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OPTICAL INSTRUMENTATION

Validation of ECHAM AGCMs Using Laser Spectrometer Data from Two Arctic Stations

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Abstract—To validate the atmospheric general circulation models ECHAM5-wiso and ECHAM6-wiso with embedded water isotopic modules, nudging mode simulations were performed to known fields of temperature, pressure, wind speed and direction derived from retrospective climate analysis. The simulation results are compared with data on the isotopic composition (δHDO and $\delta H_2{}^{18}O$) of water vapor in atmospheric air near the surface received at two monitoring stations: in Labytnangi (66.660° N, 66.409° E) and in Igarka (67.453° N, 86.535° E). The superiority of the newer model ECHAM6-wiso could not be unambiguously concluded, because the results of simulation in this model show a better agreement with data from Igarka, while the model ECHAM5-wiso shows a better agreement with the data measured in Labytnangi. The simulation results can be used as an a priori ensemble for the solution of the inverse problems of remote atmospheric sensing in western Siberia.

Keywords: atmospheric general circulation model, water isotopologues

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INTRODUCTION

Global warming is one of the main problems of our time, and it is expected that it will manifest itself most strongly at high latitudes, especially in the Arctic latitudes of the Northern Hemisphere [1–3]. Arctic landscapes are especially sensitive to temperature changes due to melting permafrost [4]. The main reason for the warming over the past 50 years is likely to be an increase in the concentration of greenhouse gases, mainly CO_2 and CH_4, in the atmosphere [5, 6]. To study climatic changes in subarctic and arctic latitudes, detailed atmospheric general circulation models (AGCM) are required, which can forecast meteorological and related environmental parameters for decades [7].

The global water and carbon cycles are important interacting components of the climate system, which largely control feedbacks of the Earth's system with disturbances in the energy balance in the troposphere. The Earth's radiation imbalance approximately doubles due to an increase in the atmospheric concentration of greenhouse gases when taking into account a concomitant increase in the water vapor concentration [8]. The water cycle has a major impact on the energy balance of the underlying surface on a regional scale through latent heat fluxes associated with evaporation and condensation. Many important processes in the hydrological cycle cannot be observed. For example, processes inside a cloud are almost inaccessible for satellite and ground-based remote sensing. Therefore, the relative concentrations of water isotopologues $H_2{}^{18}O$ and $HD^{16}O$, usually denoted as $\delta^{18}O$ and δD, can be used as an analytical tool to identify various "hidden" but key aspects of the water cycle [9]. The relative concentration (denoted by symbol δ) is usually defined as $\delta HDO = \left(\frac{HDO/H_2O}{(HDO/H_2O)_{SMOW}} - 1\right) \times 1000‰$, where the chemical formulas are the concentrations of the respective substances, and the SMOW is the standard mean ocean water index.

The use of stable water isotopologues $H_2{}^{18}O$ and HDO in models of general atmospheric circulation considering their fractionation during evaporation and condensation due to different masses of isotopologues began to be actively developed several decades ago as a clear and most effective method for climate study. Already in 1964, Dansgaard showed the main effect of climate variations on the isotopic composition of precipitation in his early work [10]. He has explained how and why the isotopic composition of precipitation linearly relate to local temperature (the so-called temperature effect) in most regions of the Earth.

It was shown in [11–13] that stable water isotopes are an important tool for paleoclimate studies. They represent a common signal among various types of natural climate records which retain past changes in the Earth's hydrological cycle. Simulation of the behavior of stable water isotopologues in different components of the hydrologic cycle contributes to better understanding of δ-signals in different natural data archives (for example, Antarctic and Greenland ice cores) [14].

