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The IAP RAS climate model: Contemporary state and major results

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ABSTRACT

Climate model developed at the A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM) includes modules describing the state of the atmosphere, the ocean, the active land layer, biogeochemical cycles, processes associated with atmospheric electricity and atmospheric chemistry. It belongs to the class of climate models of intermediate complexity (EMICs) and participates in relevant international comparison projects. A specifics of the model is the parameterisation of synoptic variability in the atmosphere and ocean, which allows reducing the computation cost by two orders of magnitude. The model rather realistically reproduces climate change over a period of instrumental measurements and is used to estimate past and future climate changes on a ten-year and longer time scale.

Keywords: climate changes, EMICs, IAP RAS CM

1. INTRODUCTION

The first (zonally-averaged) version of the climate model (CM) of the A.M. Obukhov Institute of the Atmospheric Physics, Russian Academy of Sciences (IAP RAS) was developed in the late 1970s[1]. In the 1990s a non-zonal version of the model was developed[2]. The IAP RAS CM is the only Russian model that belongs to the class of climate models of intermediate complexity (EMICs)[3,4] and participates in relevant international comparisons[5-7]. Along with the general circulation model of the Institute of Computational Mathematics (INM) of the Russian Academy of Sciences[8-19], it is one of two Russian three-dimensional climate models. The results obtained with the IAP RAS CM are included, in particular, in the Fifth Assessment Report 2013 of the Intergovernmental Panel on Climate Change[20] (IPCC).

The IAP RAS CM includes modules for the transfer of shortwave and longwave radiation, convection, cloud formation and precipitation[1-3,5-7,21-26]. Currently, the short-wave radiation transfer scheme takes into account the influence of the parameters of the Earth's orbit, surface albedo, characteristics of cloudiness, water vapor, ozone, and tropospheric and stratospheric sulfate aerosols. The module of longwave radiation transfer takes into account the temperature and humidity of the atmosphere, cloudiness, carbon dioxide, methane, nitrous oxide and freons. Large-scale atmospheric dynamics (with a more synoptic scale) are considered explicitly[1-3,5]. Synoptic processes are parametrised assuming that they form Gaussian ensembles. This allows to significantly reduce the time required for model calculations. The characteristics of sea ice in the IAP RAS CM are calculated depending on the surface temperature and the ocean surface temperature. In recent years, the IAP RAS CM has been supplemented with detailed modules of soil thermophysics[27-29], carbon[24,25,30-35] and methane cycles[36-38]. The horizontal resolution of the IAP RAS CM is 4.5^{o} in latitude and 6^{o} in longitude with 8 vertical levels in the atmosphere (up to 80 km) and 3 levels in the ocean.

At the interdecadal timescale, the model rather realistically describes the climate response to external forcings[6,22-26]. Changes in the characteristics of the state of climate and ecosystems in the model under various scenarios of anthropogenic forcing on climate in the 21st century are within the interval, according to the results with other modern climate models[7,22-26]. The equilibrium change of the globally averaged mean annual temperature of the atmosphere near the surface with a doubling of the carbon dioxide content in the atmosphere for the IAP RAS CM is 2.2 K, which is close to the lower limit of the interval from 2 K to 4.5 K, typical of modern models[20].

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The computational efficiency of the IAP RAS CM allows to carry out ensemble numerical experiments with a length of up to tens of thousands of years with an analysis of the dependence of the results obtained on the initial conditions, control parameters of the model, or scenarios of external influences on the system[21,25,29,30,39-43].

Among the results obtained with the IAP RAS CM, estimates of the causes of climate change in the last centuries and millennia, climate changes in the next several centuries, the contribution of various anthropogenic and natural forcings on the climate in its changes, the effects of climate change on the peculiarities of processes in the active layer of the land (including in permafrost).

Below these results are considered in larger details.

