On the multi-annual to decadal potential predictability of the Arctic Ocean state in the INM RAS climate model

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Abstract

The potential predictability of basic ocean and ice fields in the North Atlantic-Arctic sector is studied on multi-annual to decadal timescales using idealized numerical experiments with the INM RAS climate model (INM-CM4-8). It is shown that the signal-to-noise ratio for the projection of the 0-300m layer average annual mean water temperature to the first EOF exceeds 1 for 4-5 years of calculations. Meridional current velocity averaged over the region 68-72N, 10-15E and salinity in the upper 300 m water layer can be predicted for about the same period. Positive water temperature and salinity anomalies are preceded by a state with an inflow of Atlantic water into the Arctic Ocean exceeding the average value for several years. The research on location of regions with significant potential oceanic fields predictability and their changes during the time is provided. Surface fields, including annual mean water temperature, salinity, ice concentration and mass, sea ice area in the Arctic have less signal-to-noise ratio than the average water temperature and salinity of the 0-300 m layer. For a time interval of 6-10 years, the signal-to-noise ratio for these fields does not exceed 1 almost everywhere.

Model & Experiments

The study is based on the experiments carried out with the INM RAS climate model INM-CM4-8 with atmospheric resolution $2^\circ \times 1.5^\circ$ in longitude and latitude, 21 vertical levels from the Earth's surface to the model top at about 30km height and oceanic resolution $1.0^\circ \times 0.5^\circ$ with 40 vertical levels. The reproduction of the modern climate by the model is considered in [1]. Model is participated in Coupled Model Intercomparison Project, Phase 6 (CMIP6)[2]. As part of this program, a **pre-industrial experiment** was carried out. All impacts on the climate system corresponded to 1850 and did not change over time. The duration of the preindustrial experiment was 500 years, without counting the time spent to reach the quasi-equilibrium regime.

Using data of pre-industrial experiment the first empirical orthogonal function (EOF) was calculated for the average annual ocean temperature at depths of $0-300$ m in the Arctic, i.e. north of 65N (see **Fig.1**). The first EOF accounts for 34% of the total variance of the Arctic Ocean temperature field, while the second EOF accounts for 16%, i.e. the first EOF is separated by variance from the next, and, apparently, represents a separate physical process.

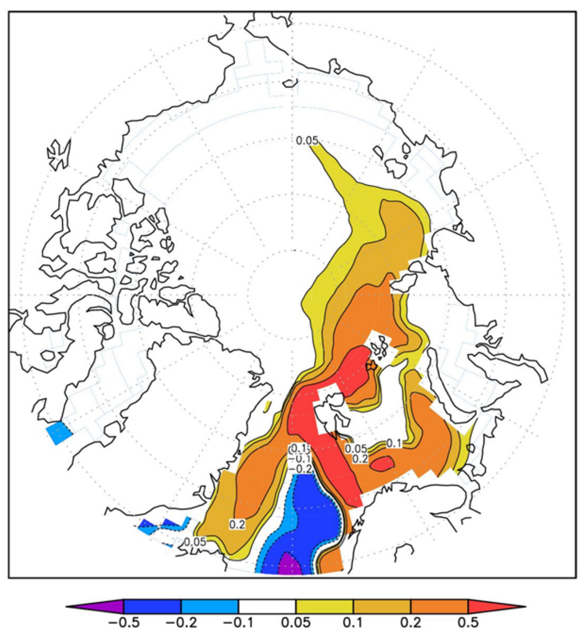

Fig.1 The first EOF of average annual ocean temperature at depths of $0-300$ m in the Arctic. Units correspond to the average temperature anomaly (K) in the layer.

