Investigation and forecast of Sudden Stratospheric Warming events with chemistry climate model SOCOL

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Abstract. To achieve better agreement of simulated Arctic winter stratospheric dynamic with observations assimilation procedure nudging was incorporated in CCM SOCOL. Trajectories based on SOCOL output winds demonstrate the reasonable agreement with trajectories based on reanalysis data inside the polar vortex and can be used for analysis and forecast of ozone related processes in winter-spring seasons. Obtained results of several recent major Arctic SSW events analysis show that CCM SOCOL could be used for SSW forecast over the period up to 8 days.

1. Introduction
A major phenomenon which defines the circulation pattern in the winter Arctic stratosphere is Sudden Stratospheric Warming (SSW). This event was discovered in the early 1950 during aerological sounding over Berlin [1]. SSW events could lead to a fast and significant increase of the polar stratospheric temperature (up to 40 K) and to a reversal of mean zonal circulation. As a result of SSW the polar stratospheric vortex could be shifted off the pole, or in some cases a splitting event may be observed. The SSW formation is associated with the intensification of wave activity propagation from the troposphere and nonlinear interaction between the planetary waves and zonal stratospheric circulation [2, 3]. According to the definition of the World Meteorological Organization, the major SSW event is characterized by the zonal wind reversal at the level of 10 hPa at 60° N. At present this definition is actively discussed [4], because some SSW events not fitting this definition of major event exert significant influence on the extratropical stratosphere–troposphere and on the ozone layer like, for example, SSW event at the beginning of January 2015 [5]. Generally the investigation of SSW continues to be an important and relevant scientific task, mainly due to two factors.

First, SSW events define meteorological conditions, on which the strength of the destruction of the ozone layer in the polar stratosphere depends. Despite the beginning of decrease in the concentration of ozone-depleting compounds in the atmosphere, anomalies of the stratospheric ozone layer in Arctic with comparable to record destruction in spring 2011 [6] may occur approximately till the middle of the 21st century [7]. More severe ozone depletion in Arctic than in spring 2011 was prevented by SSW event occurred at the end of January 2016 [8].

We know enhanced UV radiation caused by comparable to spring 2011 ozone depletion in the Arctic may be observed in the Northern Hemisphere over the next few months [9]. Anomalies of stratospheric ozone in the Arctic in 1980-2000 that occur during the winter seasons without SSW events could have an effect on temperature, wind in the troposphere, and precipitation, reaching the largest effect in the North Atlantic and Eurasia in April-May [10].

Second, variability of polar stratospheric dynamics associated with SSW may influence tropospheric circulation and weather conditions in middle-high latitudes over the period of up to two months [11-14]. The SSW impact is also registered in the upper atmosphere: for example, the amplitude of SSW-induced electron density perturbations in the equatorial ionosphere allows comparing their effects with the impact of moderate geomagnetic storms [15, 16]. The influence of the
SSW events is not limited to middle and high latitudes: due to the acceleration of the meridional circulation, they affect the temperature of the lower equatorial stratosphere [17].

Due to the higher upper model boundary including and better vertical resolution the SSW forecast has been improved in recent years [18]. SSW events are predicted in 7-10 days on average, e.g. [19]. It was shown that in the ECMWF forecasting system for the period from 1993 to 2016, the average deterministic forecast of SSW events is limited to about a week, while the probabilistic forecast (with ensemble calculations) by about 8-12 days [20, 21].

Some SSW events can be predicted over a longer period, for instance the majority of forecast system participating in Sub-Seasonal to Seasonal forecast (S2S) project probably thanks to favorable initial conditions (QBO, MJO) and boundary conditions (moderate El Niño, solar minimum [22] were able to predict major SSW in early January 2019 over 18 days [23]. Although the large differences in forecast of some dynamical processes after the SSW between models were detected.

Dynamical processes of Arctic winter extratropical stratosphere are closely coupled with chemistry processes that define stratospheric ozone state. Accounting of interactive ozone chemistry in climate models lead to improvement of temperature variability and extremes in the Arctic polar stratosphere realization [24], stratospheric polar vortex and its variability, frequency of SSW, and near surface temperature response on variability of polar stratosphere [10, 25].

The aim of present study is an investigation of SSW forecast possibility using chemistry climate model CCM SOCOL [26], that was employed in many studies of chemical and dynamical processes of middle atmosphere and ozone layer changes [27-29].

2. Data and methods of analysis

The chemistry-climate model SOCOL v.3 consists of the middle-atmosphere GCM MA-ECHAM5 [30] and CTM MEZON [31]. The two parts of the model are interactively coupled by the 3-dimensional fields of temperature and wind and by radiative forcing. The model has T31 horizontal spectral truncation, which approximately corresponds to 3.75° × 3.75° resolution in a grid spacing, and 39 vertical levels in a grid sigma-pressure coordinate system from the surface to 0.01 hPa (~80 km). The model time step for dynamical processes and physical parameterizations is 15 min. The CTM MEZON is called every 2 h. Full radiative transfer is calculated every 2 h, but heating and cooling rates are calculated every 15 min.

