

# PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://SPIDigitalLibrary.org/conference-proceedings-of-spie)

## The IAP RAS climate model: contemporary state and major results

Alexey V. Eliseev, Igor I. Mokhov

Alexey V. Eliseev, Igor I. Mokhov, "The IAP RAS climate model: contemporary state and major results," Proc. SPIE 11208, 25th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 112086C (18 December 2019); doi: 10.1117/12.2538952

**SPIE.**

Event: XXV International Symposium, Atmospheric and Ocean Optics, Atmospheric Physics, 2019, Novosibirsk, Russian Federation

# The IAP RAS climate model: Contemporary state and major results

Alexey V. Eliseev<sup>\*a,b,c</sup>, Igor I. Mokhov<sup>a,b,d</sup>

<sup>a</sup>Faculty of Physics, Lomonosov Moscow State University, 1-2 Leninskiye Gory, Moscow, Russia 119991; <sup>b</sup>A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, 3 Pyzhevsky, Moscow, Russia 119017; <sup>c</sup>Institute of Environmental Sciences, Kazan Federal University, 5 Tovarichsheskaya, Kazan, Russia 420097; <sup>d</sup>Faculty of Aerodynamics and Space Physics, Moscow Institute of Physics and Technology, 9 Institutsky, Dolgoprudny, Russia 141701

## 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 specific 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<sup>1</sup>. In the 1990s a non-zonal version of the model was developed<sup>2</sup>. The IAP RAS CM is the only Russian model that belongs to the class of climate models of intermediate complexity (EMICs)<sup>3,4</sup> and participates in relevant international comparisons<sup>5-7</sup>. Along with the general circulation model of the Institute of Computational Mathematics (INM) of the Russian Academy of Sciences<sup>8-19</sup>, 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<sup>20</sup> (IPCC).

The IAP RAS CM includes modules for the transfer of shortwave and longwave radiation, convection, cloud formation and precipitation<sup>1-3,5,7,21-26</sup>. 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<sup>1-3,5</sup>. 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<sup>27-29</sup>, carbon<sup>24,25,30-35</sup> and methane cycles<sup>36-38</sup>. The horizontal resolution of the IAP RAS CM is 4.5° in latitude and 6° 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<sup>6,22-26</sup>. 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<sup>7,22-26</sup>. 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<sup>20</sup>.

\*eliseev.alexey.v@gmail.com; phone +7 (495)939-20-89; fax +7(495)932-88-20

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<sup>21,25,29,30,39-43</sup>.

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<sup>5,21,23</sup>.

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 parameters of the Earth orbit, which are calculated internally by the model according to the Berger equations<sup>44</sup>; ii) total solar irradiance reconstructed from <sup>10</sup>Be data<sup>45</sup>; iii) optical depth of stratospheric (volcanic) aerosols<sup>46</sup> (only for 1500-2000 CE); iv) ice core-derived concentrations of well-mixed greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) in the atmosphere<sup>47</sup>; 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)<sup>48</sup>; total burden of tropospheric sulphates<sup>49</sup> 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 20<sup>th</sup> century but underestimates interannual and interdecadal variability (Fig. 1). The latter respect is similar to other contemporary EMICs<sup>3-7</sup>. In particular, the 20<sup>th</sup> century increase in global SAT is 0.58°C in reasonable agreement with the HadCRUT4 dataset<sup>50,51</sup> (~0.7°C). The difference between these (model and observational) estimates probably reflects contribution of the natural variability into the 20<sup>th</sup> century global mean warming.

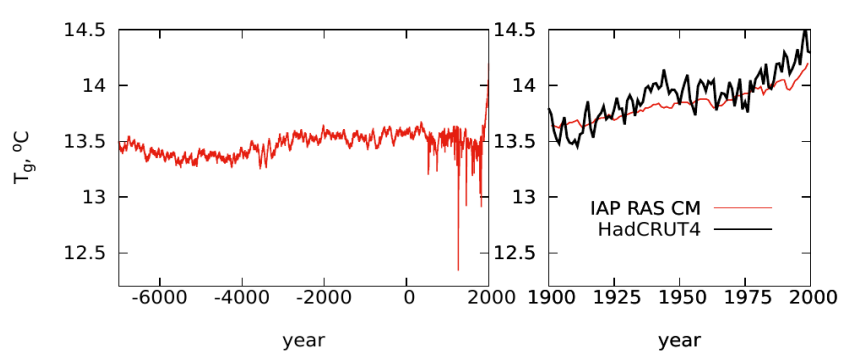


Fig. 1. Global mean surface air temperature in the IAP RAS CM Holocene simulation (left). The right panel shows the 20<sup>th</sup> century part of the simulation in comparison to the HadCRUT4 observational dataset.

The mid-Holocene optimum is not visible at the global scale. This is consistent with the present-day known PAGES2k.gpge<sup>52,53</sup>. 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<sup>54</sup>. 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<sup>55</sup>.

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<sup>56-58</sup> (Global Precipitation Climatology Project, version 2.3) observational dataset (Fig. 3). Such and even much larger biases are characteristic for contemporary Earth system models<sup>59</sup>.