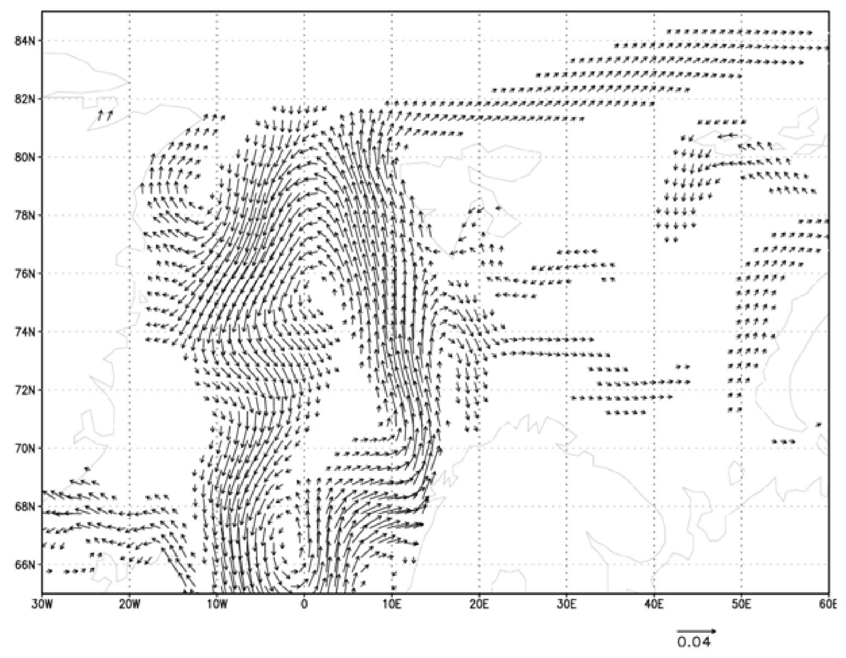

Fig.2 Current velocity anomalies at a depth of 10 m in the Atlantic sector of the Arctic Ocean. Only vectors greater than 0.005 m/s in magnitude are shown.

Let F be the expansion coefficient of the 1st EOF.
For each year n of the pre-industrial experiment, let us calculate its rate of change in time ΔF_n as the difference between the values of F, averaged over K following years and K previous ones:

$$\Delta F_n = \frac{1}{K}\left(\sum_{k=1}^{K} F_{n+k} - \sum_{k=1}^{K} F_{n-k}\right) \quad (1)$$

Let Ψ be some field that characterizes the state of the ocean: temperature, salinity, current velocity component or sea level, and Ψ_n' is the deviation of this field for year n from the average for the entire pre-industrial experiment.
Let us find the composite C_Ψ of the field anomaly Ψ_n' corresponding to the positive value of ΔF_n, that is, the growth of F:

$$C_\Psi = \frac{\sum_{n=1}^{N} \Delta F_n \cdot \Psi_n'}{\sqrt{\frac{\sum_{n=1}^{N} \Delta F_n^2}{N}}} \quad (2)$$

Here N is the number of years in the pre-industrial experiment for which the value of ΔF_n was positive. The physical meaning of the value C_Ψ is that it is an anomaly of the field Ψ, averaged over those years, for which K years later a positive value of F should be expected.

In order to conduct numerical experiments two initial states were generated. The state of the atmosphere, land surface, soil, ocean and sea ice averaged over 500 years of pre-industrial experiment for January 1 was obtained.
For the **initial state** 1:

- The corresponding composites C_Ψ were added to the averaged fields of temperature, salinity, and sea level.
- The ocean current velocity components were averaged over 500 years, as they adjust to the density field in a short time.
- The state of the atmosphere and soil was also averaged over 500 years, as only information about the initial state of the ocean significantly affects the state of the climate system over the next few years.

Similar to the **initial state** 1, **initial state** 2 was generated, but, in contrast to the first, the corresponding field C_Ψ was added to the average climatic fields of ocean temperature, salinity and sea level with a **minus sign**.

From initial states 1 and 2 two ensembles of 10 calculations were carried out. Each experiment lasted 10 model years. The calculations were distinguished by small initial disturbances in the state of the atmosphere, which, due to the instability of atmospheric dynamics, significantly increased in amplitude during the first few days of calculations.

