Investigation of boreal storm tracks in historical simulations of INM CM5 and reanalysis data

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Abstract. Ensemble simulations of the 5th version of the INM coupled climate model are employed to analyze the Northern Hemisphere storm track characteristics in the winter season. The results show similar features of the North Atlantic and North Pacific storm tracks that dominate in the Northern Hemisphere in the model simulations and reanalysis data. A composite analysis of the weakening/strengthening of Arctic stratospheric polar vortex events with their influence on the troposphere shows an equatorward/poleward shift in the North Atlantic storm track. As a response to the recent Arctic amplification, a poleward shift in the Pacific storm track and weakening of the North Atlantic storm track have been revealed when comparing two periods: 1998-2014 and 1980-1997.

1. Introduction

Storm tracks are marked by regions with the strongest meridional temperature gradient where extratropical cyclones are generated. These intense cyclones bring strong winds and heavy precipitation. The storm tracks transport large amounts of heat, momentum, and moisture poleward, and are observed in the mid-latitudes with a maximum at 40°N. The strongest activity of two dominant storm tracks in the Northern Hemisphere - over North Atlantic and North Pacific - is observed in the cold season [1, 2]. The North Atlantic storm track peaks in mid-winter, whereas the North Pacific storm track peaks in spring and fall and displays a mid-winter weakening (suppression) when the zonal wind speed exceeds a threshold of 44 m/s at 250 hPa, which, in turn, is accompanied by reduced baroclinic wave activity [3, 4]. The European and Mediterranean weather in winter is defined by cyclone propagation generated in the storm track area in North Atlantic. Shift or expansion of storm tracks leads to precipitation and weather changes. In the Southern Hemisphere storm tracks are observed between 60°S and 30°S over a more continuous band with a maximum over the Indian Ocean.

The interannual variability of storm tracks is influenced by ENSO / Southern Oscillation, quasi-biennial oscillation of stratospheric wind over equator (QBO), and Arctic stratospheric polar vortex changes. The North Pacific storm track area shifts equatorward and expands eastward in seasons of extreme El Niño. As a result, stronger cyclones bring heavy precipitation and mudflows to the western USA. The La Nino seasons are associated with a North Pacific storm track shift in the opposite direction [5]. During the easterly QBO, a poleward shift of the North Pacific storm track is observed. The North Atlantic storm track is characterized by downward shrinking in easterly QBO and upward expansion in westerly QBO winters [6]. Weakening of the Arctic stratosphere polar vortex is accompanied by an equatorward shift of the tropospheric jet stream related to storm tracks, whereas strengthening of the polar vortex leads to a poleward shift [7, 8, 9].

On the subseasonal time scale, the North Pacific storm track is influenced by the Madden–Julian oscillation (MJO) [6]. The eastward movement of anomalous tropical convection associated with the
MJO over the Indian Ocean and the western Pacific is accompanied by the extension of the North Pacific storm track northeastward.

The storm track time–mean position and intensity depend on the surrounding areas: the underlying surface which forms the lower boundary, the overlying stratosphere, and the tropical and high latitude troposphere on either side.

Considering significant impacts of storm tracks on the weather and regional climate and its response to climate change [10-13], our study is aimed at analyzing storm tracks realization in simulations of the 5th version of a coupled climate model developed at the Marchuk Institute of Numerical Mathematics of the Russian Academy of Sciences (INM CM5). The INM CM5 is the only Russian climate model involved in a Coupled Model Intercomparison Project (CMIP). It should be noted that notwithstanding the recent progress in the development of climate models mainly related to improvement of its horizontal resolution, increase of the vertical levels and higher upper boundary, there are still problems with realization, by such models, of the stratosphere-troposphere dynamic coupling and critical extratropical circulation processes, such as heat and cold waves and extreme precipitation events [14].

Analysis of 12 climate models has shown that biases in the winter European blocking frequency are related to the North Atlantic storm track tilt [15]. Therefore, improvement in the simulation of storm tracks in climate models is essential for better representation of other important extratropical dynamic processes.

2. Data and methods of analysis

To analyze the storm tracks we used data of five 50-year realizations of ensemble simulations with the INM CM5 with a longitude-latitude resolution of 2° × 1.5° in the atmosphere. These simulations differ from each other by slightly disturbing initial conditions. Also, two 50-year simulations of the coupled and the only atmospheric model version with a high resolution of 0.67° × 0.5° were analyzed. All these model data cover the final period (1965–2014) of the historical climate simulation for 1850–2014.

The INM CM5 includes atmosphere, ocean, sea ice, land, and aerosol modules [16]. The main novelties in comparison to the previous version of this model are improvement of the atmosphere model (increase in the vertical resolution for the upper stratosphere and lower mesosphere and improvement of the parameterization of large-scale condensation and cloudiness, and addition of the aerosol module [17]). Important model improvements in the description of the stratosphere are the ability to simulate the quasi-biennial oscillation of the equatorial zonal wind in the stratosphere and better statistics of Sudden Stratospheric Warming events. The land model includes modules responsible for the calculation of soil, underlying surface, and vegetation parameters.

