The mechanism of 60-year and 15-year Arctic climate oscillations in climate model INM-CM5-0

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1200 years of piControl run with climate model INM-CM5-0 (Volodin et al., 2017, doi: 10.1007/s00382-017-3539-7) is used to study decadal and multidecadal natural climate variability in Arctic. The first EOF of 5-year mean surface temperature is localized in Arctic (Fig.1)

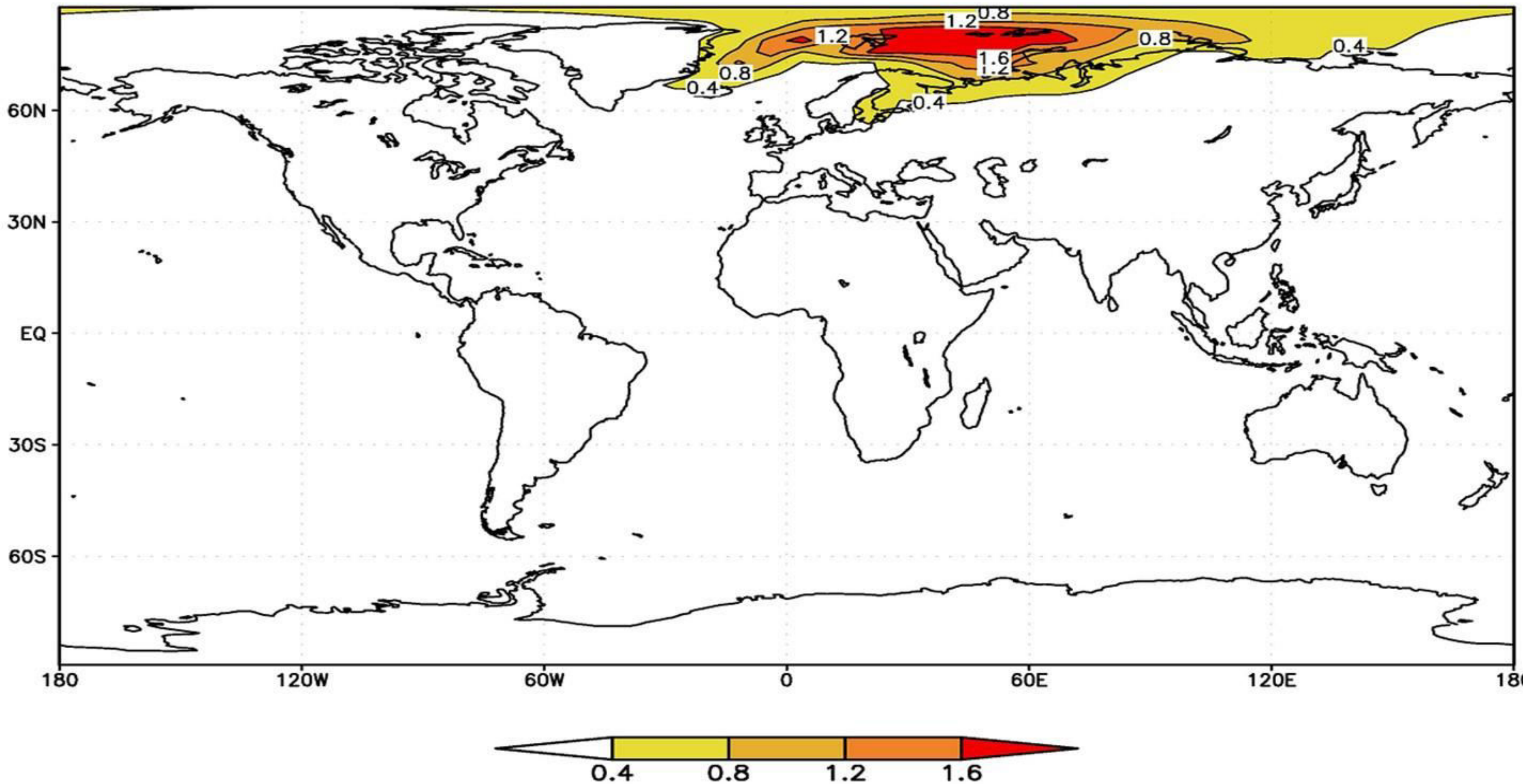


Fig.1. EOF-1 of 5-year mean surface temperature in piControl run

Time spectrum of expansion coefficient for EOF-1 has peaks at periods of about 60 years and 15 years (Fig.2).