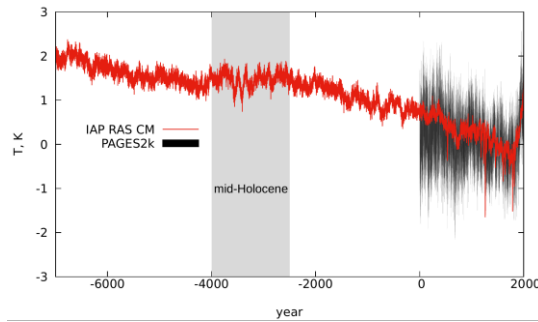


Fig. 2: Simulated SAT during in Europe (35-70°N; 10-40°E) in comparison to the PAGES2k reconstruction. Shown are anomalies relative to mean values over 1500-2000 CE.

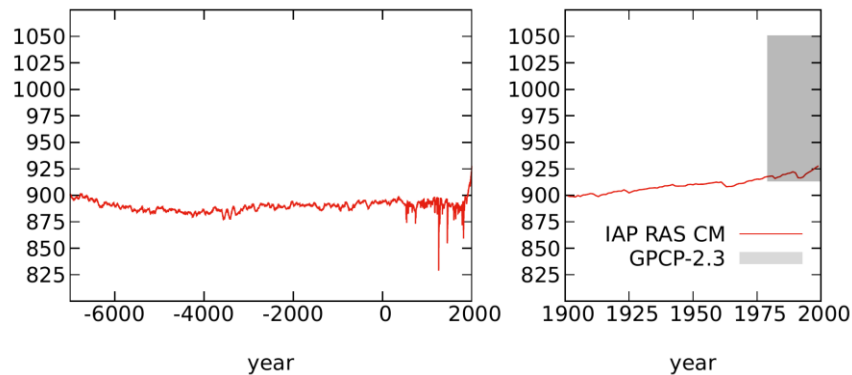


Fig. 3. Global annual precipitation in the IAP RAS CM Holocene simulation (left). The right panel shows the 20<sup>th</sup> century part of the simulation in comparison to the GPCP-2.3 with uncertainty estimates<sup>57</sup>.

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<sup>60</sup>. 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<sup>61</sup>.

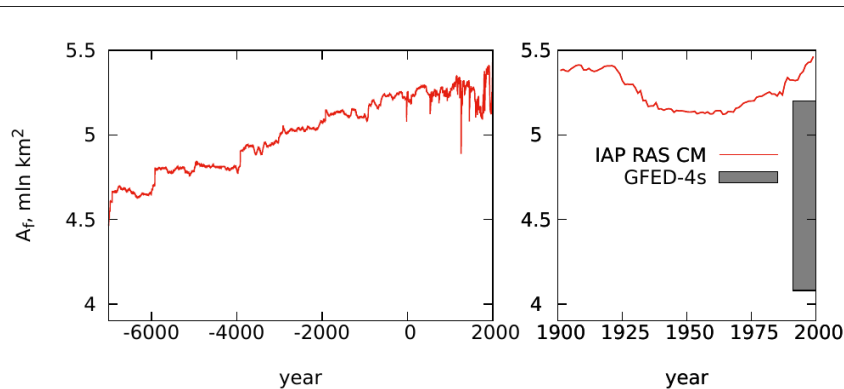


Fig. 4. Global burned area in the IAP RAS CM Holocene simulation (left). The right panel shows the 20<sup>th</sup> century part of the simulation in comparison to the GFED4s uncertainty range. GFED4s estimates belong to 2001-2010 CE, but here they are ascribed to 1991-2000 CE for plotting convenience.

### 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<sup>62</sup>, or with scenario families SRES (Special Report on Emission Scenarios)<sup>63</sup> and RCP (Representative Concentration Pathways)<sup>64,65</sup>.

Here, the new set of scenarios is used to drive the IAP RAS CM. These are so called Shared Socioeconomic Pathways (SSPs)<sup>66</sup>, 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<sub>2</sub> emissions due to fossil fuel burning and cement production; ii) CH<sub>4</sub> and N<sub>2</sub>O 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<sup>66</sup>. Carbon cycle implemented in the IAP RAS CM allows to compute landuse-related carbon dioxide emissions into the atmosphere and to project the CO<sub>2</sub> atmospheric concentration,  $q_{CO_2}$ , explicitly (see below).

In these numerical experiments,  $q_{CO_2}$  in year 2017 is 407 ppmv in excellent agreement with the observations (407 ppmv<sup>67</sup>). In 2050,  $q_{CO_2}$  is projected to be larger by 15-136 ppmv than in 2017 depending on scenario (Fig. 5). In the second half of the 21<sup>st</sup> century, scenarios diverge, and the CO<sub>2</sub> 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 CO<sub>2</sub> in our projections is smaller than in original, CMIP6-provided SSP scenarios.