What is the ocean state anomaly corresponding to an increase of F? Its main feature is a larger than average flow of Atlantic water along the Scandinavian coast into the Barents Sea and into the central part of the Arctic Ocean at depths from the surface to 1 km. For example, **Fig.2** shows the current velocity anomaly at a depth of 10 m. Outside the Arctic Ocean, the most interesting features of the initial state are negative temperature and salinity anomalies in the upper ocean layer in the North Atlantic. The influence of such anomalies on the subsequent state of the Arctic Ocean needs further investigation.

Expansion coefficient

The projection of the 0-300m layer average annual mean water temperature anomaly to the first EOF for the **first** and **second** ensembles of experiments is shown in **Fig.3**.

- In the first year of the experiments, in both the **first** and **second** cases, the ensemble average projection value is close to zero, but in the next few years in the **first** ensemble, the projection values averaged over all members of the ensemble become **positive**, and in the **second** ensemble - **negative**.
- In the **first** series of experiments, in years 3 and 4, all members of the ensemble show a **positive** projection, and the ratio of the signal (ensemble mean) to noise (standard deviation, or RMSE in the ensemble) is 1.1 for the second year, 2.5 for the third year, and 1.8 for the fourth year. For other years, the signal-to-noise ratio is less than 1.
- In the **second** series of experiments, in years 3 to 5, all members of the ensemble show a **negative** sign of the projection, the ratio of the signal to noise value is 1.0 for the second year, 2.2 for the third year, 1.9 for the fourth and fifth years, and even for 6, 9 and 10 years the signal-to-noise ratio exceeds 1.

Thus, the projection of the $0-300$m layer average annual mean water temperature to the first EOF is potentially predictable for a period of $4-5$ years.

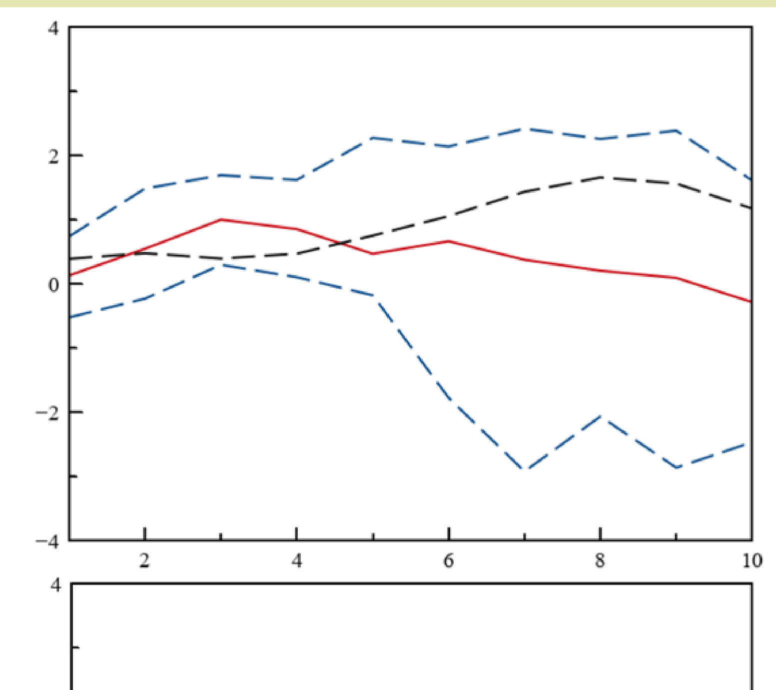

Fig.3 Expansion coefficient of the first EOF of the 0-300m layer water temperature in the Arctic (K) according to the data of an ensemble of experiments that started from the **first** (top) and **second** (bottom) initial state. The red line is the average for 10 experiments, the blue dashed lines show the ensemble spread. The black dashed line is the value of the standard deviation in the ensemble, taken with a **plus** sign (top) and with a **minus** sign (bottom).