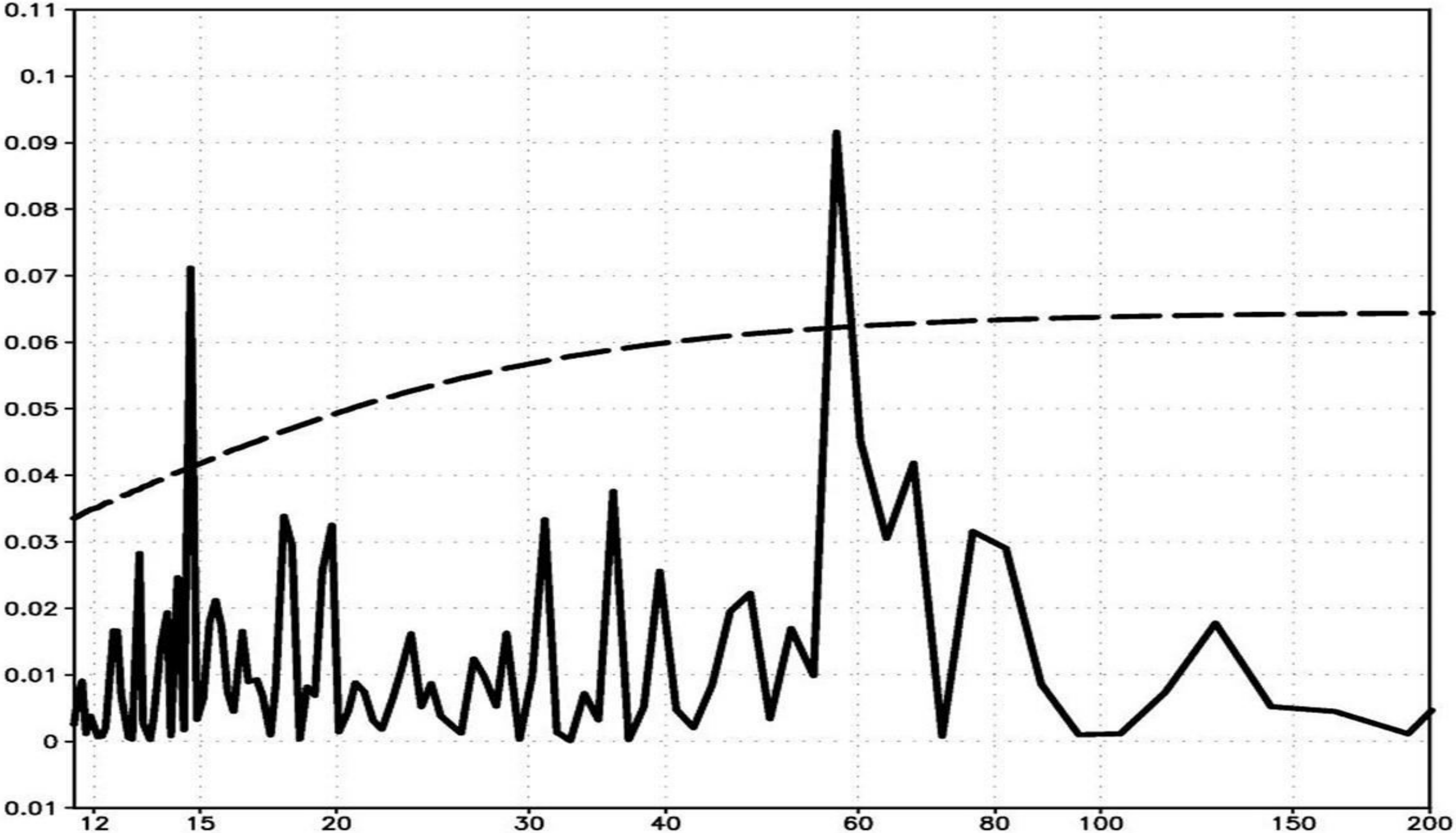
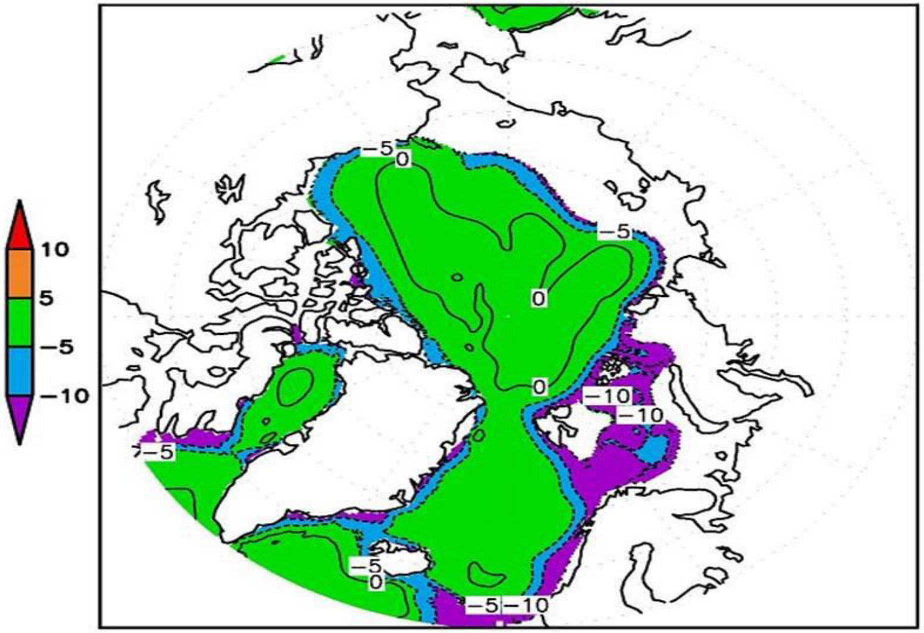