2. CLIMATE SIMULATION FOR THE HOLOCENE AND LAST CENTURIES

Earlier simulations for the last few millennia and for the last few centuries with the IAP RAS CM are available in[5,21,23].

Recently, a Holocene simulation (last 10 kyr) simulation with the model was performed. This was forced by the following external forcings: i) changes of the parametres of the Earth orbit, which are calculated internally by the model according to the Berger equations[44]; ii) total solar irradiance reconstructed from ^{10}Be data[45]; iii) optical depth of stratospheric (volcanic) aerosols[46] (only for 1500-2000 CE); iv) ice core-derived concentrations of well-mixed greenhouse gases (CO_2, CH_4, and N_2O) in the atmosphere[47]; v) change of crops and pastures extent and change of population density according to the HYDE-3.2 (History Database of the Global Environment, version 3.2)[48]; total burden of tropospheric sulphates[49] extended back in time assuming that the 1850 CE reflects the distribution of natural sulphates, and this distribution is representative for the whole Holocene.

Our model reasonably reproduces surface air temperature (SAT) variations in the 20th century but underestimates interannual and interdecadal variability (Fig. 1). The latter respect is similar to other contemporary EMICs[3-7]. In particular, the 20th century increase in global SAT is 0.58°C in reasonable agreement with the HadCRUT4 dataset[50,51] (~0.7°C). The difference between these (model and observational) estimates probably reflects contribution of the natural variability into the 20th century global mean warming.

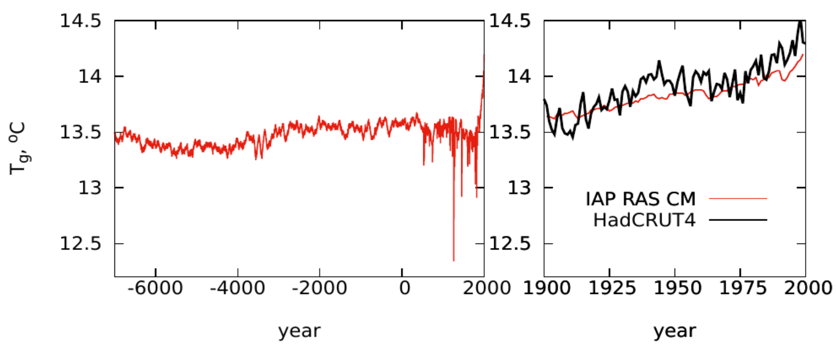

Fig. 1. Global mean surface air temperature in the IAP RAS CM Holocene simulation (left). The right panel shows the 20th century part of the simulation in comparison to the HadCRUT4 observational dataset.

The mid-Holocene optimum is not visible at the global scale. This is consistent with the present-day knowledPAGES2k.gpge[52,53]. However, in Northern extratropics during summer, temperature maximum is visible (Fig. 2). However, this maximum may be underestimated due to neglect of shifts in vegetation zones[54]. We note, in addition, that our model basically reproduces long-term regional SAT changes during last two millennia if compared with the PAGES2k (Past Global Changes, project for last 2 kyr) reconstruction[55].

Precipitation basically changes in parallel to SAT (Fig. 3). However, this correlation is not perfect and breaks down during the mid-Holocene because of difference in latitudinal and seasonal distribution of solar energy available for evaporation. For the present-day period, our model slightly (by ~5%) underestimates precipitation amount in comparison to the GPCP-2.3[56-58] (Global Precipitation Climatology Project, version 2.3) observational dataset (Fig. 3). Such and even much larger biases are characteristic for contemporary Earth system models[59].