ECHAM5 AND ECHAM6 MODELS

The ECHAM6 model is currently the latest version of the atmospheric general circulation model created at the Max Planck Institute in Hamburg; its predecessor is ECHAM5 [15, 16]. Both models describe atmospheric dynamics based on data from the European Center for Medium-Range Weather Forecasts (ECMWF). The source code of ECHAM models is written in the Fortran programming language and, due to its modular structure, allows modification and addition with new process models. This circumstance made it possible to supplement ECHAM5 with six isotope modules which considered the fractionation of water isotopologues. That was made at the Alfred Wegener Institute of Marine and Polar Research (Bremerhaven, Germany). The new module was named wiso, and the models supplemented by it were named ECHAM5-wiso and ECHAM6-wiso [17, 18]. Accounting for stable water isotopologues $H_2^{18}O$ and HDO is embedded in the model hydrological cycle [19, 20]. Isotopologues and "normal" water are accounted for in the same way when no phase transitions occur. Additional fractionation processes are specified for the model variables responsible for the content of water isotopologues when a phase transition (evaporation or condensation) occurs. Many assumptions made in ECHAM5- and 6-wiso are typical for other isotopic models of general atmospheric circulation, such as CAM [21], HadCM [22], and LMDZ [23]. The Stable Water Isotope Intercomparison Group (SWING) project, organized to compare these models, has shown, at present, insufficient observational data on isotopes in precipitation to estimate differences in the models [24]. The isotopic module ECHAM5-wiso was previously verified within the WSibIso project in western Siberia based on data on the isotopic composition of precipitation [25].

The aim of this work is to validate the isotopic versions of ECHAM5-wiso and ECHAM6-wiso for western Siberia using the monitoring data on the relative concentrations of water vapor isotopologues in the surface air layer.

The models can work on various spatial grids, such as T63L47, T63L95, and T127L95, which correspond to a horizontal resolution of 1.9° × 1.9° (T63) or 0.95° × 0.95° (T127) in latitude and longitude and 47 or 95 vertical layers between the surface and the level corresponding to a pressure of 1 hPa. Input data are required to run the model executables, including initial and boundary conditions. The main groups of these data include the initial state of the atmosphere (vorticity, temperature, pressure, and humidity), surface parameters (albedo, landscape, shape of the land–ocean interface, soil moisture, etc.), average temperatures of the land surface and oceans for the longest possible period preceding the modeling period, ice distribution in the ocean, optical properties of aerosols, distribution of greenhouse gases, and ozone distribution in the atmosphere. The basic equations of the dynamic kernel of the ECHAM5 and 6 models are the Navier–Stokes, continuity, and thermodynamic equations; hydrostatic approximation is applied. A grid of hybrid isobaric sigma equations is used as a discrete vertical coordinate, where the vertical coordinate corresponding to the surfaces which envelope the relief in the lower atmosphere smoothly passes to isobaric surfaces in the upper atmosphere. In horizontal coordinates, the equations are solved using the spectral method, which significantly simplifies the derivation. The variables are presented as a truncated series of spherical harmonics. The ECHAM5- and 6-wiso models also consider the fractionation of water isotopologues during phase transitions in clouds and in processes when rain drops fall through air depleted in heavy water isotopologues [17].

MONITORING STATIONS

The stations for monitoring the isotopic composition of water vapor are organized by the Laboratory of Climate and Environmental Physics of the Institute of Natural Sciences and Mathematics of the Ural Federal University in cooperation with the Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, and the Melnikov Permafrost Institute, Siberian Branch, Russian Academy of Sciences, on the territory of the stations of the last: the Arctic Research Station in Labytnangi (66.660° N, 66.409° E) and the Igarka geocryological laboratory in Igarka (67.453° N, 86.535° E). Both monitoring stations are equipped with identical Picarro L2130-i laser spectrometers, designed exclusively for measuring the water vapor isotopic composition in air or pure nitrogen. The spectrometers are periodically calibrated against standard samples of liquid water, which are dosed into an evaporator, are mixed there with atmospheric air dried by a column with desiccant, and fed to an analyzer. Both stations are also equipped with automatic weather stations (Vaisala WXT520) controlled via the Internet. Air is taken from the top of masts (8 m in Labytnangi and 15 m in Igarka) during periods of serviceability of all equipment and in the presence of a power supply; the continuous analysis is carried out with the measurement of the concentrations of water isotopologues approximately once every

