Section 7

Global and regional climate models, sensitivity and impact experiments, response to external forcing, monthly and seasonal forecasting.

Regional climate changes in the Holocene according to model estimates

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Regional climatic changes in the high latitudes of the Northern Hemisphere impact the thermal regime of permafrost, resulting in disruption of permafrost zone stability. This instability might result in adverse economical, environmental and social consequences, such as disruptions of communication and power lines, as well as of oil and gas pipelines. Moreover, the development of destructive geomorphological processes leads to subsidence, water logging and release of greenhouse gases, such as carbon dioxide and methane. The exclusion of these gases from the biogeochemical circulation chain causes an increase of their emissions and, therefore, strengthening of the positive feedback between the permafrost ecosystems and the atmosphere. Additionally, the dissociation of relict gas hydrates generates gas emissions that can also contribute to regional climatic changes.

The growth of near-surface temperature affects the thermal regime of permafrost. In this research, the warmest over the last 10 thousand years periods are analyzed: the Holocene optimum (about 6 thousand years ago) and the present time period (Fig.1.). Fig. 2 (a) presents the estimates of the linear trend of average annual surface temperature for northern Eurasia according to the ERA-Interim reanalysis for 1991-2016.

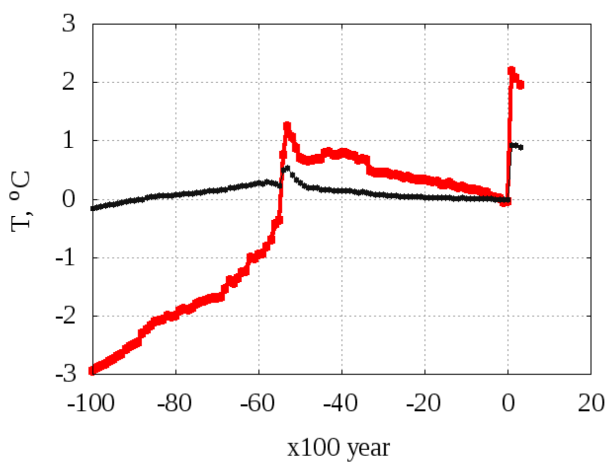

Fig. 1. Anomalies of the global (black line) and regional (north of Western Siberia) (red line) surface temperature according to CLIMBER-2 [1].

Maximum near-surface warming trends were obtained for the northern regions of Western Siberia. According to observations for the period 1979-2014, the growth rate of air temperature in the permafrost regions is 2.5 times higher than the global warming rate over this period [2]. The spatial heterogeneity of the obtained trend estimates is revealed. In particular, the regions with negative trends are observed. The spatial distribution of the surface air temperature trend is compared to the trend of the temperature in the upper 3 m of permafrost, calculated with the model of heat transfer in permafrost [3] using the data of the global climate models of the CMIP5 project (CSIRO-Mk3-6-0, GISS-E2-R, IPSL-CM5A-LR, MIROC-ESM). The strong correlation of the maximum trends (more than 0.03–0.04 °C / year) of the surface air temperature and the permafrost temperature in the northern part of Western Siberia is revealed. The trend of the surface temperature in the winter and autumn seasons is 0.04 and 0.05 °C / year.

In order to compare the current climatic conditions of the Yamal Peninsula and its adjacent areas with the Holocene optimum, the surface temperature according to the ensemble of global climate models of the international project PMIP3 - Paleoclimate Modeling Intercomparison Project Phase III (https://pmip3.lsce.ipsl.fr) is analyzed.

(a) (b)

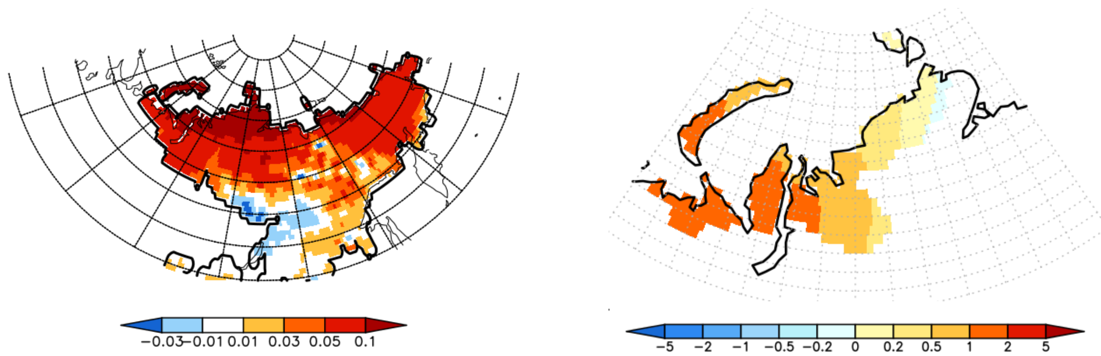

Fig. 2. (a) Trend of surface temperature (°C / year) for the regions of the northern Eurasia permafrost according to the ERA-Interim reanalysis for 1991-2016. (b) The difference in summer surface temperature (°C) in 2009–2013 and in the Holocene optimum according to calculations with an ensemble of climate models.