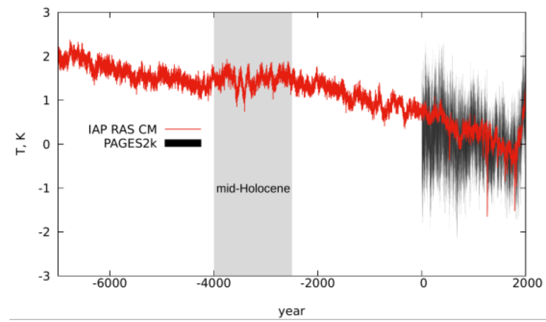

Fig. 2: Simulated SAT during in Europe (35-70°N; 10-40°E) in comparison to the PAGES2k reconstruction. Shown are anomalies relative to mean values over 1500-2000 CE.

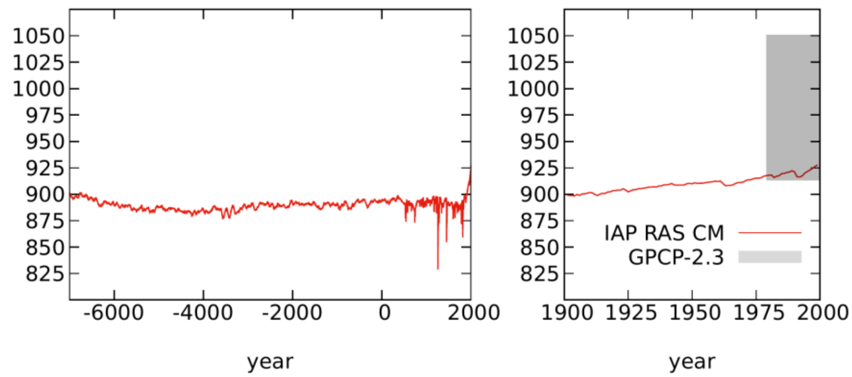

Fig. 3. Global annual precipitation in the IAP RAS CM Holocene simulation (left). The right panel shows the 20th century part of the simulation in comparison to the GPCP-2.3 with uncertainty estimates[57].

Area burned (BA) due to natural fires increases gradually during the Holocene in our simulations owing to increase of the number of anthropogenic ignitions (Fig. 4). However, it starts to decrease in the mid-20th century due to compensation because of fire suppression by humans. For the present-day period, the model slightly overestimate the BA relative to the GFED-4s (Global Fire Emission Database, version 4s) data[60]. We note that, currently, only a handful of Earth system models implements fire modules, and the spread in the present day BA as simulated by those models is severalfold[61].

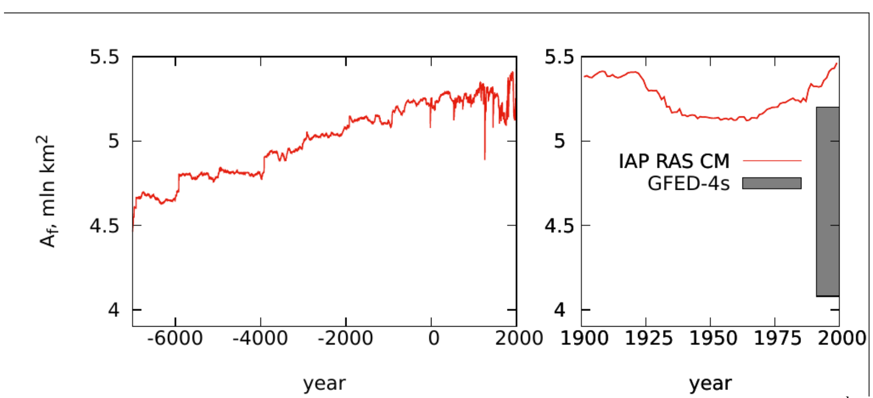

Fig. 4. Global burned area in the IAP RAS CM Holocene simulation (left). The right panel shows the 20th century part of the simulation in comparison to the GFED4s uncertainty range. GFED4s estimates belong to 2001-2010 CE, but here they are ascribed to 1991-2000 CE for plotting convenience.

3. CLIMATE CHANGES DURING NEXT SEVERAL CENTURIES

Earlier projections of future climate changes with the IAP RAS CM were performed either with the IS92 scenario family[62], or with scenario families SRES (Special Report on Emission Scenarios)[63] and RCP (Representative Concentration Pathways)[64,65].

