Atlantic Polar Lows in a limited area model Tellus 60 620–31
Zolina O and Gulev S K 2002 Improving the accuracy of mapping cyclone numbers and frequencies Mon. Weather Rev. 130 748–59