The average difference in surface air temperatures in 2009–2013 and in the Holocene optimum for the Yamal Peninsula by the ensemble of model calculations is obtained equal to 1.2 ± 0.8 °C. According to the model results, modern warming in the north of Western Siberia already exceeds that of the Holocene optimum. According to [4], in recent decades there has been a rapid increase in the summer temperature in Yamal. According to the data (acquired in this research), the positive temperature anomalies already exceeded the temperature anomalies of the Holocene optimum even at the beginning of the XXI century.

Acknowledgments. This work was supported by the Russian Foundation for Basic Research (17-05-00561, 18-05-60111, 19-05-00409); the Presidium of the Russian Academy of Sciences.

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Model assessment of contribution of natural and anthropogenic GHG emissions from Russian regions to climate change in the 21st century

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An analysis of the ability of natural carbon reservoirs to take up and release carbon requires an adequate account of the carbon balance of Russian boreal forests, wetlands and other ecosystems. We performed simulations with the Earth system model of intermediate complexity developed at the A.M. Obukhov Institute of Atmospheric Physics of Russian Academy of Sciences to assess the contribution of anthropogenic and natural emissions from the territory of Russia in the 21st century to global climate change under various scenarios of anthropogenic emissions.

The climate change impacts of pulse emissions of different greenhouse gases can be compared using simplified metrics such as global warming potential and global temperature change potential. The Absolute Global Temperature change Potential (AGTP) is the change in global mean surface temperature at time H in response to a 1 kg pulse emission of gas x at time t = 0. It is often written as a convolution integral of the radiative forcing:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H - t)\,dt\,, \qquad (1)$$

where RF_x is the radiative forcing due to a pulse emission of a gas x, and R_T is the temporally displaced climate response to a unit forcing. Equations for $AGTP_{CO2}$ and $AGTP_{CH4}$ in IPCC reports imply time constant CO2 and CH4 radiative forcing and CH4 lifetime.

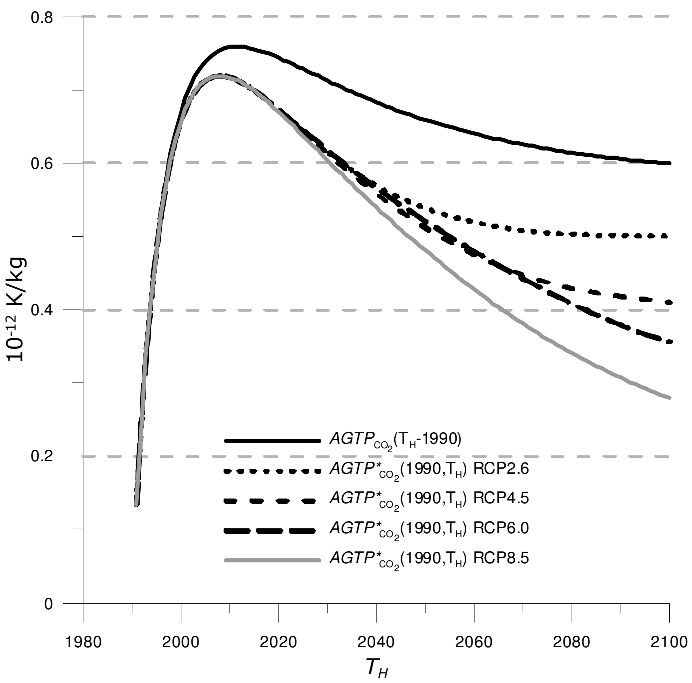

Fig. 1 AGTP and AGTP* for CO2 under various anthropogenic scenarios.