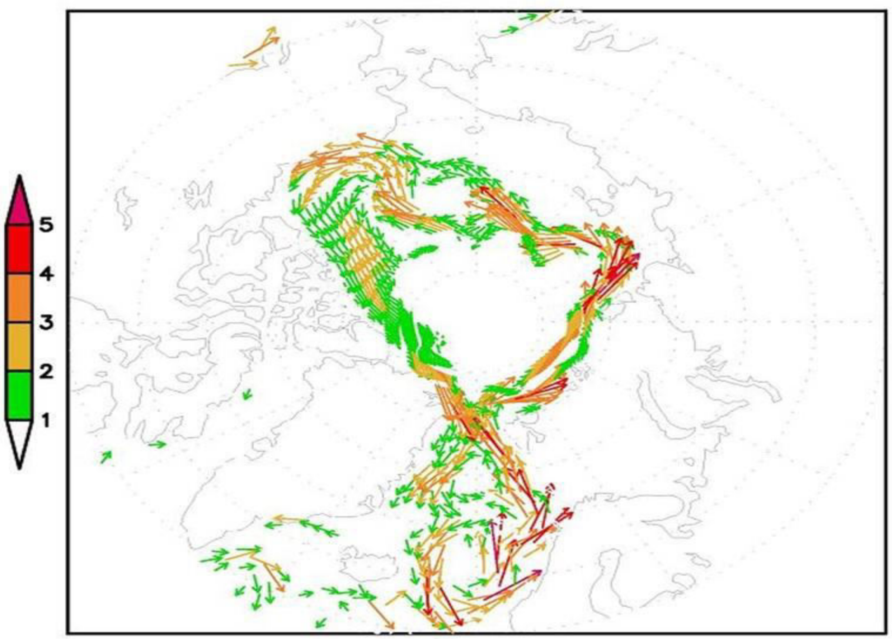