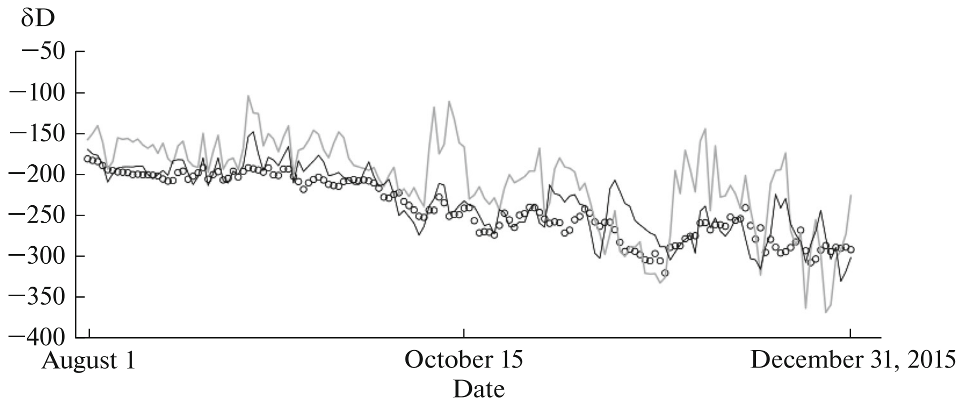

Fig. 1. Time variation in δHDO in Igarka in 2015 according to direct measurements (circles) and calculations in ECHAM5-wiso (gray line) and ECHAM6-wiso (black line) models.