Recommended for Phase 6 of the CMIP, the following external forcings on the climate system were specified for all model simulations: concentrations of CO₂, CH₄, and N₂O as average annual values; volcanic aerosol concentration as monthly mean fields depending on the latitude and height; ozone values as monthly mean fields depending on the longitude, latitude, and height and taking into account the ozone layer depletion since the early 1980s; the emission of SO₂, black and organic carbon as monthly mean fields depending on the longitude and latitude. The solar constant and the spectral distribution of radiation were specified in the form of monthly mean values.

The following storm track characteristics were calculated using a high-pass filter [18]:

the variance \( \nu \nu = \left[ v(t + 24) - v(t) \right]^2 \)

the eddy momentum flux \( \nu u = \left[ u(t + 24) - u(t) \right] \cdot \left[ v(t + 24) - v(t) \right] \cos \varphi \)

the eddy heat flux \( \nu T = \left[ v(t + 24) - v(t) \right] \cdot \left[ T(t + 24) - T(t) \right] \)

the eddy moisture flux \( \nu q = \left[ v(t + 24) - v(t) \right] \cdot \left[ q(t + 24) - q(t) \right] \).
where $u$, $v$ are the zonal and meridional wind velocity, $T$ is the temperature, $q$ is the specific humidity, $\varphi$ is the latitude, the overbar over the right-hand side denotes the average over a selected period (usually the monthly mean), and $t+24$ means the next time step (or day).

If the storm track variance $vv$ is a part of the eddy kinetic energy transferred from eddies to the zonal flow, the eddy momentum flux $uv$ characterizes the interaction of baroclinic waves (that are components of the storm tracks) and a large-scale low-frequency circulation. The eddy heat flux $vT$ defines the transfer of sensible heat, whereas the transfer of latent heat associated with evaporation and condensation is estimated by the moisture flux $vq$.

The storm track parameters calculated by the INM CM5 were compared with the ones derived using NCEP reanalysis data from 1968 to 2018 and ERA-Interim reanalysis data from 1979 to 2018. Since the storm track parameters in both reanalysis data are in agreement, only figures with NCEP reanalysis are shown.

3. Results

3.1. Realization of storm tracks in model simulations

The obtained results show that spatial structure and temporal variability of the storm tracks in model simulations are comparable with NCEP and ERA-Interim reanalysis data. However, the maximum variance of both storm tracks in the model simulation is 20-25% weaker (Figure 1a-b).

![Figure 1](image-url)

**Figure 1.** Storm track variance [m$^2$/s$^2$] at 300 hPa in December-February in model simulations (experiments HIST1-5) (a), with high resolution and interactive ocean HIRES-HIST (b), with high resolution and specified SST HIRES-AMIP (c) averaged over 1965 - 2014, the same but in NCEP reanalysis data averaged over 1968-2018 (d). Latitudes are from 20° N to 90° N.
Improvement of both storm-tracks variance realization in December-February averaged over 50 winters was found in the simulation with high-resolution INM CM5 in comparison with the low resolution model (Figure 1c). The realization of both storm tracks in the high-resolution atmospheric model simulation with specified sea surface temperature (SST) is better than with interactive ocean (Figure 1d). This is possibly due to biases in the simulated SST.

Analysis of the interseasonal variability of storm tracks in the upper troposphere reveals similar features in the model simulation and reanalysis data: the maximum variance of the North Pacific storm track is observed at 40-50° N in fall and spring and suppression, in the mid-winter (Figure 2a-b). The North Atlantic storm track displays the maximum variance at 50°N in December-January (Figure 2c-d).

The eddy momentum and heat fluxes of storm tracks revealed in the model simulation and reanalysis data are also similar (not shown). Zonal mean momentum fluxes of storm tracks averaged over December-February peak between pressure levels of 300 hPa and 200 hPa and in the latitudinal band of 30-40°N. The zonal mean heat fluxes display two maximums: in the lower troposphere at 850 hPa and 40-50°N and the second one, in the upper troposphere with values that are about two times less than the first maximum. Note that the upper tropospheric maximum of the storm track heat flux in the model simulation is about two times weaker than in NCEP reanalysis.

Then the eddy moisture flux of the storm tracks responsible for the transfer of latent heat was analyzed. A maximum of the zonal mean eddy moisture fluxes of the storm tracks averaged over December-February is observed in the lower troposphere at 40°N, and their values in the model simulation and reanalysis data are comparable (Figure 3).
3.2. North Atlantic storm track response to weakening and strengthening of stratospheric polar vortex

Using composite analysis, the extension of the North Atlantic storm track caused by weakening and strengthening of the Arctic stratospheric polar vortex events with the detected influence on the troposphere was studied. These events in the model and NCEP reanalysis data were revealed early [19] and defined as follows: if the daily geopotential height anomalies from the climate mean averaged over 60-90°N and normalized with the standard deviation exceed a threshold value of $+/-1.5 \sigma$ and propagate continuously downward from the middle stratosphere at a pressure level of 30 hPa to the upper troposphere at 300 hPa, such events were considered as troposphere-affecting, and vice versa.