Fig.2 Time spectrum of annual mean surface temperature in Arctic. X-axis shows period in years. Dashed line means significance at 99% level.

60-year oscillation





To study 60 year oscillation we calculated composites for different phases of oscillation. Time filter was applied to data to remove oscillations with periods higher than 90 years and lower than 36 years. Figure 3 shows composites of anomalies of of salinity in layer 200-1000 m and currents at 200 meters depth for time 15 years (a quarter of period) before maximum of Arctic warming. One can see negative salinity anomaly near coasts and slopes of Arctic ocean. This leads to negative anomaly of density in coastal regions, and counterclockwise rotation at 200 meters depth. This lead to increase of Atlantic water inflow to Arctic ocean.

Fig. 3. Composites of salinity anomalies in the layer of 200–1000 m, 10−3 g/kg (top) and currents at the depth of 200 m, m/s (bottom, only velocity vectors exceeding 10−3 m/s are shown) for 15-year intervals preceding the Arctic warming.

Figure 4 shows composites of salinity and currents corresponding maximum Arctic warming. Gradients of salinity became smaller, but counterclockwise current anomaly in Arctic ocean goes on. It happens probably due to surface wind stress.

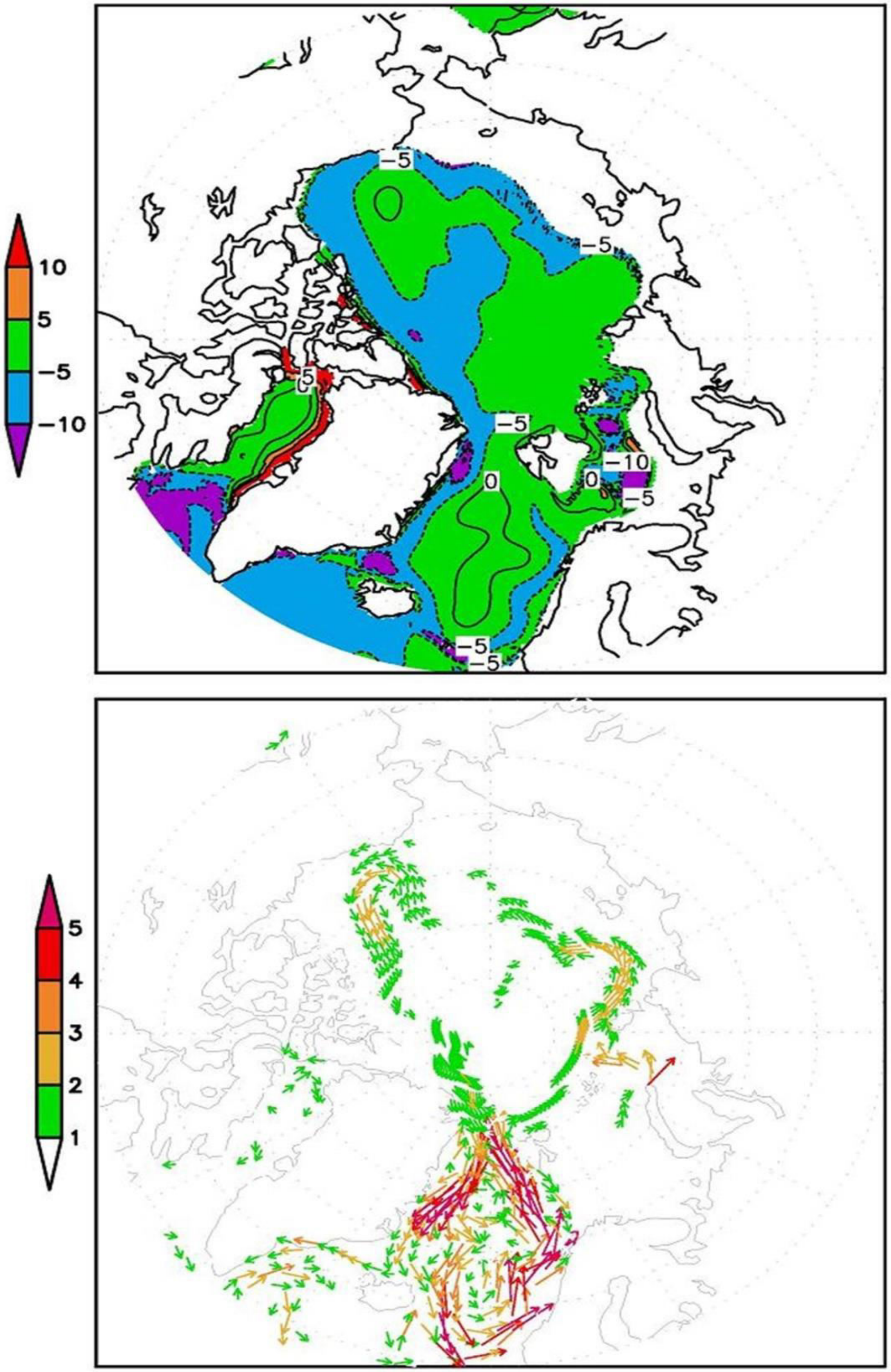
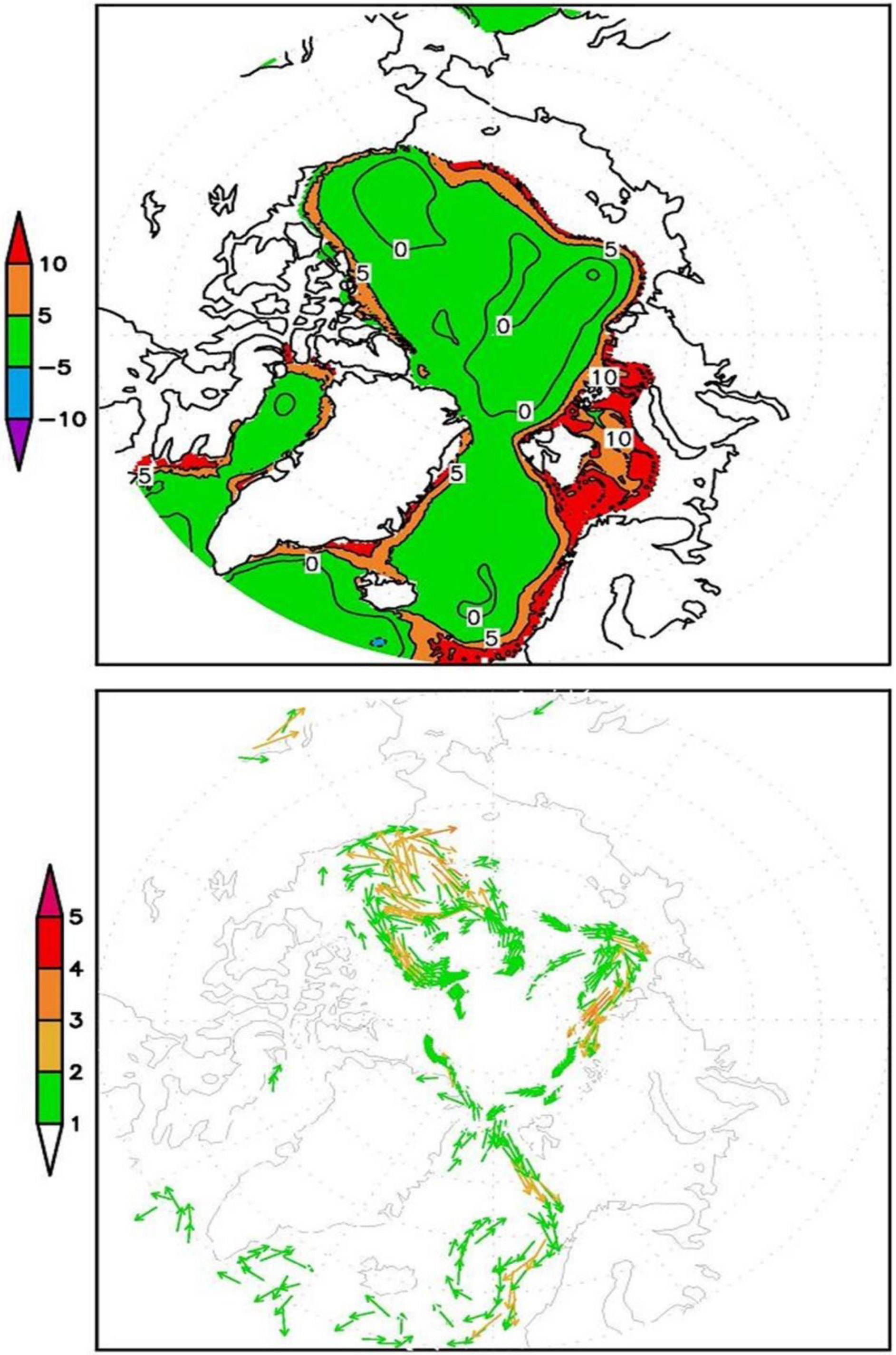