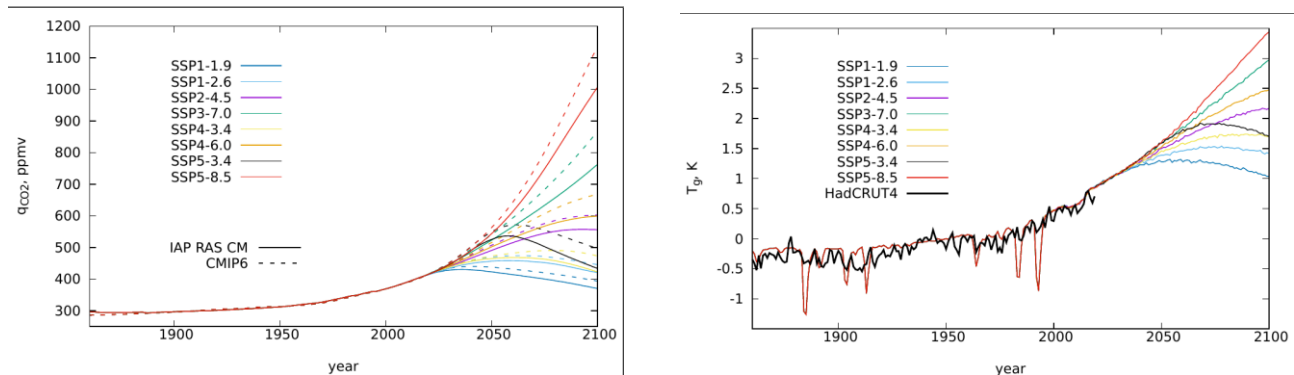


Fig. 5. Simulated and projected CO<sub>2</sub> concentration in the atmosphere (left) and global mean SAT (relative to 1961-1990, right) under different SSP scenarios. Original CMIP6 scenarios are identical to global mean empirical data until 2015.

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. Then, similar to that exhibited for  $q_{CO_2}$ , 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<sup>40,41</sup>. Albeit simplistic, this implementation allowed to simulate atmospheric CO<sub>2</sub> concentration  $q_{CO_2}$  (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<sup>40,41</sup> or eventual saturation of this feedback under sufficiently long external CO<sub>2</sub> emissions into the atmosphere<sup>68,69</sup>. Further, a spatially explicit terrestrial carbon cycle was implemented<sup>24,25,32-35</sup> including module to simulate natural fires including peat fires<sup>30,31</sup>.

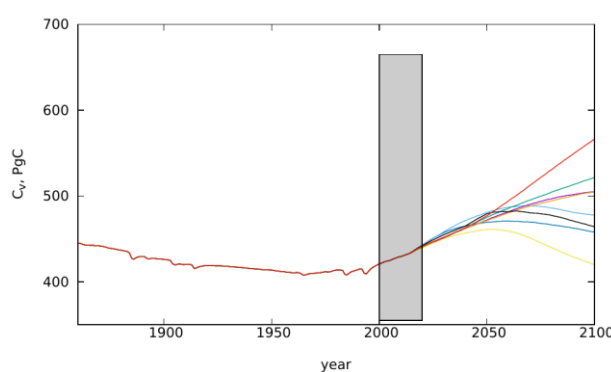


Fig. 6. Simulated and projected vegetation carbon stock under different SSP scenarios together with estimates<sup>20</sup>.

Among with the carbon cycle, an interactive methane cycle is implemented in the IAP RAS CM. In the first versions<sup>36</sup>, only CH<sub>4</sub> emissions from wetlands into the atmosphere were computed internally. Then CH<sub>4</sub> lifetime in the atmosphere was able to be computed internally as well<sup>37,38</sup>. The most important outcome of these simulation is that, under external methane emissions, the climate-methane cycle feedback adds substantially to the CH<sub>4</sub> 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<sup>15</sup>.

## 5. PERMAFROST SIMULATIONS

The IAP RAS CM is equipped with the Deep Soil Simulator<sup>27-29</sup> (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<sup>28</sup>.

The present-day near-surface permafrost extent  $A_p$  in the model is 22 mln km<sup>2</sup> (Fig. 7). This is within the observational estimates summarised in<sup>29,70</sup>. 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<sup>8,70</sup>. In response to climate warming in the 21<sup>st</sup> century,  $A_p$  decreases to the value in year 2100, which varies from 16 mln km<sup>2</sup> to 4 mln km<sup>2</sup> depending on SSP scenario. This is within the range obtained for other climate models<sup>70,71</sup>. Sensitivity of  $A_p$  to unit temperature change is from  $-(4.7 \pm 0.1)$  mln km<sup>2</sup>/K to  $-(5.5 \pm 0.1)$  mln km<sup>2</sup>/K depending on SSP scenario. This is in the upper part of similar sensitivities estimated for the CMIP5 (CMIP, phase 5) ensemble<sup>70</sup>.

When the model was forced by scenarios which assume initial increase of  $q_{CO_2}$ , which is then followed by the decrease of the CO<sub>2</sub> atmospheric content our model produces two distinct  $A_p$  trajectories: one for increasing  $q_{CO_2}$  and another for decreasing  $q_{CO_2}$ <sup>29</sup>. This result extends the findings<sup>72</sup>. It was referred to as 'transient permafrost hysteresis'<sup>29</sup> 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<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, total solar irradiance, tropospheric and stratospheric sulphates, land use, change of the orbital parameters) were progressively implemented into the IAP RAS CM<sup>2-7,22-26</sup>. This allows to isolate their role in the ongoing climate changes. In particular, it was shown that, in agreement with<sup>20,62,63</sup>, the major role in the late 20<sup>th</sup> century-early 21<sup>st</sup> century is due to anthropogenically-induced greenhouse effect, which is somewhat compensated by increasing burden of anthropogenic aerosols in the troposphere<sup>22</sup>. Land use became only important since the early 18<sup>th</sup> century and lost its global-scale importance in the mid-20<sup>th</sup> century<sup>23</sup>, which agrees with<sup>73</sup>. However, it is still important at the regional scale, somewhat suppressing precipitation in the region of intensive land use because of lowered surface albedo<sup>23</sup>.