For changing background conditions AGTP can be modified and written as a sum of integrals for each year:

$$AGTP_x * (T_1, T_2) = \sum_{k=T_1+1}^{T_2} \int_{k-1}^{k} RF_{x,k}(t) R_T(T_2 - T_1 - t)\,dt\,, \qquad (2)$$

where T_1 is the year of emission and $T_2 = T_1 + H$. $RF_{x,k}$ can be achieved in assumption of CO2 and CH4 radiative forcing and CH4 lifetime being step functions, constant for each particular year k. The result of this modification can be seen in Fig. 1. It is shown that changes in climatic conditions under different anthropogenic emission scenarios can strongly influence the indicators of the impact of various greenhouse gas emissions on the climate system, especially at large time horizons.

Finally the cumulative potential, based on modified AGTP, is introduced to evaluate the impact of GHG sources and sinks:

$$CTP_x(T_0, T_H) = \sum_{t=T_0}^{T_H - 1} E_x(t) AGTP_x * (t, T_H) \tag{3}$$

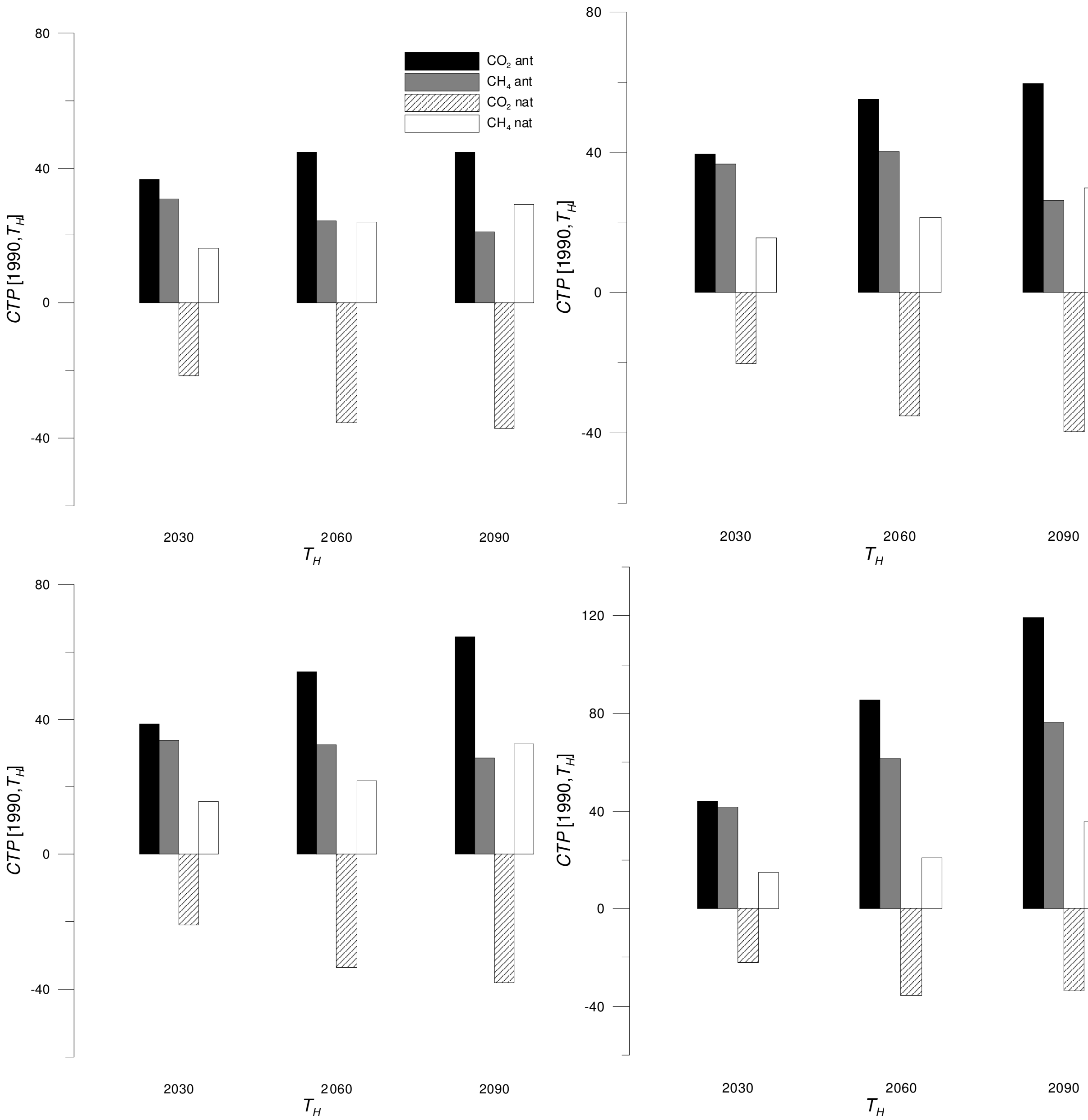

Fig. 2 CTP for anthropogenic and natural fluxes of CO2 and CH4 on [1990;2030], [1990,2060], and [1990,2090] time intervals

In current climate conditions, natural fluxes in the Russian regions have stabilizing effect on climate at relatively short time horizons (Fig. 2). To the end of the 21st century, their stabilizing ability is greatly reduced due to strong increase of natural CH4 emissions and decrease of CO2 absorption. Anthropogenic CTP of Russia stabilizes to the end of 21st century under RCP 2.6 and 4.5 scenarios and continue to rise under more intensive scenarios.