The model is driven by prescribed monthly means of global sea surface temperatures and sea ice coverage from HadISST1 dataset as well as the prescribed monthly means of observed sulfate aerosol physical and pre-calculated optical parameters.

The chemical part of MEZON includes 41 chemical species of the oxygen, hydrogen, nitrogen, carbon, chlorine and bromine groups, 140 gas-phase reactions, 46 photolysis reactions, and 16 heterogeneous reactions on stratospheric aqueous sulfuric acid aerosols as well as three types of polar stratospheric clouds (PSCs). As input data for the model run monthly means of atmospheric concentration of the most relevant greenhouse gases (CO₂, CH₄, N₂O) are used as well as surface mixing ratio of ozone depleting substances, NOₓ emission from the surface and aircraft and so on. A detailed model description is given in [26].

The model runs in parallel mode on 16 CPUs, so the calculation of one model year requires about 3 h. For the SSW events experiment study, the CCM SOCOL was run in special dynamic mode. We employed the assimilation of the external meteorological fields from reanalysis data. The model run is forced by a linear relaxation (“nudging”) of three thermodynamic parameters: temperature and divergence and vorticity of the wind field to approach the simulated temperature and wind values to the reanalysis data. This approach was successfully used in Central Aerological Observatory within the framework of HEPPA-II project for investigation of the impact of energetic particle precipitation (EPP) on the chemical composition in the stratosphere and mesosphere during the SSW event in January 2009 [32], as well for calculation of the forecast winds and temperature for a single site [33, 34].
As assimilated data source we use Japanese reanalysis (JRA-55) daily near-real time data with 6 h time resolution. The delay of data update is one day. The nudging is applied from 850 hPa to 1 hPa while model simulation being unconstrained above. The relaxation time is set to 48 h for divergence, 6 h for vorticity and 24 h for temperature following [35].

3. Results

3.1 Realization of stratospheric dynamics in model simulations

Firstly the reproducing the climate means of the main parameters of the stratospheric dynamics in the CCM SOCOL simulations in comparison with ERA-Interim reanalysis data for the boreal winter season was analyzed.

The largest difference between the zonal mean temperature in January averaged over 1989-2012 in the model simulation and the reanalysis data averaged over 1989-2012 is observed in the region of the lower stratosphere at high latitudes, where the temperature in the model calculations is underestimated by 6-10 K (Figure 1a). This cold bias in the lowermost stratosphere is a widespread feature of CCM models [26]. The reasons for the cold bias are not yet fully understood and might differ between different models. It could be partly caused by a severe wet bias in the extratropical lower-middle stratosphere, resulting in an excessive longwave cooling.

Further amplitude of wavenumber 1-3 in model simulations averaged over the period of 1989-2012 and ERA-Interim reanalysis data averaged over 1979-2008 were calculated. Dominated in the stratosphere wavenumber 1 averaged over December-February agrees with revealed in reanalysis data (Figure 1 b-c). Amplitude of wavenumber 2 is slightly weakened and its maximum is shifted downward in comparison with ERA-Interim reanalysis data (Figure 1 d-e) whereas amplitude of wavenumber 3 is comparable (Figure 1 f-g).
Generally obtained results show that CCM SOCOL is characterized by relevant reproducing of boreal extratropical stratospheric dynamic in comparison with reanalysis data.

### 3.2 Simulation of SSW events with nudging

In this study we followed the WMO definition for the SSW event, that is the SSW onset is set to date when the zonal mean zonal wind at 60°N and 10 hPa level reverses from westerlies to easterlies. For the evaluation of the SSW forecast possibility using CCM SOCOL, eight SSW events of different type (major or minor) from 2000 to 2010 were selected. For each of eight SSW events we have carried out four sets of 1-month long runs. Some results of the model experiments are shown in Figure 2.

The first set of experiments was performed using nudging mode over the whole calculation period to estimate the efficiency of nudging procedure, which was evaluated by its ability to reproduce as accurately as possible the wind and temperature changes in the stratosphere. As seen from Figure 2 good agreement with reanalysis data was obtained. In order to evaluate the model forecast capability in free run, in the next three sets of model runs we stopped nudging procedure over 10, 7 and 4 days before the SSW events, while the model run being unconstrained after this date. The initialization of the model simulations at the beginning of the month was made from the previous model calculations. As seen from Figure 2a the model good enough reproduces the zonal mean zonal wind changes when nudging mode is stopped over 4 days and 10 days before the SSW, whereas for 7 days period the zonal wind reverse is not observed. This result requires further study. The simulation of SSW event in
February 2008 has better results (Figure 2b). In all three cases the modeled data show good agreement with reanalysis data, only for a lead time of 10 days data the excess of zonal wind amplitude is observed in a few days after the SSW.