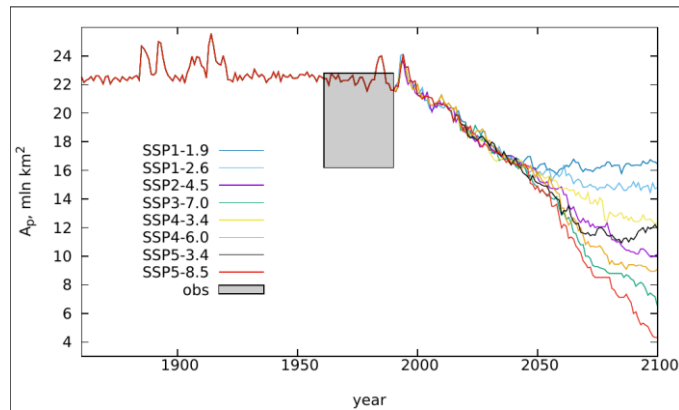


Fig. 7. Simulated and projected near-surface terrestrial permafrost extent under different SSP scenarios together with estimates<sup>29</sup>.

In turn, change of total solar irradiance contributes at most 15% of the 20<sup>th</sup>-century climate warming<sup>39-42,74</sup>. The latter is in agreement with other estimates<sup>75-78</sup>. In addition our simulations show that change of total solar irradiance for 21<sup>st</sup> 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<sub>2</sub> build up in the atmosphere<sup>39-42,74</sup>, which is again in agreement with independent estimates<sup>79-81</sup>.

It was observed that to these data the  $q_{CO_2}$  lags (rather than leads) temperature in glacial cycle by few centuries<sup>82-85</sup>. Similar, albeit smaller in magnitude lag (around 50 yr) was observed for  $q_{CO_2}$  and temperature changes during last millennium (e.g., during Little Ice Age)<sup>86,87</sup>. 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<sup>88-91</sup>), 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<sup>43</sup>. It was exhibited that lag between  $q_{CO_2}$  and global mean SAT depends on different factors, e.g., on the type of the external forcing (either with applied external CO<sub>2</sub> 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 several 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<sup>35</sup>. This allows on to extend the research area which may be covered by the our model.

## ACKNOWLEDGEMENT

This work has been supported by the Russian Foundation for Basic Research (grants 18-05-00087, 18-05-60111), and the Fund for State Support of Kazan (Privolzhskii) Federal University aimed at improving the competitive capability among leading scientific and educational centers in the world, using the results obtained within RAS programs. The results related to the permafrost dynamics and those related to the vegetation changes in the high northern latitude are supported by the Russian Science Foundation project 18-47-06203.