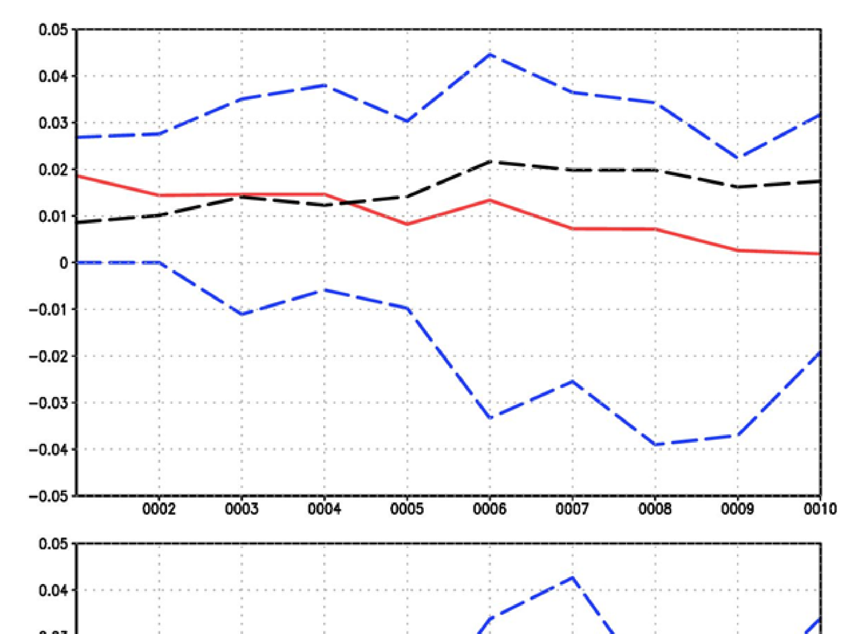

Fig.4 Anomalies of the meridional component of the current velocity (m/s), averaged over depths of $0-300$ m and over the region 68N-72N, 10E-15E according to the data of the ensemble of experiments that started from the **first** (top) and **second** (bottom) initial state. The red line is the average for 10 experiments, the blue dashed lines show the ensemble spread. The black dashed line is the value of the standard deviation in the ensemble, taken with a **plus** sign (top) and with a **minus** sign (bottom).

Meridional current velocity anomaly

As a measure of the Atlantic water flow in the Arctic Ocean, the meridional current velocity averaged over the 68N-72N, 10E-15E region and over the layer of $0-300$m depth was chosen (see **Fig.2**). The current velocity anomaly for the **first** and **second** ensemble of numerical experiments is shown in **Fig.4**.

- In the **first** ensemble, there is a gradual decrease in the **positive** velocity anomaly, and by the 10th year it becomes close to zero. In all years, including the first, there is at least one member of the ensemble in which the velocity anomaly was negative. Nevertheless, the signal-to-noise ratio in the first 4 years exceeds 1.
- For the **second** ensemble, the mean value of the velocity anomaly is **negative** in all years, but for each year there is at least one member of the ensemble in which the velocity anomaly is positive. The signal-to-noise ratio is greater than 1 for 1-5 years.

Meridional current velocity averaged over the region 68-72N, 10-15E in the upper 300 m water layer can also be predicted for the period of 4-5 years.