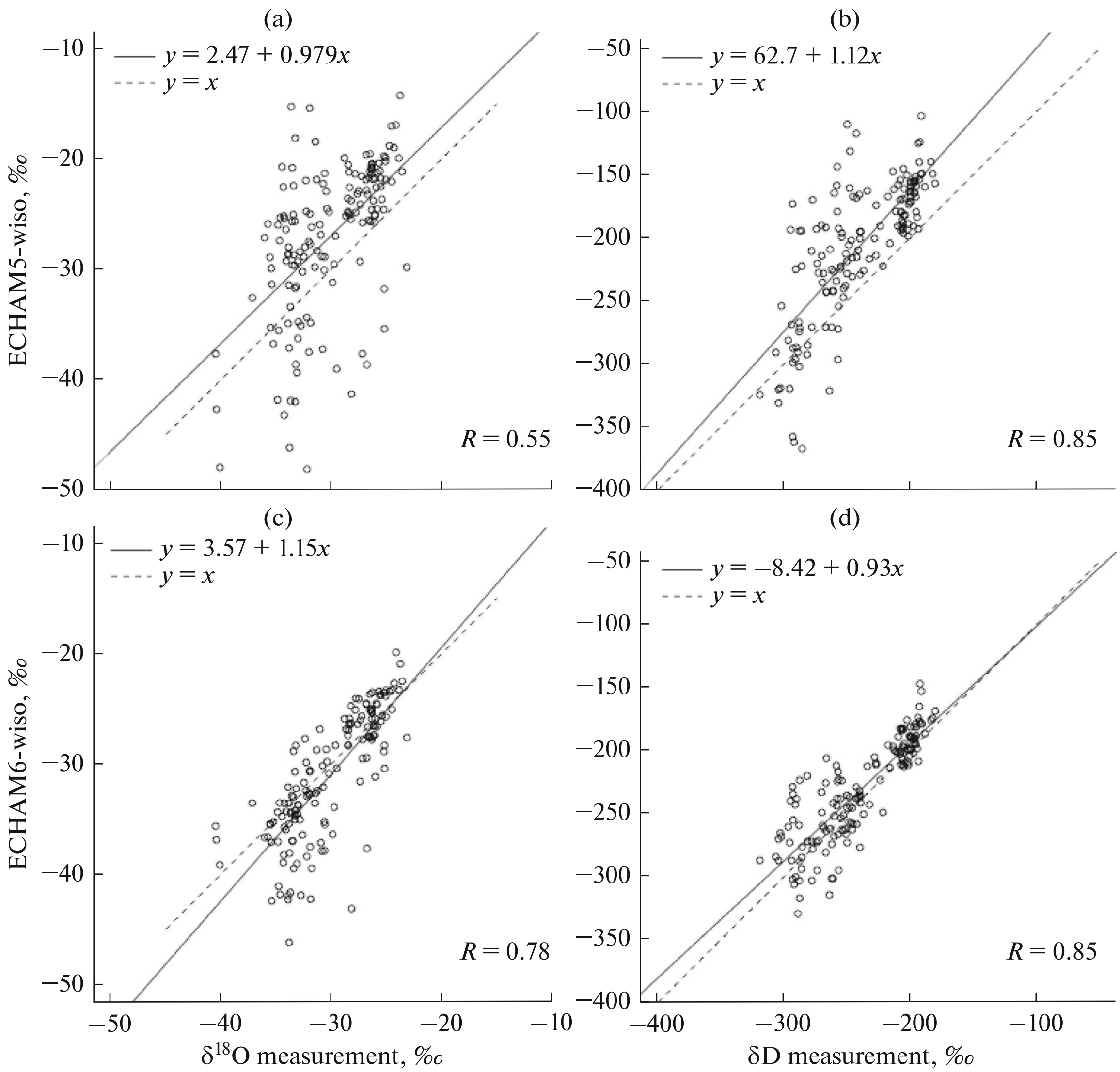

Fig. 2. Scatter charts for the Igarka station.