Here, the new set of scenarios is used to drive the IAP RAS CM. These are so called Shared Socioeconomic Pathways (SSPs)[66], which are prepared for use in the CMIP6 (Coupled Models Intercomparison Project, phase 6). We used the following agents to force the model: i) anthropogenic CO_2 emissions due to fossil fuel burning and cement production; ii) CH_4 and N_2O concentrations in the atmosphere; iii) change of extent of crops and pastures iv) total burden of stratospheric aerosols; v) total solar irradiance. In addition, we used vi) total burden of tropospheric sulphates and vii) population density. The latter two forcings are unavailable to public community at time of writing this paper. Thus, we adopted them from the RCP scenarios assuming corresponding pair between RCP and SSP scenarios[66]. Carbon cycle implemented in the IAP RAS CM allows to compute landuse-related carbon dioxide emissions into the atmosphere and to project the CO_2 atmospheric concentration, q_{CO2}, explicitly (see below).

In these numerical experiments, q_{CO2} in year 2017 is 407 ppmv in excellent agreement with the observations (407 ppmv[67]). In 2050, q_{CO2} is projected to be larger by 15-136 ppmv than in 2017 depending on scenario (Fig. 5). In the second half of the 21st century, scenarios diverge, and the CO_2 concentration in the atmosphere in 2100 is, depending on scenario, is either smaller (by 37 ppmv) or larger (by up to 600 ppmv) than in 2017. Atmospheric burden of CO2 in our projections is smaller than in original, CMIP6-provided SSP scenarios.

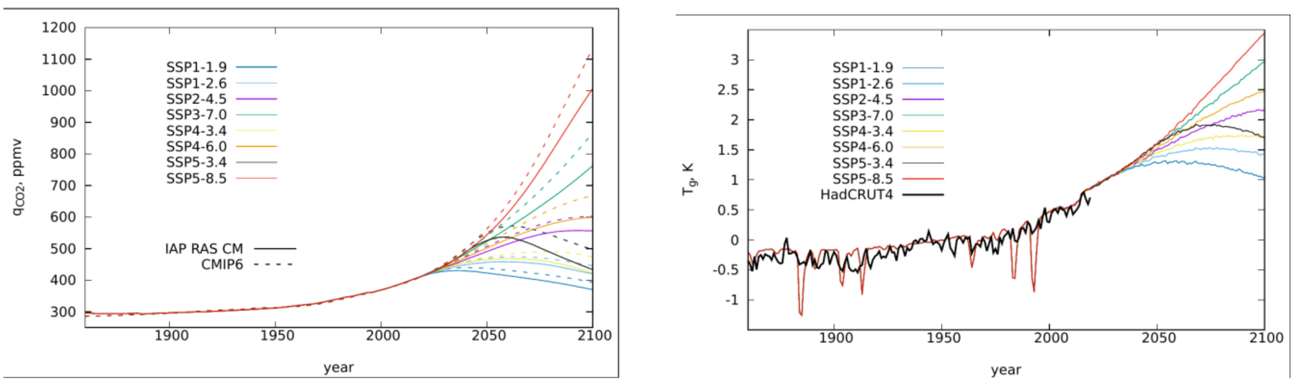

Fig. 5. Simulated and projected CO_2 concentration in the atmosphere (left) and global mean SAT (relative to 1961-1990, right) under different SSP scenarios. Original CMIP6 scenarios are identical to global mean empirical data until 2015.

Depending on scenario, global mean SAT is projected to increase by 1.-2-1.5 K relative to the mean over 1961-1990 in year 2050. Than, similar to that exhibited for q_{CO2}, warming either continues or stopped and replaced by slight cooling. Relative to 1961-1990, global mean SAT is larger by 1.0-3.4 K in 2100 depending on scenarios.