This work was supported by the Russian Foundation for Basic Research projects (18-05-60111, 19-05-00409).

The Second Phase of the WGNE Aerosol Project: Evaluating aerosol impacts on Numerical Weather and Subseasonal Prediction

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1. Introduction

The role of aerosols due to their interaction with radiation (direct effect) and changes in cloud lifecycle and precipitation (indirect effect) impacts the climate circulation and has been explored in several studies, serving as one of the main uncertainties on Earth's energy budget and radiative forcing for climate change estimation (Boucher et al. 2013). However, despite the importance of aerosols on the climate variability, their impact on Numerical Weather (NWP) and Climate Prediction (CP) have been addressed recently, first with the incorporation of climatologies of aerosols to improve the skill of global models (e.g. Tompkins et al. (2005)) and then with the inclusion of real-time treatment (or interactive aerosols with respect of dynamics, radiation and microphysics) in operational forecasting systems in regional (e.g. Freitas et al. (2005)) and global models (e.g. Reale et al. (2011)), there is still uncertainty regarding the magnitude of the impact as well as the degree of model sophistication that is needed to capture fully the effects of aerosols. It is known that interactive aerosols increase the computational cost of a numerical prediction system the more complex the aerosol scheme. The representation of aerosols and atmospheric feedback on numerical models vary extensively around the world mainly due computational capabilities in meteorological centres, and it is not clear which level of complexity is required to better represent aerosol-cloud-radiation interactions, as well as provide skillful information to early warning from weather to climate timescales as well as air quality forecasts. Benedetti and Vitart (2018) performed sub-seasonal experiments using the European Centre for Medium-Range Weather Forecasts (ECMWF) coupled model including the direct effect of dust and carbnaceous aerosols in an interactive approach and found significant skill in predicting the weekly variability of aerosols and also significant improvements in the tropical and extratropical circulation skill scores. In addition, the authors suggest a modulation of dust aerosols by the Madden Julian Oscillation (MJO) which is an important source of predictability in the Tropics at the subseasonal to seasonal (S2S) timescales.

Weather and climate sciences are advancing for an integrated and "seamless" Earth-System approach to provide numerical forecasts from short to climate timescales for the wellbeing of society. The responses of weather and climate forecasts to the atmospheric composition changes are key factors (Baklanov et al. 2017) that should be addressed by meteorological centres. The adoption of a fully integrated weather/climate/chemistry forecast system is necessary to better represent the atmospheric feedbacks and provide skillful forecasts in a seamless approach, both for weather and climate as well as air quality management. Therefore it is important understand what the current capabilities of meteorological operational centres worldwide in representing aerosols are and their impacts on different timescales. The development of a joint collaboration from weather and climate communities is necessary to understand the impact of aerosols.

The Working Group on Numerical Experimentation (WGNE; http://wgne.meteoinfo.ru/), jointly established by the World Climate Research Programme (WCRP), Joint Scientific Committee (JSC) and the World Meteorological Organization (WMO) Commission for Atmospheric Sciences (CAS) has been promoting numerical experimentation linking international research with the goal to explore atmospheric variability and predictability, as well as ways to refine numerical techniques and physical process formulations. Examples are the Drag (Sandu et al. 2017) and the Grey Zone (Tomassini et al. 2017) Projects. In the same way, WGNE conducted a project to evaluate the impact of aerosols on NWP (Freitas 2015). The main goal of the project was to understand how important aerosols are for atmospheric predictability at short timescales. Three case studies were chosen considering selected strong or persistent events of aerosols and included a dust storm over Egypt on 18 April 2012, urban pollution in China on 12-16 January 2013 and smoke event associated with biomass burning in South America on 5-15 September 2012. To diagnose their impacts on NWP, eight operational meteorological centres worldwide provided their NWP systems and performed a set of experiments considering runs with no aerosols and with prognostic aerosols. Only one centre provided data from a numerical system considering climatological aerosols instead a prognostic configuration. Centres also provided observational data for model evaluation. Four of them provided inputs from their global operational models and four from limited–area models. The global configuration was provided by ECMWF, the Japan Meteorological Agency (JMA), the National Aeronautic and Space Administration (NASA) and the National Centres for Environmental Prediction (NCEP) in the USA, while the limited–area configuration was provided by the Barcelona Supercomputer Center (BSCC) in Spain, the Center for Weather Forecasting and Climate Studies of the Brazilian National Institute for Space Research (CPTEC/INPE), the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (ESRL/NOAA) in the United States of America (USA) and the Meteorological Service of France/Meteorological Service of Algeria (Météo-France). Different model characteristics (domain, grid-spacing, aerosol species, emissions, aerosol and cloud physics, and assimilation techniques) were considered, taking into account the complexity of the operational systems