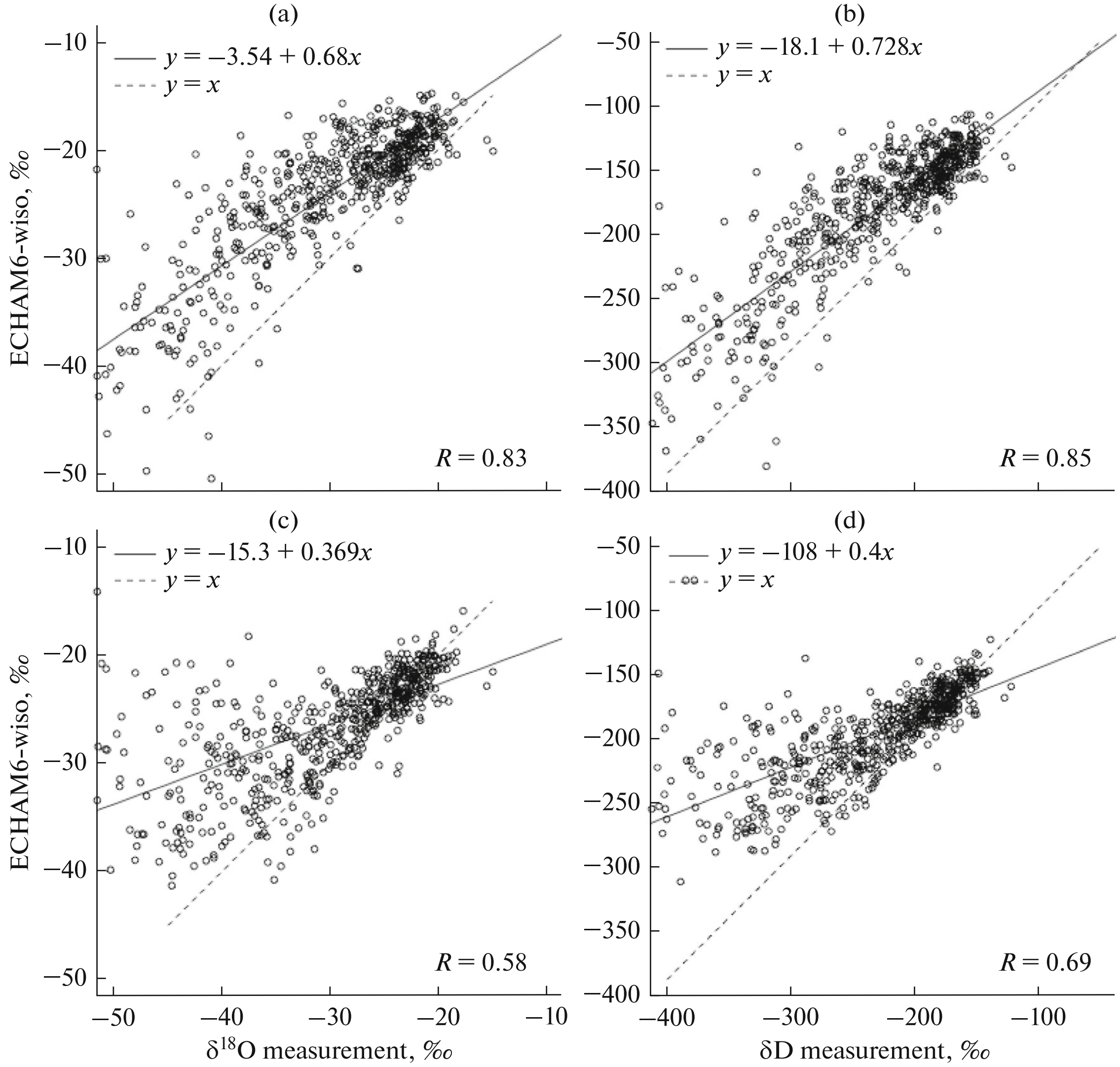

Fig. 3. Scatter charts for the Labytnangi station.

1–5 s. The monitoring sites are located on the banks of the Ob and Yenisei rivers, which causes data perturbation due to the mixing of water vapor directly from the water surface of the rivers during the warm season.

COMPARISON OF SIMULATION RESULTS WITH OBSERVATION DATA

To verify the ECHAM5-wiso and ECHAM6-wiso models, the daily average data on the isotopic composition of water vapor in the atmospheric air near the surface from the monitoring stations are compared with the simulation results.

The simulation was carried out in the following mode: for ECHAM5-wiso, the spectral resolution T106 (corresponds to a spatial grid of 1.125° × 1.125°), time step of 6 min, start on January 1, 2011, end on January 31, 2016; relaxation mode to the fields of temperature, pressure, and wind divergence and vorticity known from the ERA-Interim reanalysis [25]. The model experiment was carried out with the use of the Uran supercomputer of the Krasovsky Institute of Mathematics and Mechanics, Ural Branch, Russian Academy of Sciences.

For ECHAM6-wiso: the spectral resolution T63 (corresponds to a spatial grid of 1.88° × 1.88°), time step of 6 min, start on January 1, 2010, end on January 31, 2017; relaxing to the fields of temperature, pressure, and wind divergence and vorticity known from the ERA5 reanalysis [26]. The Ollie supercomputer of the Alfred Wegener Institute for Polar and Marine Research was used.

Figure 1 shows an example of a δHDO time series plotted from measurement data from Igarka and the results of model experiments.

The scatter charts for Igarka (Fig. 2) show better agreement of the ECHAM6-wiso simulation results as compared to the ECHAM5-wiso. The situation is the opposite for Labytnangi (Fig. 3). This may be due to the lower horizontal resolution in the computational experiment in the ECHAM6-wiso model, as well as to the fact that the base of the atmosphere is ~100 m in the model calculations, while measurements are made at the surface. In addition, a gas boiler house is located near the observation station in Labytnangi, whose emissions of water vapor from the pipe disturb the measurement results. In the present work, data were not sampled in the wind direction, because the periods of failure of an automatic weather station are significantly longer than the periods of failure of a spectrometer located in a warm room.

CONCLUSIONS

The results witness that both models generally reflect seasonal variations in the isotopic composition of water vapor in the atmospheric air at both monitoring stations. We used two model–reanalysis combinations. The newer model ECHAM6-wiso with the new ERA5 reanalysis data better reproduce the daily average data measured in Igarka, while their predecessors ECHAM5-wiso and ERA-Interim show the better agreement with the data from Labytnangi. This means that the choice of a model and reanalysis to provide model data suitable for further use requires additional computational experiments with the selection of the spatial resolution and other initial parameters, with possible filtering of data along the wind direction from local sources. Since the results of computational experiments are provided with a global coverage and throughout the vertical grid of the model, these data can be used as an a priori ensemble in problems of remote sensing of the vertical distribution of water isotopologues in the atmosphere (see, for example, [27–29]).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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