Regions of potential predictability

Temperature anomalies in the $0-300$m layer

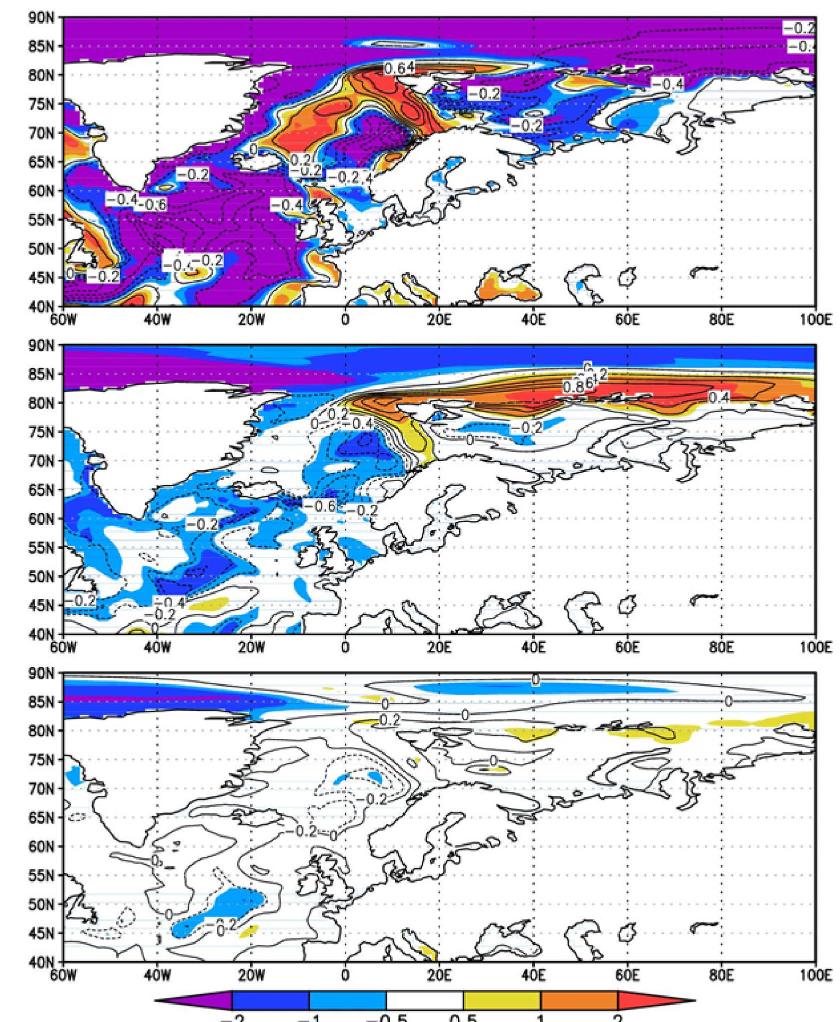

Fig.5 Temperature anomalies (K) in the $0-300$m layer in the ensemble of experiments that started from the **first** initial state, averaged over the first year (top), years $3-5$ (middle), and years $6-10$ (bottom). Isolines show temperature anomalies, color - the ratio of the anomaly to the standard deviation in the ensemble.