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available in the participating centres. The results of the case studies showed strong differences across the forecasts, which was expected due to the range of different model configurations. The impact of aerosols was observed in most meteorological variables analyzed. The main results of including aerosols in the forecast systems were observed in a local scale and impacted the radiative shortwave flux at surface and 2-meter air temperature, in association with the aerosol direct effect. The mean difference between the experiments considering prognostic aerosols and no–aerossols indicated a strong negative decrease in radiative shortwave flux at surface and 2–meter air temperature when considering prognostic aerosols, indicating the cooling effect associated with high concentration of aerosols. Rémy et al. (2015) described the results from the same dust episode of 18 April 2012 considered in the WGNE experiment in addition to another dust storm, which took place on 12 and 13 April 2012 in the central Sahara region and pointed out the impact of dust over the radiative fluxes at the surface as well as the feedback on the dust load though modifications in the planetary boundary layer. Freitas (2015) also pointed out that when climatological aerosol fields are used within the forecast systems instead of interactive aerosols, the transient and strong pollution events are not realistically represented in the forecasts. Despite the important results found with the First Phase of the WGNE Aerosol Project (hearafter WGNE-AerI), a lack on the statistical significance of results was identified due to the nature of the study which was based on case studies.

Considering that the effects of aerosol on NWP should be better understood by a more statistically robust study that considers a larger number of cases or a longer period of model evaluation, and that their effects should be more considerable in extended-range forecasts as shown by Benedetti and Vitart (2018), WGNE jointly with the WWRP/S2S Steering Group and the WMO Global Atmosphere Watch (GAW) Scientific Advisory Group (SAG) on Modelling Applications (SAG–APP) is proposing the extension of the aerosol project, lauching the WGNE-S2S-GAW Aerosol Project (hearafter WGNE-S2S-GAW-Aer) in 2019 to address the role of aerosols on NWP both at the short to medium-range and subseasonal timescales. This article provides information on how the WGNE-S2S-GAW-Aer will be designed and conducted. The Section 2 describes the main details of the WGNE-S2S-GAW-Aer and finally the Section 3 presents the main considerations regarding the WGNE–S2S–SAG–APP initiative.

2. The second phase of the WGNE Aerosol Project

Currently few operational meteorological centres are able to run a fully integrated weather/chemistry NWP system with interactive aerosols and even less are able to run fully coupled modelling systems for longer timescales, like S2S. All the operational S2S models contributing to the S2S WWRP–WCRP joint research project database use climatological aerosols (WWRP/WCRP 2018), which may represent a limitation in S2S forecasts (for more information about S2S project visit `http://s2sprediction.net`). Such models do not represent the direct and indirect effects of aerosols, impacting the skill of the atmospheric circulation and do not represent persistent and intense events specially considering biomass burning and synoptic dust events. The S2S WWRP–WCRP joint research project (WWRP/WCRP 2018) recognizes the importance of aerosols on subseasonal to seasonal timescales that was not explored in WGNE-AerI and understands that the incorporation of interactive aerosols on S2S models can be an opportunity to improve the skill of models as well as contribute strongly to support policy makers and end-users providing skillful air quality forecasts. As the aerosols often have serious impacts on air quality and human health, there may be socioeconomic benefits in the use of S2S air quality forecasts specially for regions highly impacted by forest fires and urban pollution (WWRP/WCRP 2018).