Other aspects of the SSP-driven IAP RAS CM projections are discussed below.

4. SIMULATION OF CARBON AND METHANE CYCLES

First, globally averaged version of the carbon cycle was implemented into the IAP RAS CM in mid-2000s[40,41]. Albeit simplistic, this implementation allowed to simulate atmospheric CO_2 concentration q_{CO2} (Fig. 5), simulate and project the state of the terrestrial ecosystem, and to study several global-scale phenomena such as climate-carbon cycle feedback intensity in the transient simulations[40,41] or eventual saturation of this feedback under sufficiently long external CO_2 emissions into the atmosphere[68,69]. Further, a spatially explicit terrestrial carbon cycle was implemented[24,25,32-35] including module to simulate natural fires including peat fires[30,31].

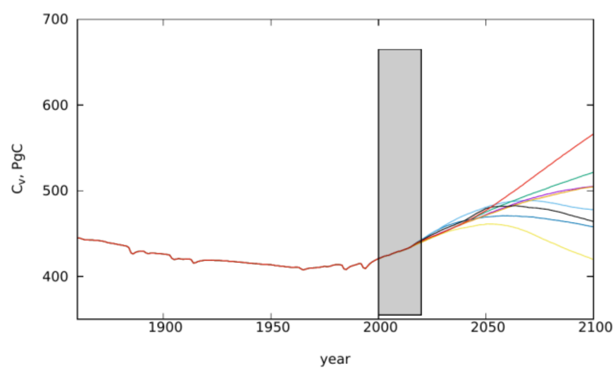

Fig. 6. Simulated and projected vegetation carbon stock under different SSP scenarios together with estimates[20].

Among with the carbon cycle, an interactive methane cycle is implemented in the IAP RAS CM. In the first versions[36], only CH_4 emissions from wetlands into the atmosphere were computed internally. Then CH4 lifetime in the atmosphere was able to be computed internally as well[37,38]. The most important outcome of these simulation is that, nder external methane emissions, the climate-methane cycle feedback adds substantially to the CH_4 buildup in the atmosphere but the respective additional radiative forcing and, thus, the climate response are small. Similar results were also obtained with the INM model[15].

5. PERMAFROST SIMULATIONS

The IAP RAS CM is equipped with the Deep Soil Simulator[27-29] (DSS), a state-of-the-art module to simulate soil thermophysics and hydrology. In the IAP RAS CM implementation, moss and peat layers are taken into account in boreal and peatland regions correspondingly[28].

The present-day near-surface permafrost extent A_p in the model is 22 mln km^2 (Fig. 7). This is within the observational estimates summarised in[29,70]. The IAP RAS CM accuracy in simulating A_p and distribution of active layer thickness is superior to most climate models existing to the date[8,70]. In response to climate warming in the 21[st] century, A_p decreases to the value in year 2100, which varies from 16 mln km^2 to 4 mln km^2 depending on SSP scenario. This is withing the range obtained for other climate models[70,71]. Sensitivity of A_p to unit temprature change is from -(4.7±0.1) mln km^2/K to -(5.5±0.1) mln km^2/K depending on SSP scenario. This is in the upper part of similar sensitivities estimated for the CMIP5 (CMIP, phase 5) ensemble[70].

When the model was forced by scenarios which assume initial increase of q_{CO2}, which is then followed by the decrease of the CO_2 atmospheric content our model produces two distinct A_p trajectories: one for increasing q_{CO2} and another for decreasing q_{CO2}[29]. This result extends the findings[72]. It was referred to as 'transient permafrost hysteresis'[29] and related to the slow thermal signal propagation in peatlands.