## REFERENCES

- [1] Petoukhov, V. K., "Zonal climatic model of heat and moisture exchange in the atmosphere over underlying layer", *Physics of the atmosphere and the problem of climate*, Nauka, Moscow, 8-41 (1980).
- [2] Petoukhov, V. K., Mokhov, I. I., Eliseev, A. V., Semenov, V. A., [The IAPRAS Global Climate Model], Dialogue-MSU. Moscow (1998).
- [3] Claussen, M., Mysak, L., Weaver, A., Crucifix, M., Fichet, T., Loutre, M.-F., Weber, S., Alcamo, J., Alexeev, V., Berger, A., Calov, R., Ganopolski, A., Goosse, H., Lohmann, G., Lunkeit, F., Mokhov, I., Petoukhov, V., Stone, P., Wang, Z., "Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models", *Clim. Dyn.*, 18 (7), 579-586 (2002).
- [4] Weber, S. L., "The utility of Earth system Models of Intermediate Complexity (EMICs)", *Wiley Intern. Rev. Clim. Change*, 1 (2), 243-252 (2010).
- [5] Petoukhov, V., Claussen, M., Berger, A., Crucifix, M., Eby, M., Eliseev, A. V., Fichet, T., Ganopolski, A., Goosse, H., Kamenkovich, I., Mokhov, I. I., Montoya, M., Mysak, L. A., Sokolov, A., Stone, P., Wang, Z., Weaver, A., "EMIC intercomparison project (EMIP-CO2): Comparative analysis of EMIC simulations of current climate and equilibrium and transient responses to atmospheric CO<sub>2</sub> doubling", *Clim. Dyn.*, 25 (4), 363-385 (2005).
- [6] Eby, M., Weaver, A. J., Alexander, K., Zickfeld, K., Abe-Ouchi, A., Cimatoribus, A. A., Cressin, E., Drijfhout, S. S., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichet, T., Forest, C. E., Goosse, H., Holden, P. B., Joos, F., Kawamiya, M., Kicklighter, D., Kienert, H., Matsumoto, K., Mokhov, I. I., Monier, E., Olsen, S. M., Pedersen, J. O. P., Perrette, M., Philippon-Berthier, G., Ridgwell, A., Schlosser, A., Schneider von Deimling, T., Shaffer, G., Smith, R. S., Spahni, R., Sokolov, A. P., Steinacher, M., Tachiiri, K., Tokos, K., Yoshimori, M., Zeng, N., Zhao, F., "Historical and idealized climate model experiments: an EMIC intercomparison", *Clim. Past*, 9 (3), 1111-1140 (2013).
- [7] Zickfeld, K., Eby, M., Weaver, A. J., Alexander, K., Cressin, E., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichet, T., Forest, C. E., Friedlingstein, P., Goosse, H., Holden, P. B., Joos, F., Kawamiya, M., Kicklighter, D., Kienert, H., Matsumoto, K., Mokhov, I. I., Monier, E., Olsen, S. M., Pedersen, J. O. P., Perrette, M., Philippon-Berthier, G., Ridgwell, A., Schlosser, A., Schneider von Deimling, T., Shaffer, G., Sokolov, A., Spahni, R., Steinacher, M., Tachiiri, K., Tokos, K. S., Yoshimori, M., Zeng N., Zhao F., "Long-term climate change commitment and reversibility: An EMIC intercomparison", *J. Climate*, 26 (16), 5782-5809 (2013).
- [8] Volodin, E. M., Dianskii, N. A., Gusev, A. V., "Simulating present-day climate with the INMCM4.0 coupled model of the atmospheric and oceanic general circulations", *Izvestiya Atmos. Ocean. Phys.* 46 (4), 414-431 (2010).
- [9] Dianskii, N. A., Galin, V. Ya., Gusev, A. V., Volodin, E. M., Iakovlev, N. G., Smyshlyaev, S. P., "The model of the Earth system developed at the INM RAS", *Rus. J. Numer. Anal. Math. Modelling.* 25 (5), 419-429 (2010).
- [10] Yurova, A. Y., Volodin, E. M., "Coupled simulation of climate and vegetation dynamics", *Izvestiya Atmos. Ocean. Phys.* 47 (5), 531-539 (2011).
- [11] Dymnikov, V. P., Lykosov, V. N., Volodin, E. M., "Modeling climate and its changes: current problems", *Herald Rus. Acad. Sci.*, 82 (2), 111-119 (2012).
- [12] Izrael, Y. A., Revokatova, A. P., Ryaboshapko, A. G., Volodin, E. M., Kostykin, S. V., "Possibility of geoengineering stabilization of global temperature in the 21st century using the stratospheric aerosol and estimation of potential negative effects", *Rus. Meteorol. Hydrol.*, 38 (6), 371-381 (2013).
- [13] Volodin, E. M., Diansky, N. A., Gusev, A. V., "Simulation and prediction of climate changes in the 19th to 21st centuries with the Institute of Numerical Mathematics, Russian Academy of Sciences, model of the Earths climate system", *Izvestiya Atmos. Ocean. Phys.*, 49 (4), 347-366 (2013).
- [14] Mareev, E. A., Volodin, E. M., "Variation of the global electric circuit and ionospheric potential in a general circulation model", *Geophys. Res. Lett.*, 41 (24), 9009-9016 (2014).
- [15] Volodin, E. M., "Influence of methane sources in Northern Hemisphere high latitudes on the interhemispheric asymmetry of its atmospheric concentration and climate", *Izvestiya Atmos. Ocean. Phys.*, 51 (3), 251-258 (2015).
- [16] Dymnikov, V. P., Lykosov, V. N., Volodin, E. M., "Mathematical simulation of Earth system dynamics", *Izvestiya Atmos. Ocean. Phys.*, 51 (3), 227-240 (2015).
- [17] Volodin, E. M., Kostykin, S. V., "The aerosol module in the INM RAS climate model", *Rus. Meteorol. Hydrol.*, 41 (8), 519-528 (2016).