To further explore the importance of interactive aerosols in short to medium-range and subseasonal predictability, it is necessary to coordinate a systematic and statistically robust study and associated database to support the analysis. This project proposes the development of the WGNE-S2S-GAW-Aer that should consider a longer period of evaluation. The project considers two main components: one is built on WGNE-AerI by running higher resolution regional models in order to address the importance of interactive aerosols on weather predictability; the second component considers subseasonal re-forecasts experiments based on ensemble approach in a global scale in order to address the importance of interactive aerosols on subseasonal predictability and will be conducted jointly with the WWRP/S2S Steering Group. Considering the expertise of the Joint Working Group on Forecast Verification Research (JWGFVR), the WGNE-S2S-GAW-Aer will benefit from the expertise of model verification experts regarding the best metrics to be used to assess both NWP and ensemble forecasts, taking advices on what metrics will fit better to evaluate meteorological and air quality variables.

Constraining the investigation to specific (prescribed) model configurations would be expensive in terms of human and computational resources. We thus propose to build WGNE-S2S-GAW-Aer on the experimental design of the WGNE-AerI, by largely relying on the existing configurations of the models used at meteorological centres and research institutes, to set-up a range of experiments that explore the effects of interactive aerosols on predictive skill. The goal of the project is the understanding of the effects of aerosols on NWP and S2S under current model capabilities available in participating institutions. Therefore, in the scope of the WGNE-S2S-GAW-Aer, a systematic study should consider the diversity and complexity of participating modelling groups. We understand the scientific importance of standardised experiments considering the same initial and boundary conditions, physical and dynamical consistencies as much as possible and pre-defined emission database. However, it would be expensive and not feasible specially for operational centres to adopt such practices due to human and computational resources. In the same way, it is not realistic to provide a feedback for such centres based on such kind of experiments and suggest the adoption of practices other than those currently adopted by centres. This is why our proposal is based on the current model, computational and human resources available in each participating institution. The proposed protocol is under definition and counts the collaboration of many expert scientists on modeling, observational and forecast verification research under the WMO WCRP, WWRP and GAW programs.

a. Experiment setup

We propose two different sets of experiments, focusing on the short timescale and the subseasonal timescale. The general model configuration to be adopted by modelling groups (grid-spacing, vertical resolution, data assimilation, cloud and aerosol complexity, spin-up for atmospheric composition, emission sources) should be compatible with the configuration of the operational system currently used for short-range and S2S prediction, if applicable. The list of variables to be used as model output is extense and includes meteorological and air quality variables as well as optical properties of aerosols. The experiments will consist of a set of runs that should include the aerosol direct effect and another with no-aerosol loading or climatological aerosols for regional experiments and climatological loading in addition to direct effect for S2S experiments. The inclusion of indirect effects will be optional for both domains.

1) Limited-area domain (focus on short timescale)

Modelling groups can contribute with limited-area models in one or more experiments for regional domains. Pre-defined domains consider South America and South Africa. A domain over Asia is under definition. The experiments configuration should consider:

- Forecast length: 72h (3-days forecasts) from 00:00 UTC;
- Time resolution: 3 hours;

The domains are chosen considering the impact of different kind of aerosols (biomass burning, desert dust, pollution in megacities). More details will be provided under the protocol to be delivered to the participating modelling groups.

2) Global domain (focus on subseasonal timescale)

The experiments configuration should consider:

- Aerosol events to be analyzed:
    1. Focus on dust over Egypt;
    2. Focus on biomass burning smoke.
- Period of analysis: 2003-2018
    1. Dust: March-April-May;
    2. Biomass burning smoke: August-September-October.
- Forecast length: 768 h (32-days) from 00:00 UTC once a month;
- Time resolution: 6 hours;
- Minimum number of ensemble members: 5.

b. Verification framework

The availability of NWP and subseasonal predictions that will be produced within the WGNE-S2S-GAW-Aer experiments requires investigating the quality of the forecasts produced by the participating modelling groups. As a common practise in NWP forecast verification, the forecast quality assessment of meteorological variables will be provided considering classical deterministic statistical scores like Root Mean Square Error (RMSE), bias [Forecast–Observation (F–O)], Contingency table scores [like Equitable Threat Score (ETS), Probability Of Detection (POD), False Alarm Ratio (FAR)], and the use of scorecards, that provide a quick visual overview over the performance of specific experiment scores compared to other experiment, presented in a simplified summary of verify error plots of domains specified by the user, scores, parameters etc (ECMWF Access: 2019).