Fig.4. As in Fig.3. but for phase of maximum Arctic warming.



15 years after maximum of Arctic warming one can see positive salinity and density anomaly near coasts that leads to clockwise currents in Arctic ocean and decrease of Atlantic water inflow to Arctic ocean. This means that before maximum of Arctic warming and during it, we have increased Atlantic water inflow, that probably leads to temperature increase and transition from negative to positive phase of oscillation. But increased Atlantic water inflow leads to increase of near coastal salinity that leads to decrease Atlantic water inflow and decrease of temperature.

Fig.5. As in Fig.3 but for 15 years after maximum Arctic warming.

To check this assumption directly, we applied technique of calculation oscillation energy generation and phase change (Volodin, 2019, doi: 10.1134.S0001433819010110) for each term in equations for temperature T and salinity S in generation of oscillation G and the impact in phase evolution P. If we have evolution equation for C:

$$\frac{\partial C}{\partial t} = \sum_{i=1}^{I} F_i$$

where C is prognostic variable (T, S, U *or* V) - I – number of terms, and terms are F_{ADV} – advection, F_{VD} – vertical diffusion and surface fluxes, F_{IS} – isopycnal diffusion, F_{RAD} – shortwave radiation (in the case of T), then we can perform Fourier transform for C and Fi:

$$C_n = CB(0) + \sum_{k=1}^{N/2} CA(k)\sin\left(2\pi\frac{nk}{N}\right) + CB(k)\cos\left(2\pi\frac{nk}{N}\right)$$

$$F_{in} = FB_i(0) + \sum_{k=1}^{N/2} FA_i(k)\sin\left(2\pi\frac{nk}{N}\right) + FB_i(k)\cos\left(2\pi\frac{nk}{N}\right)$$

where k is number of Fourier harmonic, N – number of time intervals. If we define generation G as follows:

$$G = \frac{\partial(C^2/2)}{\partial t} = \sum_{i=1}^{I} CF_i$$

then generation of *k*-th harmonic by *Fi* will be calculated as:

$$G_i(k) = CA(k)FA_i(k) + CB(k)FB_i(k)$$

If we have steady oscillation, then generation by all forcings will be zero: $\Sigma Gi(k) = 0$. Positive Gi(k) means that forcing number I generates energy of harmonic k, negative sign means dissipation.

Also we can calculate the impact of each forcing *Fi* to evolution of oscillation phase of harmonic *k* *Pi(k)*. Details of this technique and implementation for study of oscillations in geophysical processes can be seen in Volodin (2019).

$$P_i(k) = \frac{-FA_i(k) \cdot CB(K) + FB_i(k) \cdot CA(k)}{\left(CA(k)^2 + CB(k)^2\right) \cdot 2\pi \frac{k}{N}}$$

The expression is normalized in a such way that sum of the impacts for all forcings is 1: $\Sigma Pi(k) = 1$

Values of *G* and *P* were calculated for temperature and salinity averaged over Arctic (66-90N) separately for depth of 0-100m and 100-1000m and averaged over harmonics with periods from 36 to 90 years to cover spectral peak at 60 years. The result can be seen in Table 1.

Advection (*ADV*) gives main impact to generation of temperature oscillation in Arctic. Forcing of shortwave radiation (*RAD*) is also positive that can be treated as positive feedback between Arctic warming, decrease of albedo and absorption of SW radiation. The impact of surface flux for *T* (*FTVD*) is negative that means that atmosphere is not generator of 60 year oscillation. In deep ocean also advection is responsible for generation of oscillations of *T*, but the impacts of vertical and isopycnal diffusion are negative.

Advection plays also major role in phase evolution of temperature oscillation in Arctic. Impacts of other forcings in phase evolution of *T* are small or negative. Generation of salinity oscillation is carried out also by advection in the upper ocean, while in deep ocean vertical diffusion gives stronger impact to generation. Advection of salinity by large scale currents is main factor responsible for evolution of oscillation phase.

Table 1. Contribution of different terms to generation G of temperature and salinity anomalies, and also to the evolution of their oscillation phase P for the Arctic in the upper ocean layer (0–100 m) and in deep ocean (100–1000 m).

		FT_{ADV}	FT_{VD}	FT_{IS}	FT_{RAD}
T 0–100 m	G, $10^{-10} K^2/s$	4.03	–3.60	–1.62	1.38
	P	1.23	–0.10	–0.01	–0.10
T 100–1000 m	G, $10^{-10} K^2/s$	0.32	–0.12	–0.20	0.00
	P	0.74	0.05	0.12	0.00
		FS_{ADV}	FS_{VD}	FS_{IS}	
S 0–100 m	G, 10^{-10} ‰$^2/s$	0.39	–0.39	0.02	
	P	0.99	–0.13	0.00	
S 100–1000 m	G, 10^{-14} ‰$^2/c$	9.9	13.9	–20.0	
	P	0.93	–0.01	0.03	

Oscillation with period of 15 years

Oscillation with period of 15 years was studied in similar way. First, composites for different phases were calculated. In the case of 15-year oscillations, oceanic anomalies are localized in the upper layer. Here we present composites of SLP and surface currents. 4 years before Arctic warming we have light clockwise circulation in GIN seas and SLP anomaly presented in Fig.6.