- [18] Vargin, P. N., Volodin, E. M., "analysis of the reproduction of dynamic processes in the stratosphere using the climate model of the Institute of Numerical Mathematics, Russian Academy of Sciences", *Izvestiya Atmos. Ocean. Phys.*, 52 (1), 1-15 (2016).
- [19] Volodin, E. M., Mortikov, E. V., Kostykin, S. V., Galin, V. Y., Lykosov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., Yakovlev, N. G., "Simulation of modern climate with the new version of the INM RAS climate model", *Izvestiya Atmos. Ocean. Phys.*, 53 (2), 142-155 (2017).
- [20] [Climate Change 2013: The Physical Science Basis], Cambridge Univ. Press, Cambridge (2007)
- [21] Demchenko, P. F., Velichko, A. A., Eliseev, A.V., Mokhov, I.I., Nechaev, V.P., "Dependence of permafrost conditions on global warming: Comparison of models, scenarios, and paleoclimatic reconstructions" *Izvestiya Atmos. Ocean. Phys.*, 38 (2), 143-151 (2002).
- [22] Eliseev, A. V., Mokhov, I. I., Karpenko, A. A., "Influence of direct sulfate-aerosol radiative forcing on the results of numerical experiments with a climate model of intermediate complexity", *Izvestiya Atmos. Ocean. Phys.*, 43 (5), 544-554 (2007).
- [23] Eliseev, A. V., Mokhov, I.I., "Effect of including land use driven radiative forcing of the surface albedo of land on climate response in the 16th-21st centuries", *Izvestiya Atmos. Ocean. Phys.*, 47, (1), 15-30 (2011).
- [24] Eliseev, A. V., Mokhov, I. I., "Uncertainty of climate response to natural and anthropogenic forcings due to different land use scenarios", *Adv. Atmos. Sci.*, 28 (5), 1215-1232 (2011)
- [25] Eliseev, A.V., "Estimation of changes in characteristics of the climate and carbon cycle in the 21st century accounting for the uncertainty of terrestrial biota parameter values", *Izvestiya Atmos. Ocean. Phys.*, 47 (2), 131-153 (2011).
- [26] Mokhov, I. I., Eliseev, A. V., "Modeling of global climate variations in the 20th-23rd centuries with new RCP scenarios of anthropogenic forcing", *Doklady Earth Sci.*, 443 (2), 532-536 (2012).
- [27] Arzhanov, M. M., Demchenko, P. F., Eliseev, A. V., Mokhov, I. I., "Simulation of characteristics of thermal and hydrologic soil regimes in equilibrium numerical experiments with a climate model of intermediate complexity", *Izvestiya Atmos. Ocean. Phys.*, 44 (5), 279-287 (2008).
- [28] Eliseev, A. V., Arzhanov, M. M., Demchenko, P. F., Mokhov, I.I., "Changes in climatic characteristics of Northern Hemisphere extratropical land in the 21st century: Assessments with the IAP RAS climate model", *Izvestiya Atmos. Ocean. Phys.*, 45 (3), 271-283 (2009).
- [29] Eliseev, A. V., Demchenko, P. F., Arzhanov, M. M., Mokhov, I. I., "Transient hysteresis of near-surface permafrost response to external forcing", *Clim. Dyn.*, 42 (5-6), 1203-1215 (2014).
- [30] Eliseev, A. V., Mokhov, I.I., Chernokulsky, A.V., "An ensemble approach to simulate CO<sub>2</sub> emissions from natural fires", *Biogeosciences*, 11 (12), 3205-3223 (2014).
- [31] Eliseev, A. V., Mokhov, I. I., Chernokulsky, A. V. "Influence of ground and peat fires on CO<sub>2</sub> emissions into the atmosphere", *Doklady Earth Sci.*, 459 (2), 1565-1569 (2014).
- [32] Eliseev, A. V., Sergeev, D. E., "Impact of subgrid scale vegetation heterogeneity on the simulation of carbon cycle characteristics", *Izvestiya Atmos. Ocean. Phys.*, 50 (3), 225-235 (2014).
- [33] Eliseev, A. V., "Impact of tropospheric sulphate aerosols on the terrestrial carbon cycle", *Glob. Planet. Change*, 124, 30-40 (2015).
- [34] Eliseev, A. V., "Influence of sulfur compounds on the terrestrial carbon cycle", *Izvestiya Atmos. Ocean. Phys.*, 51 (6), 599-608 (2015).
- [35] Eliseev, A. V., Zhang, M., Gizatullin, R. D., Altukhova, A. V., Perevedentsev, Yu. P., Skorokhod, I. A., "Impact of sulfur dioxide on the terrestrial carbon cycle", *Izvestiya Atmos. Ocean. Phys.*, 55 (1), 38-49 (2019).
- [36] Eliseev, A. V., Mokhov, I. I., Arzhanov, M. M., Demchenko, P. F., Denisov, S. N., "Interaction of the methane cycle and processes in wetland ecosystems in a climate model of intermediate complexity", *Izvestiya Atmos. Ocean. Phys.*, 44 (2), 139-152 (2008)
- [37] Denisov, S. N. Eliseev, A.V., Mokhov, I.I., "Climate change in IAP RAS global model taking account of interaction with methane cycle under anthropogenic scenarios of RCP family", *Rus. Meteorol. Hydrol.*, (38) 11, 741-749 (2013).
- [38] Denisov, S. N., Eliseev, A.V., Mokhov, I. I., Arzhanov, M. M., "Model estimates of global and regional atmospheric methane emissions of wetland ecosystems", *Izvestiya Atmos. Ocean. Phys.*, 51 (5), 482-487 (2015).
- [39] Mokhov, I. I., Bezverkhniy, V. A., Eliseev, A.V., Karpenko, A. A., "Model estimates of global climatic changes in the 21st century with account for different variation scenarios of solar activity", *Doklady Earth Sci.*, 411 (8), 1327-1330 (2006).