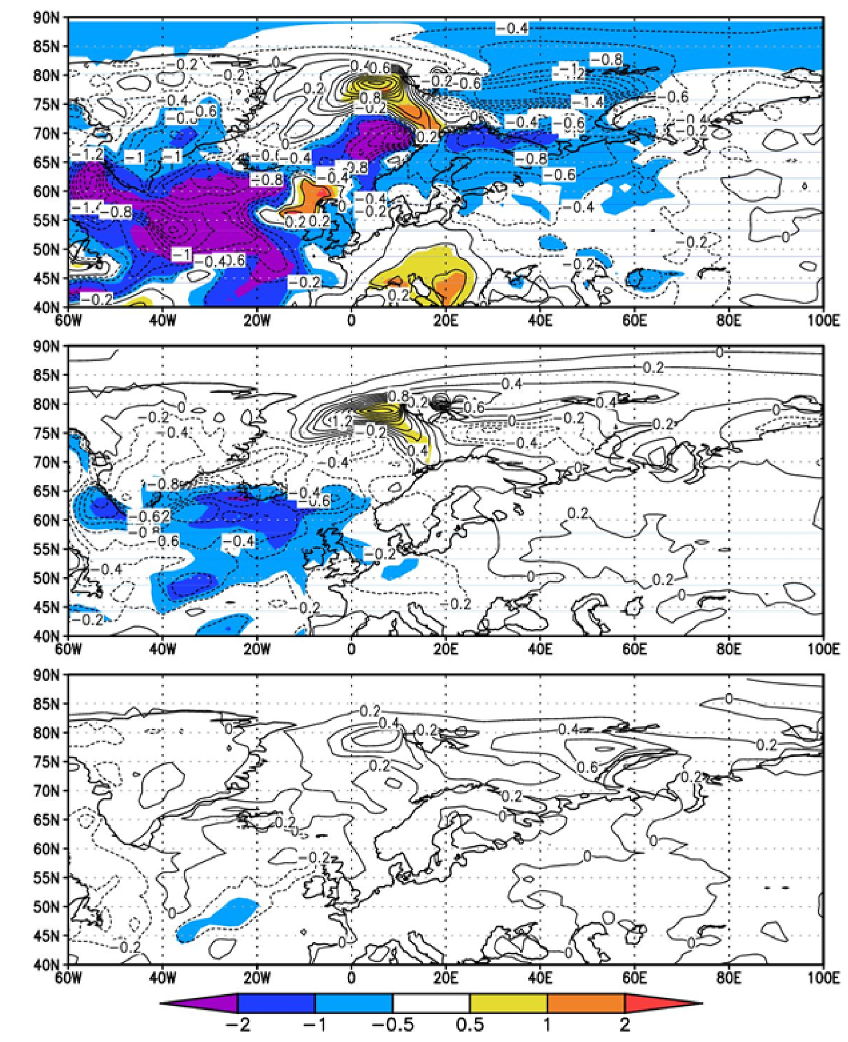

Fig.6 Surface temperature anomalies (K) in the ensemble of experiments that started from the **first** initial state, averaged over the first year (top), years 3-5 (middle), and years 6-10 (bottom). Isolines show temperature anomalies, color - the ratio of the anomaly to the standard deviation in the ensemble.

Temperature anomalies in the $0-300$m layer in the ensemble of experiments that started from the **first** initial state for different years are presented in **Fig.5**.

- In the first year, almost everywhere in the region, $0-300$m layer temperature anomalies are below zero, with the exception of those areas of the Greenland-Norwegian and Barents Seas, where the warm current flows directly from the North Atlantic. The signal-to-noise ratio over most of the area is greater than $1-2$.
- In years $3-5$, the above zero temperature anomaly spreads along 80N to the more eastern regions of the Arctic Ocean, up to Severnaya Zemlya, and the signal-to-noise ratio is $1-2$ there. Negative water temperature anomalies persist with a signal-to-noise ratio exceeding 1 in the central part of the Arctic Ocean, in the center of the Greenland-Norwegian Sea, and in some regions of the North Atlantic.
- In years $6-10$, the below zero temperature anomaly with a signal-to-noise ratio exceeding 1 persists only north of Greenland.

Surface temperature anomalies

For surface temperature, predictability at all considered time scales is worse than for the temperature of $0-300$m layer.

Surface temperature anomalies in the ensemble of experiments that started from the **first** initial state for different years are presented in **Fig.6**.

- In the first year, surface temperature anomalies of minus $1-2$ degrees take place in the North Atlantic, almost everywhere from 40N to 65N. There, the signal-to-noise ratio is $1-2$. Approximately the same negative anomalies take place in the central part of the Greenland-Norwegian Sea. There are also small areas with above zero temperature anomalies, where the signal-to-noise ratio is greater than 1, including the region to the south of Svalbard.
- In years $3-5$, negative anomalies with a signal-to-noise ratio of more than 1 persist only in the North Atlantic. Although positive surface temperature anomalies in the Atlantic sector of the Arctic reach 2 degrees, the signal-to-noise ratio is everywhere less than 1.
- In years $6-10$, the signal-to-noise ratio for surface temperature is everywhere less than 1, and almost everywhere, except for a small area in the North Atlantic, is less than 0.5.
- Attention is drawn to the fact that negative anomalies of the water layer $0-300$m in the central part of the Arctic Ocean and north of Greenland in years $3-5$ and $6-10$ do not manifest themselves in the surface temperature.