The differences between the composites consisting of troposphere-affecting weakening and strengthening of the Arctic stratospheric polar vortex events shows that weakening of the polar vortex leads to an extension of the North Atlantic storm track towards lower latitudes (Figure 4a-b). The strengthening of the polar vortex, in turn, leads to an extension of this storm track towards the high latitudes. The strongest changes of the North Atlantic storm track occur at 300 hPa. Statistically significant responses of this storm track to strengthening/weakening of the stratospheric polar vortex were revealed in the model simulations and reanalysis data. Due to the mid-winter suppression of the North Pacific storm track, its response to variability of the Arctic polar vortex is less pronounced.
3.3. Storm tracks response to Arctic amplification

The warming trend in the Arctic in the recent two decades is almost twice as large as the global mean temperature trend. This result of the recent climate change is called Arctic amplification and has been accompanied by a rapid loss of sea ice, with a maximum in autumn. Observational and modeling studies suggest that the Arctic amplification may affect the middle latitudes weather [e.g., 20-24].

![Figure 4](image)

**Figure 4.** Altitude-latitude cross-section of the difference between the North Atlantic storm track variance [m$^2$/s$^2$] in the longitudinal band of 60° W - 0° in January-March between composites with strengthening and weakening of the Arctic stratospheric polar vortex with a tropospheric impact in the model simulation (a) and reanalysis data (b). Zones where the difference between the composites is statistically significant at a confidence level of 95% are shown by grey dots. The difference in the storm track variance [m$^2$/s$^2$] at 300 hPa in December-February between 1998 - 2014 and 1980 - 1997 in the model simulation (c) and reanalysis data (d).
The factors that contribute to the amplified warming in the Arctic include [20]:
- albedo-temperature feedback associated with a reduction of the sea ice;
- increased atmospheric humidity and the associated increase of the downwelling longwave radiation;
- increased poleward transports of heat and moisture by the ocean and atmosphere.

A number of mechanisms for middle latitude circulation response to the Arctic warming and sea ice reduction have been recently suggested, including the following [20]:
- the impact of the Arctic warming on the pressure fields and the subsequent changes of the blocking frequency;
- the Arctic and middle latitude connection via the terrestrial snow cover.

It was also shown that the Northern Hemisphere storm tracks are influenced by the Arctic amplification: a weakening of the North Atlantic storm track and a poleward shift of the North Pacific storm track were revealed using the Community Earth System Model Large Ensemble project [13].

Similar storm track changes were revealed in the model simulations with high resolution and specified SST: a poleward shift of the North Pacific storm track and a weakening of the North Atlantic storm track between two winter periods, 1998-2014 and 1980-1997 (Figure 4c-d). Similar changes of the storm tracks were revealed in reanalysis data. Both main areas of the variance change display a slight westward shift in comparison with reanalysis data.

The following explanation was suggested on the basis of analysis of the model simulations: the weakening of the North Atlantic storm track is caused by the decreased baroclinicity associated with the Arctic amplification, whereas the poleward shift of the North Pacific storm track is influenced by the La Niña–like change in the sea surface temperature [13].

4. Summary

The main characteristics of Northern Hemisphere storm tracks have been revealed and analyzed in five 50-year simulations of the INM-CM5 model version with a longitude-latitude resolution of 2.5°×2.5°, two 50-years simulations with a higher resolution (0.67°×0.5°), as well as NCEP and ERA-Interim reanalysis data. Although the spatial structure, variance, and other parameters of the simulated North Pacific and North Atlantic storm tracks are comparable with those revealed in reanalysis data, their maximum variance is weaker by about 20%. The high-resolution INM CM5 version reproduces the storm tracks better: their variance is comparable to that of reanalysis data.

The results of the composite analysis show that strengthening of the Arctic stratospheric polar vortex with its revealed tropospheric impact lead to an extension of the North Atlantic storm track toward high latitudes: its strengthening is observed at 50°N and weakening, at 30–40°N. Weakening of the Arctic polar vortex, in turn, leads to an extension of the North Atlantic storm track to lower latitudes.

A poleward shift of the Pacific storm track and weakening of the North Atlantic storm track have been revealed in INM CM5 simulations with high resolution and specified SST comparing two periods: 1998-2014 and 1980-1997. Similar changes in the storm track associated with the recent Arctic amplification have been revealed in reanalysis data. These are in agreement with the results of [13].

Finally, we conclude that the realization of Northern Hemisphere storm tracks in the INM CM5 historical simulations and their responses to the strengthening and weakening of the Arctic stratospheric polar vortex with the tropospheric impact and the recently observed Arctic amplification are comparable with the storm track parameters revealed in the reanalysis data.

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