The verification strategy proposed for subseasonal predictions includes the assessment of deterministic predictions considering a reduced number of ensemble members as a minimum of 5. Following recent subseasonal prediction quality assessments [e.g. Coelho et al. (2018); Benedetti and Vitart (2018); de Andrade et al. (2019)] the metrics that will be considered include: bias of the ensemble mean; correlation between ensemble mean anomalies and corresponding observations; mean squared error skill score (MSSS); standard deviation ratio (ratio of the predicted ensemble mean anomaly standard deviation and the observed anomaly standard deviation); and the use of the scorecards. However, the verification approach will also consider that it is important to determine the difference of the probabilistic skill between experiments produced by different models, and learn if the difference between them is statistically significant, which is a slightly different issue for verification. Leutbecher (2018), using the fair Continuous Ranked Probability Score (CRPS) proposed by Ferro (2014) pointed out that small ensemble size (for example 5 members) is sufficient to detect differences between experiments for research and development purposes. Therefore, the fair CRPS will also be computed.

3. Concluding remarks

The impact of aerosols on weather and climate is largely heterogeneous and can impact meteorological variables. The lack of understanding on how aerosols can impact significantly the quality of the forecast skill at the regional and global scales will be addressed by the WGNE-S2S-GAW Aerosol Project in a systematic study. Understanding how accurate air quality forecasts provided by modelling groups are and how models differ from one another mainly based in their complexities will provide important information that has the potential to address future investments. The undestanding of how skillful meteorological and air quality forecasts from weather to subseasonal timescales are can contribute to the development of early warning systems with important societal benefits. The joint collaboration between the different WMO programs maximize opportunities to integrate research and development on seamless coupled chemistry-meteorology/climate modelling.

Acknowledgments. The WMO Joint Working Group on Forecast Verification Research (JWGFVR) is acknowledged for providing recommendations on verification metrics for assessing the quality of the predictions that will be produced. We also thank WGNE members for their useful suggestions that improved the quality of the manuscript. We also thank Elena Astakhova for providing recommendations on how to advertise the WGNE-S2S-GAW Aerosol Project in the 2019 WGNE Blue Book.

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Future change of annual cycle of Indian rainfall and Eurasian snow in the CMIP5 models

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1. Introduction

Global climate and particularly monsoon climate have varied on a wide spectrum of time scales in the past and is expected to do so in future. Of late, there has been very much concern in international scientific community regarding the behaviour of monsoon in the future climate change. Still, the present understanding of future climate change, especially over the monsoon regions, remains as one of large uncertainties with respect to circulation and precipitation [Intergovernmental Panel on Climate Change Fourth assessment report, sections 3.7, 8.4.10 and 10.3.5.2]. Multi-model projections suggest an increase in precipitation in the Asian monsoon in a warmer climate. Linkage between Eurasian snow extent/depth and subsequent Indian summer monsoon rainfall is well established (Hahn and Shukla 1976; Parthasarathy and Yang 1995; among others). The present study examines future changes pertaining to Annual Cycle (AC) of precipitation averaged over Indian land (INDP) and snow averaged over Eurasia (EURS) under anthropogenic global warming using five coupled models that participated in phase five of the Coupled Model Intercomparison Project (CMIP5) by comparing two types of runs: a historical run for 1861–2005 and Representative Concentration Pathway (RCP) runs for 2006–2100. Three RCP runs from CMIP5 namely RCP2.6, RCP4.5 and RCP8.5 are considered in the study.

2. Data

Model data of five CMIP5 models (Table 1) from historical and three RCP runs (RCP2.6, RCP4.5 and RCP8.5) is obtained from http://pcmdi3.llnl.gov/esgcet/home.htm. The detailed information on CMIP5 models and experiments is available [(Taylor et al. 2012) and (http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html)]. The radiative forcing in RCP2.6, RCP4.5 and RCP8.5 increases throughout the twenty-first century before reaching a level of about 2.6 Wm^{-2}, 4.5 Wm^{-2} and 8.5 Wm^{-2} respectively, at the end of the century (Taylor et al. 2012).

Table 1: CMIP5 models used in the present study (atmospheric horizontal resolution (in °E X °N))

No.	Model name	Atmosphere horizontal resolution
1.	CCSM4	1.2x0.9
2.	CNRM-CM5	1.4x1.4
3.	GFDL-ESM2G	2.5x2.0
4.	MIROC4h	T213L56
5.	NorESM1-M	2.5x1.9

3. Results

The ACs of INDP averaged over the domain (68-98°E, 8-38°N) in the historical and three RCP runs are shown for five CMIP5 models in Figures 1(a-e) respectively. Similarly, ACs of EURS averaged over region (20-140°E, 50-70°N) for five CMIP5 models are depicted in Figures 1(f-j) respectively. Most of the annual rainfall in India occurring from June-September is noticed in historical and RCP runs of all five models. RCP runs of the majority of models project an increase in INDP for May-December in future relative to historical run. Future change in INDP during January-April of all five models' RCP runs in comparison with historical runs is imperceptible. In contrast to abundant EURS during January-March and November-December, negligible EURS during June-August is observed in historical and RCP runs of all models. Future projections from RCP runs indicate the increment in EURS during January-February and its reduction during April-May and September-October with respect to the historical run in all models. There is no consensus among three RCP runs and also among five models in future projection of EURS during March and November-December.