- [40] Eliseev, A. V. Mokhov, I. I., "Carbon cycle-climate feedback sensitivity to parameter changes of a zero-dimensional terrestrial carbon cycle scheme in a climate model of intermediate complexity", *Theor. Appl. Climatol.*, 89 (1-2), 9-24 (2007).
- [41] Mokhov, I. I., Bezverkhni, V. A., Eliseev, A. V., Karpenko, A. A., "Model estimations of possible climatic changes in 21st century at different scenarios of solar and volcanic activities and anthropogenic impact", *Cosmic Res.*, 46 (4), 354-357 (2008)
- [42] Eliseev, A. V., Mokhov, I. I., "Extra-terrestrial factors' influence on climate: Possible mechanisms and modeling results", *Fundamental Appl. Climatol.*, 1, 119-132 (2015).
- [43] Muryshev, K. E., Eliseev, A. V., Mokhov, I. I., Timazhev, A. V. "Lead-lag relationships between global mean temperature and the atmospheric CO<sub>2</sub> content in dependence of the type and time scale of the forcing", *Glob. Planet. Change*, 148, 29-41 (2017).
- [44] Berger, A. L., "Long-term variations of daily insolation and Quaternary climatic changes", *J. Atmos. Sci.*, 35 (12), 2362-2367 (1978)
- [45] Steinhilber, F., Beer, J., Fröhlich, C., "Total solar irradiance during the Holocene", *Geophys. Res. Lett.*, 36 (19) L19704 (2009).
- [46] Gao, C., Robock, A., Ammann, C., "Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models", *J. Geophys. Res.*, 113 (D23), D23111 (2008).
- [47] Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D. M., Fraser, P. J., Montzka, S. A., Rayner, P. J., Trudinger, C. M., Krummel, P. B., Beyerle, U., Canadell, J. G., Daniel, J. S., Enting, I. G., Law, R. M., Lunder, C. R., O'Doherty, S., Prinn, R. G., Reimann, S., Rubino, M., Velders, G. J. M., Vollmer, M. K., Wang, R. H. J., Weiss, R. "Historical greenhouse gas concentrations for climate modelling (CMIP6)", *Geosci. Model Dev.*, 10 (5), 2057-2116 (2017).
- [48] Klein Goldewijk, K., Beusen, A., Doelman, J., Stehfest, E., "Anthropogenic land use estimates for the Holocene – HYDE 3.2", *Earth Syst. Sci. Data*, 9 (2), 927-953 (2017).
- [49] Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., van Vuuren, D. P., "Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application", *Atmos. Chem. Phys.*, 10 (15), 7017-7039 (2010)
- [50] Morice, C. P., Kennedy, J. J., Rayner, N. A., Jones, P. D., "Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset", *J. Geophys. Res.*, 117 (D8), D08101 (2012).
- [51] Osborn, T. J., Jones, P. D., "The CRUTEM4 land-surface air temperature data set: construction, previous versions and dissemination via Google Earth", *Earth Syst. Sci. Data*, 6, 61-68 (2014).
- [52] Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J. O., Küttel, M., Müller, S. A., Prentice, I. C., Solomina, O., Stocker, T. F., Tarasov, P., Wagner, M., Widmann, M., "Mid- to Late Holocene climate change: An overview", *Quaternary Sci. Rev.*, 27 (19-20), 1791-1828 (2008).
- [53] Bartlein, P. J., Harrison, S. P., Brewer, S., Connor, S., Davis, B. A. S., Gajewski, K., Guiot, J., Harrison-Prentice, T. I., Henderson, A., Peyron, O., Prentice, I. C., Scholze, M., Seppa, H., Shuman, B., Sugita, S., Thompson, R. S., Viau, A. E., Williams, J., Wu, H., "Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis", *Clim. Dyn.*, 37 (8), 775-802 (2011).
- [54] Texier, D., de Noblet, N., Harrison, S. P., Haxeltine, A., Jolly, D., Joussaume, S., Laarif, F., Prentice, I. C., Tarasov, P., "Quantifying the role of biosphere-atmosphere feedbacks in climate change: coupled model simulations for 6000 years BP and comparison with palaeodata for northern Eurasia and northern Africa", *Clim. Dyn.*, 13, 865-882 (1997).
- [55] PAGES 2k Consortium, "Continental-scale temperature variability during the past two millennia", *Nature Geosci.*, 6 (5), 339-346 (2013).
- [56] Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P., Nelkin, E., "The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present)", *J. Hydrometeorol.*, 4(6), 1147-1167, (2003)
- [57] Adler, R. F., Gu, G., Sapiano, M., Wang, J.-J., Huffman, G. J., "Global precipitation: means, variations and trends during the satellite era (1979-2014)", *Surv. Geophys.*, 38 (4), 679-699.

- [58] Adler, R. F., Sapiano, M. R. P., Huffman, G. J., Wang, J.-J., Gu, G., Bolvin, D., Chiu, L., Schneider, U., Becker, A., Nelkin, E., Xie, P., Ferraro, R., Shin, D.-B., "The Global Precipitation Climatology Project (GPCP) Monthly Analysis (New Version 2.3) and a Review of 2017 Global Precipitation", *Atmosphere*, 9(4), 138 (2018).
- [59] Liu, Z., Mehran, A., Phillips, T. J., AghaKouchak, A., "Seasonal and regional biases in CMIP5 precipitation simulations", *Clim. Res.*, 60 (1), 35-50 (2014).
- [60] Randerson, J. T., Chen, Y., van der Werf, G. R., Rogers, B. M., Morton, D. C., "Global burned area and biomass burning emissions from small fires", *J. Geophys. Res.: Biogeosciences*, 117 (G4), G04012 (2012).
- [61] Kloster, S., Lasslop G., "Historical and future fire occurrence (1850 to 2100) simulated in CMIP5 Earth System Models", *Glob. Planet. Change*, 150, 58-69 (2017).
- [62] *Climate Change: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge Univ. Press, Cambridge (1992).
- [63] *Climate Change 2001: the Scientific Basis*, Cambridge Univ. Press, Cambridge (2001).
- [64] van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., "The representative concentration pathways: an overview", *Clim. Change*, 109 (1-2), 5-31 (2011).
- [65] Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Lioussé, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., van Vuuren, D. P., "Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application", *Atmos. Chem. Phys.*, 10 (15), 7017-7039 (2011).
- [66] Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K., "Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century", *Geosci. Mod. Devel.*, 12 (4), 1443-1475 (2019).
- [67] Le Quèrè, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P. A., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Arneeth, A., Arora, V. K., Barbero, L., Bastos, A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Doney, S. C., Gkritzalis, T., Goll, D. S., Harris, I., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Johannessen, T., Jones, C. D., Kato, E., Keeling, R. F., Klein Goldewijk, K., Landschützer, P., Lefèvre, N., Lienert, S., Liu, Z., Lombardozzi, D., Metzl, N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rocher, M., Rödenbeck, C., Schuster, U., Schwinger J., Sèfèrian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., Wright, R., Zaehle, S., Zheng, B., "Global carbon budget 2018", *Earth Syst. Sci. Data*, 10 (4), 2141-2194 (2018).
- [68] Eliseev, A. V., Mokhov, I. I., Karpenko, A.A., "Climate and carbon cycle variations in the 20th and 21st centuries in a model of intermediate complexity", *Izvestiya Atmos. Ocean. Phys.*, 43 (1), 1-14 (2007)
- [69] Mokhov, I. I., Eliseev, A.V. "Explaining the eventual transient saturation of climate-carbon cycle feedback", *Carbon Balance and Management*, 3, 4 (2008).
- [70] Koven, C. D., Riley, W. J., Stern, A., "Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth system models", *J. Climate*, 26 (6), 1877-1900 (2013).
- [71] Slater, A. G., Lawrence, D. M., "Diagnosing present and future permafrost from climate models", *J. Climate*, 26 (15), 5608-5623 (2013).
- [72] Boucher, O., Halloran, P. R., Burke, E. J., Doutriaux-Boucher, M., Jones, C. D., Lowe, J., Ringer, M. A., Robertson, E., Wu, P., " Reversibility in an Earth System model in response to CO<sub>2</sub> concentration changes", *Env. Res. Lett.*, 7 (2), 024013 (2012).
- [73] Brovkin, V., Claussen, M., Driesschaert, E., Fichet, T., Kicklighter, D., Loutre, M. F., Matthews, H. D., Ramankutty, N., Schaeffer, M., Sokolov, A., "Biogeophysical effects of historical land cover changes simulated by six Earth system models of intermediate complexity", *Clim. Dyn.*, 26, 587-600 (2006).
- [74] Mokhov, I. I., Bezverkhni, V A., Eliseev, A.V., Karpenko, A. A., "Interrelation between variations in the global surface air temperature and solar activity based on observations and reconstructions", *Doklady Earth Sci.*, 409 (5), 805-809 (2006).