6. ROLE OF EXTERNAL FORCINGS IN THE 20TH CENTURY CLIMATE CHANGES

Different external forcing agents (CO_2, CH_4, N_2O, total solar irradiance, tropospheric and stratospheric sulphates, land use, change of the orbital parameters) were progressively implemented into the IAP RAS CM[2-7,22-26]. This allows to isolate their role in the ongoing climate changes. In particular, it was shown that, in agreement with[20,62,63], the major role in the late 20[th] century-early21st century is due to anthropogenically-induced greenhouse effect, which is somewhat compensated by increasing burden of anhropogenic aerosols in the troposphere[22]. Land use became only important since the early 18[th] century and lost its global-scale importance in the mid-20th century[23], which agrees with[73]. However, it is still important at the regional scale, somewhat suppressing precipitation in the region of intensive land use because of lowered surface albedo[23].

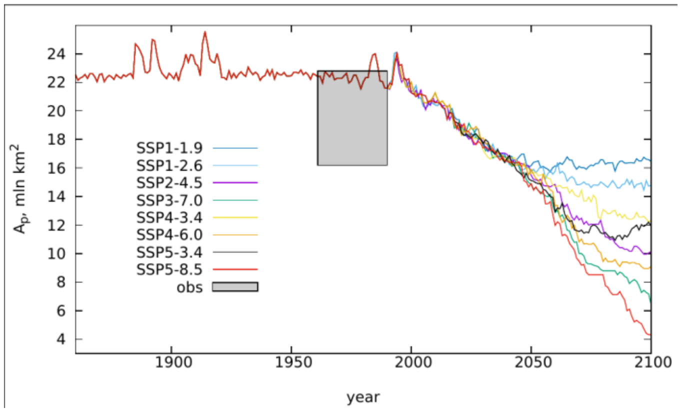

Fig. 7. Simulated and projected near-surface terrestrial permafrost extent under different SSP scenarios together with estimates[29].

In turn, change of total solar irradiance contributes at most 15% of the 20th-century climate warming[39-42,74]. The latter us in agreement with other estimates[75-78]. In addition our simulations show that change of total solar irradiance for 21st century climate projections is of secondary importance as well because radiative forcing due to solar variability is much smaller than the radiative forcing under continuing, strong CO_2 build up in the atmosphere[39-42,74], which is again in agreement with independent estimates[79-81].

It was observed that to these data the q_{CO2} lags (rather than leads) temperature in glacial cycle by few centuries[82-85]. Similar, albeit smaller in magnitude lag (around 50 yr) was observed for q_{CO2} and temperature changes during last millennium (e.g., during Little Ice Age)[86,87]. While there is a caveat in the interpretation of such lags for glacial cycles (because all listed papers employed data from the Antarctic boreholes, and Antarctic temperature leads the global mean one by about 1.3 kyr in glacial cycles[88-91]), it is important to show that such lags do not contradict the role which anthropogenic greenhouse gases play in the 20th-century climate changes. This issue was addressed in the simulations with the IAP RAS CM[43]. It was exhibited that lag between q_{CO2} and global mean SAT depends on different factors, e.g., on the type of the external forcing (either with applied external CO_2 emissions or without them) and on the forcing timescale, and can not be used to infer causal relationships between the Earth system compartments. Thus, such lag does not contradict the major contribution of anthropogenic greenhouse gases into climate changes observed during last severale decades.

7. CONCLUSIONS

In this paper, a structure of the climate model A.M. Obukhov Institute of the Atmospheric Physics, Russian Academy of Sciences (IAP RAS CM) is figured out and the major results obtained with this model are reviewed in comparison to the corresponding results obtained with other state-of-the-art climate models (or Earth system models). It is demonstrated that the IAP RAS CM realistically reproduces the preindustrial and current state of the climate system, as well as the general climate change in the Holocene, including those observed in the 20th century. Being computationally cheap, our model is particular suitable for ensemble simulations.

The IAP RAS CM is continuously under further development. The most recent ones are related to implementation of cloudiness scheme and partly interactive sulphur cycle[35]. This allows on to extend the research area which may be covered by the our model.

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