References

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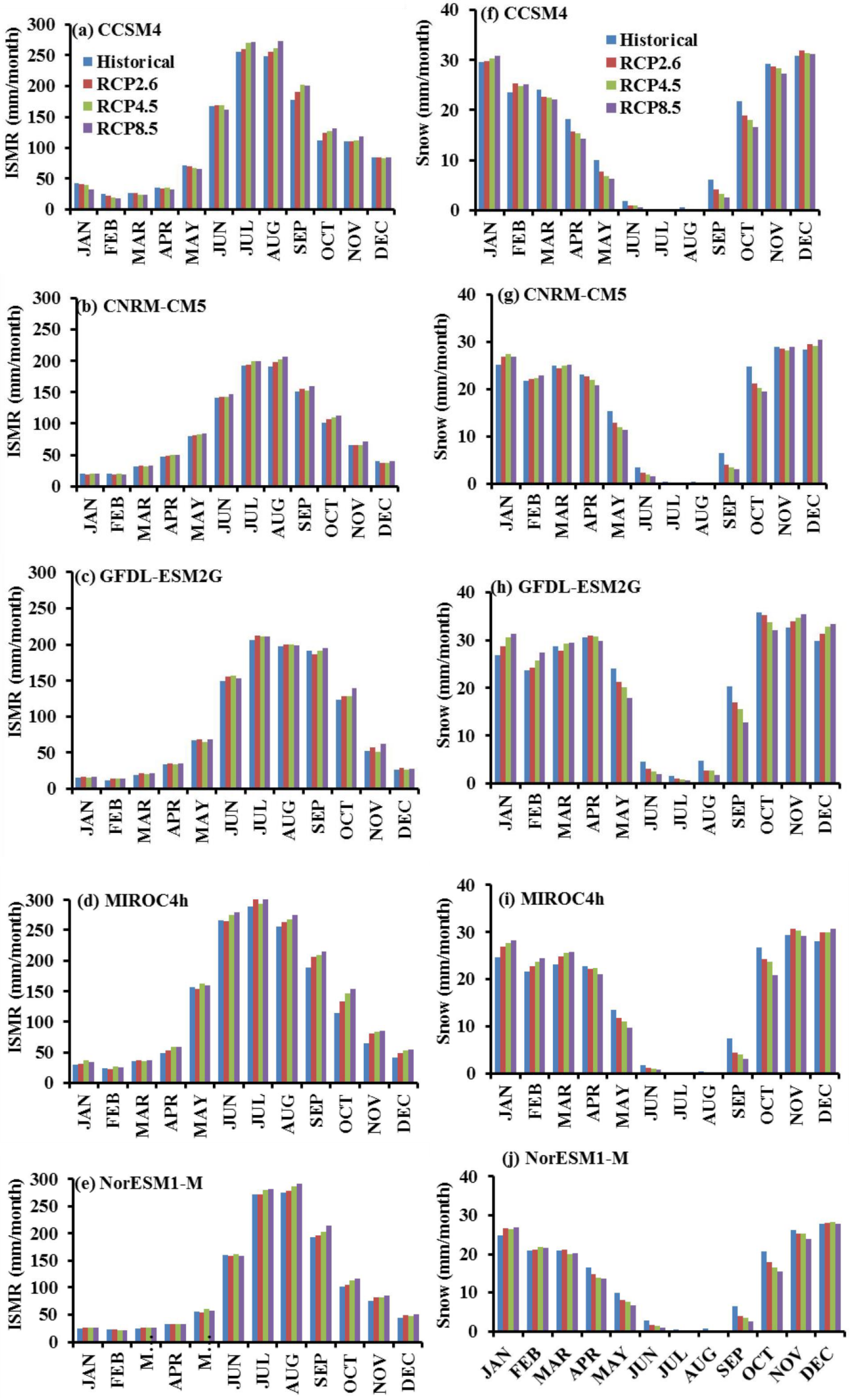

Figure 1:(a-e) Annual cycle of precipitation averaged over Indian land from historical and three RCP runs in five CMIP5 models; (f-j) Same as in (a-e) except for snow averaged over Eurasia