Salinity anomalies in the 0-300m layer

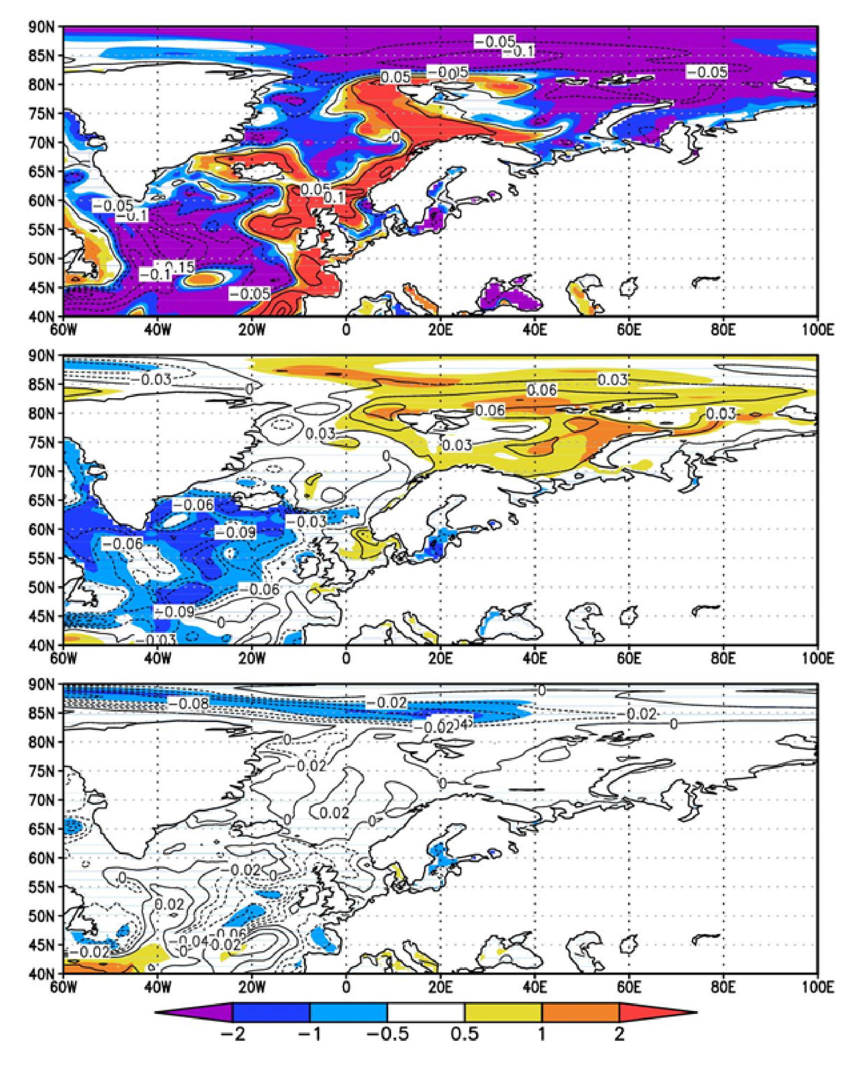

Fig.7 Anomalies of the mean salinity in the $0-300$m layer (PSU) in the ensemble of experiments that started from the **first initial state**, averaged over the first year (top), years 3-5 (middle), and years 6-10 (bottom). Isolines show salinity anomalies, color - the ratio of the anomaly to the standard deviation in the ensemble.