- [75] Lean, J. L., Rind, D. H., "How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006", *Geophys. Res. Lett.*, 35 (18), L18701 (2008).
- [76] Zhou, J., Tung, K.-K., "Solar cycles in 150 years of global sea surface temperature data", *J. Climate*, 23 (12), 3234-3248 (2010).
- [77] Solanki, S. K., Krivova, N. A., Haigh, J. D., "Solar irradiance variability and climate", *Ann. Rev. Astronomy Astrophys.* 51, 311-351 (2013).
- [78] Schurer, A. P., Tett, S. F. B., Hegerl, G. C., "Small influence of solar variability on climate over the past millennium", *Nature Geosci.*, 7 (2), 104-108 (2014).
- [79] Feulner, G., Rahmstorf, S., "On the effect of a new grand minimum of solar activity on the future climate on Earth", *Geophys. Res. Lett.*, 37 (5), L05707 (2010).
- [80] Jones, G. S., Lockwood, M., Stott, P. A., "What influence will future solar activity changes over the 21st century have on projected global near-surface temperature changes?", *J. Geophys. Res.: Atmospheres*, 117 (D5), D05103 (2012).
- [81] Arsenovic, P., Rozanov, E., Anet, J., Stenke, A., Schmutz, W., Peter, T., "Implications of potential future grand solar minimum for ozone layer and climate", *Atmos. Chem. Phys.*, 18 (5), 3469-3483 (2018).
- [82] Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T., Raynaud, D., Barnola, J. M., "Atmospheric CO<sub>2</sub> concentrations over the last glacial termination", *Science* 291 (5501), 112-114 (2001).
- [83] Caillon, N., Severinghaus, J., Jouzel, J., Barnola, J. M., Kang, J., Lipenkov, V., "Timing of atmospheric CO<sub>2</sub> and Antarctic temperature changes across Termination III", *Science* 299 (5613), 1728-1731 (2003).
- [84] Mokhov, I. I., Bezverkhny, V. A., Karpenko, A. A., "Diagnosis of relative variations in atmospheric greenhouse gas contents and temperature from Vostok Antarctic ice-core paleoreconstructions", *Izvestiya Atmos. Ocean. Phys.* 41 (5), 523-536 (2005).
- [85] Bereiter, B., Lüthi, D., Siegrista, M., Schüpbach, S., Stocker, T., Fischer, H., "Mode change of millennial CO<sub>2</sub> variability during the last glacial cycle associated with a bipolar marine carbon seesaw", *Proc. Nat. Acad. Sci.* 109 (25), 9755-9760 (2012).
- [86] Scheffer, M., Brovkin, V., Cox, P. M., "Positive feedback between global warming and atmospheric CO<sub>2</sub> concentration inferred from past climate change", *Geophys. Res. Lett.*, 33 (10), L10702 (2006).
- [87] Cox, P., Jones, C., "Illuminating the modern dance of climate and CO<sub>2</sub>", *Science*, 321 (5896), 1642-1644 (2008).
- [88] Stocker, T., Johnsen, S., "A minimum thermodynamic model for the bipolar seesaw", *Paleoceanography* 18 (4), 1087 (2003).
- [89] Schmittner, A., Saenko, O., Weaver, A., "Coupling of the hemispheres in observations and simulations of glacial climate change", *Quat. Sci. Rev.* 22 (5-7), 659-671 (2003).
- [90] Ganopolski, A., Roche, D., "On the nature of lead-lag relationships during glacial-interglacial climate transitions", *Quat. Sci. Rev.* 28 (27-28), 3361-3378 (2009).
- [91] Shakun, J. D., Clark, P. U., He, F., Marcott, S. A., Mix, A. C., Liu, Z., Otto-Bliesner, B., Schmittner, A., Bard, E., "Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation", *Nature*, 484 (7392), 49-54 (2012).