According to the results of eight SSW events study, we can conclude that CCM SOCOL is able to forecast the SSW events at a lead time up of 7-10 days. The predictability of temperature changes (not shown) is better.

Among other calculations we had estimated the zonal wind predictability during the SSW event for some single sites using CCM SOCOL. The simulation results for Baikonur Cosmodrome (45°N, 63°E) for the SSW in January 2006 are shown in Figure 2c for example.
c)

Figure 2. Modeled zonal mean zonal wind at 60°N and 10 hPa in January 2003 (a), February 2008 (b), and zonal wind in January 2006 (c) for the Baikonur. Results with nudging over the whole calculation period (red curve) and switched off nudging over 10 (green), 7 (purple) and 4 (rose) days before the SSW event in comparison with ERA-Interim reanalysis data (blue curve). Vertical dark blue line corresponds to the SSW onset date at 60°N. Colored triangles mark the dates when the nudging mode was stopped.

When the nudging mode is stopped with a lead time of 4 days, a good agreement with reanalysis data is observed, whereas for 7 days period the zonal wind direction change also is observed, but its amplitude is weaker, and for 10 days period the zonal wind reverse does not occur. It should be noted that Baikonur is located 15 degrees south of 60°N latitude, what probably explains the little time shift of zonal wind reverse from the date of the SSW onset, which is observed both in the model and reanalysis data. This and other results of model simulations show that CCM SOCOL is capable to forecast not only zonal mean zonal wind, but as well zonal wind at a single site for a short period.

For this study the model was used in a single mode. In the future we intend to perform model calculations in ensemble mode, which should lead to improvement of predictability of SSW events and increase of a lead time period.

3.3 Trajectory analysis

The model was also used for calculation of prognostic trajectories inside the polar stratospheric vortex. Trajectories based on SOCOL output forecast winds were compared with trajectories calculated by using reanalysis data.

In this study the trajectory model TRACAO and ERA-Interim winds were applied. TRACAO was developed to analyze the dynamical and chemical processes related to the ozone loss inside the polar vortex [36] and to determine the origin of air masses arriving to observational location. Also it can be used for simulation of thin horizontal structure of tracers (for example polar vortex filaments), stratosphere-troposphere exchange and so on.

The time integration of the particle advection equation expressed with spherical coordinates is performed using the fourth-order Runge-Kutta method with analyzed wind data linearly interpolated in time and space. The model calculates forward/backward and isentropic/3-d wind trajectories.
TRACAO usually uses reanalysis data, but it can be easily adapted to any gridded data including SOCOL output winds.

![Figure 3. 10-day forward isentropic trajectories on 500 K level (~20 km) based on SOCOL simulations (blue) and ERA-Interim (red) winds for 7 of February (a) and 17 of February (b) 2008. The green star indicates the initial point of trajectories, chosen inside the vortex.](image)

Since the radiative cooling inside the polar vortex is relatively slow process the 10-day isentropic trajectories were applied for comparisons. In February 2008 (SOCOL nudging was stopped at 18 of February) forward trajectories were calculated inside the polar vortex based on nudged data for all ten days of the trajectory duration (initiated on 7 of February 2008) and with nudging only for the first day of the trajectory (initiated on 17 of February 2008). Results of comparisons are presented in Figure 3. The green star indicates the initial point of trajectories on 500K level of potential temperature (~20 km), which was chosen inside the vortex in both cases. Figure demonstrates that in the case of 10- day nudging, trajectories run more closely and do not diverge irreversibly during 10 days. In the case of 1- day nudging the trajectories completely diverge after 6 days. Nevertheless the trajectories on the right figure remain inside the vortex even after the vortex stretching 20 of February. Similar trajectories calculated on upper levels 600 K and 750 K also showed the agreement with trajectories based on reanalysis data during first several days.

4. Summary

CCM SOCOL with assimilation procedure "nudging" was employed to analyze a possibility of SSW event forecast. We analyzed several recent major SSW events observed in recent boreal winters and switch off "nudging" over 10, 7 and 4 days before SSW events. Obtained result showed that CCM SOCOL with nudging can be successfully used for SSW event forecast up to 6-8 days under comparison with reanalysis data. Trajectories calculated using SOCOL output winds and initialized inside the polar vortex in the lower and middle stratosphere during pre-warming phase are in the agreement during first several days with calculated ones using reanalysis data. It confirms that simulated characteristics of lower and middle stratosphere polar vortex are comparable with ones revealed in reanalysis data.

CCM SOCOL with nudging can be used similar to chemical transport models for studies of ozone related processes (ozone depletion, chlorine activation, denitrification and etc.) inside the polar vortex for chosen winter-spring season as well as for short-term (some days) forecast of these processes.
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