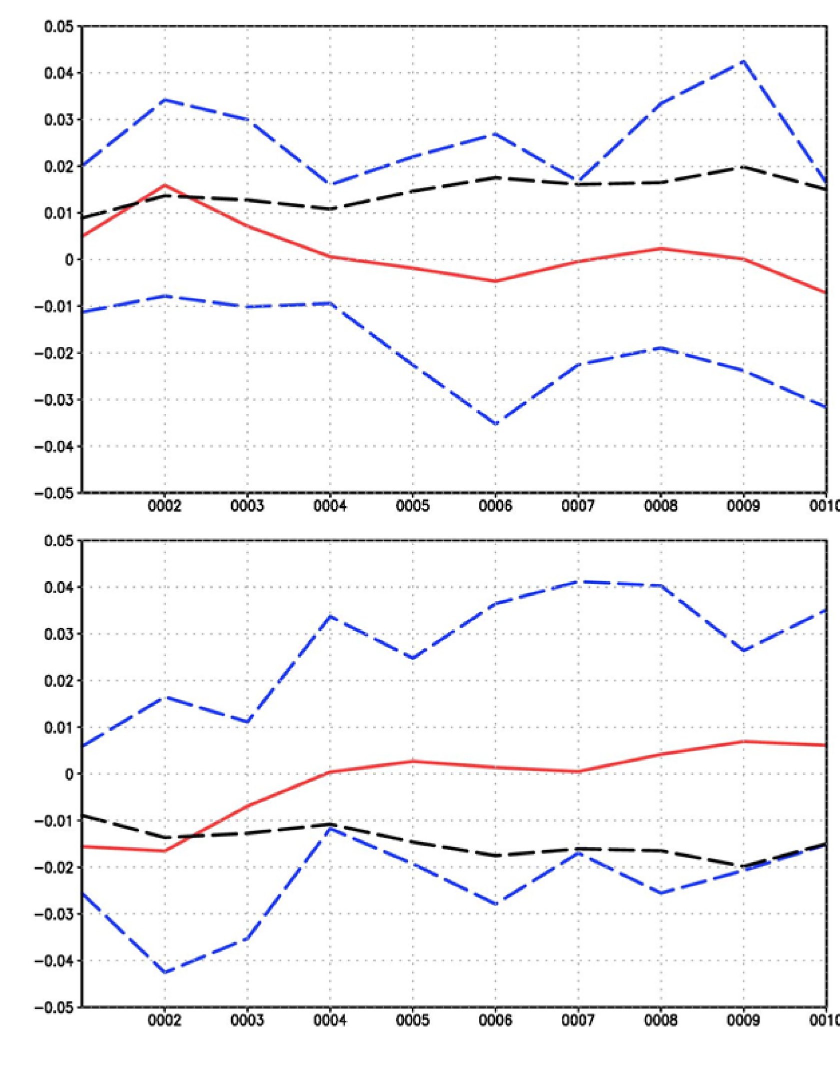

Fig.8 Anomalies of the mean sea ice concentration in the Arctic (north of 60N) according to the data of the ensemble of experiments that started from the **first** (top) and **second** (bottom) initial states. The red line is the average for 10 experiments, the blue dashed lines show the ensemble spread. The black dashed line is the value of the standard deviation in the ensemble, taken with a plus sign (top) and with a minus sign (bottom).

Anomalies of the mean salinity in the $0-300$m layer in the ensemble of experiments that started from the **first initial state** for different years are presented in **Fig.7**.

- In the first year, negative salinity anomalies take place in most of the North Atlantic and Arctic Ocean, except for the outskirts of the Greenland-Norwegian Sea and areas close to the coast of Europe, where salinity anomalies are positive. The signal-to-noise ratio is almost everywhere greater than 1.
- In years $3-5$, salinity increases in the Atlantic sector of the Arctic Ocean, and in some places, especially in the Barents Sea, the signal-to-noise ratio becomes greater than 1. Negative salinity anomalies with a signal-to-noise ratio greater than 1 remain locally in the North Atlantic.
- In years $6-10$, negative salinity anomalies with a signal-to-noise ratio of more than 1 persist only in some regions of the central part of the Arctic Ocean, in the same areas where the negative temperature anomalies are.

The signal-to-noise ratio for salinity of the surface is significantly worse than for the salinity of the $0-300$m layer.

Other surface variables

Other oceanic fields that characterize surface conditions are even less predictable than surface temperature.

For example, for ice concentration and ice mass only for the first year, there are two small areas where the signal-to-noise ratio is greater than 1: near the southern tip of Greenland and to the north of Svalbard. For other years, the signal-to-noise ratio is everywhere less than 1.

Anomalies of the mean sea ice concentration in the Arctic are shown in **Fig.8**.

- For the **first** series of experiments, only in the second year the signal slightly exceeds the noise.
- For the **second** series of experiments, the signal-to-noise ratio slightly exceeds 1 in the first and second years.
- In all years, in both series of experiments, there are members of the ensemble with both positive and negative anomalies of the Arctic sea ice area.

References

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[2] Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev.* **9** (2016), 1937-1958.