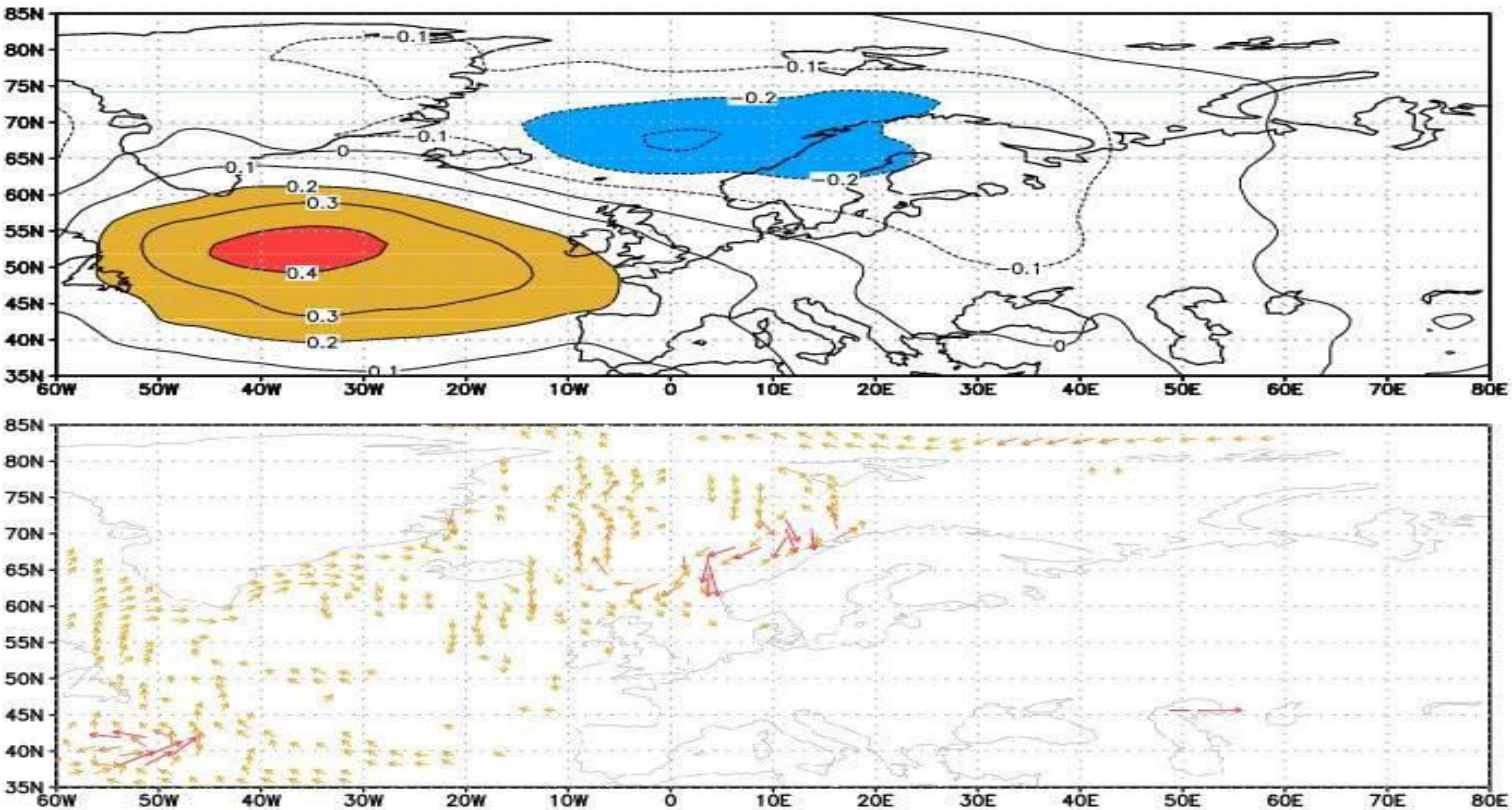


Fig.6. Composites of SLP, hPa (top) and surface current, m/s (bottom) for 4 years before maximum Arctic warming for 15 year oscillation.

Two years before maximum Arctic warming we have NAO-like pattern in SLP. West wind produce surface currents from north-west over most North Atlantic, counter-clockwise circulation over GIN seas, enhanced Atlantic water inflow to Barentz and Kara seas.

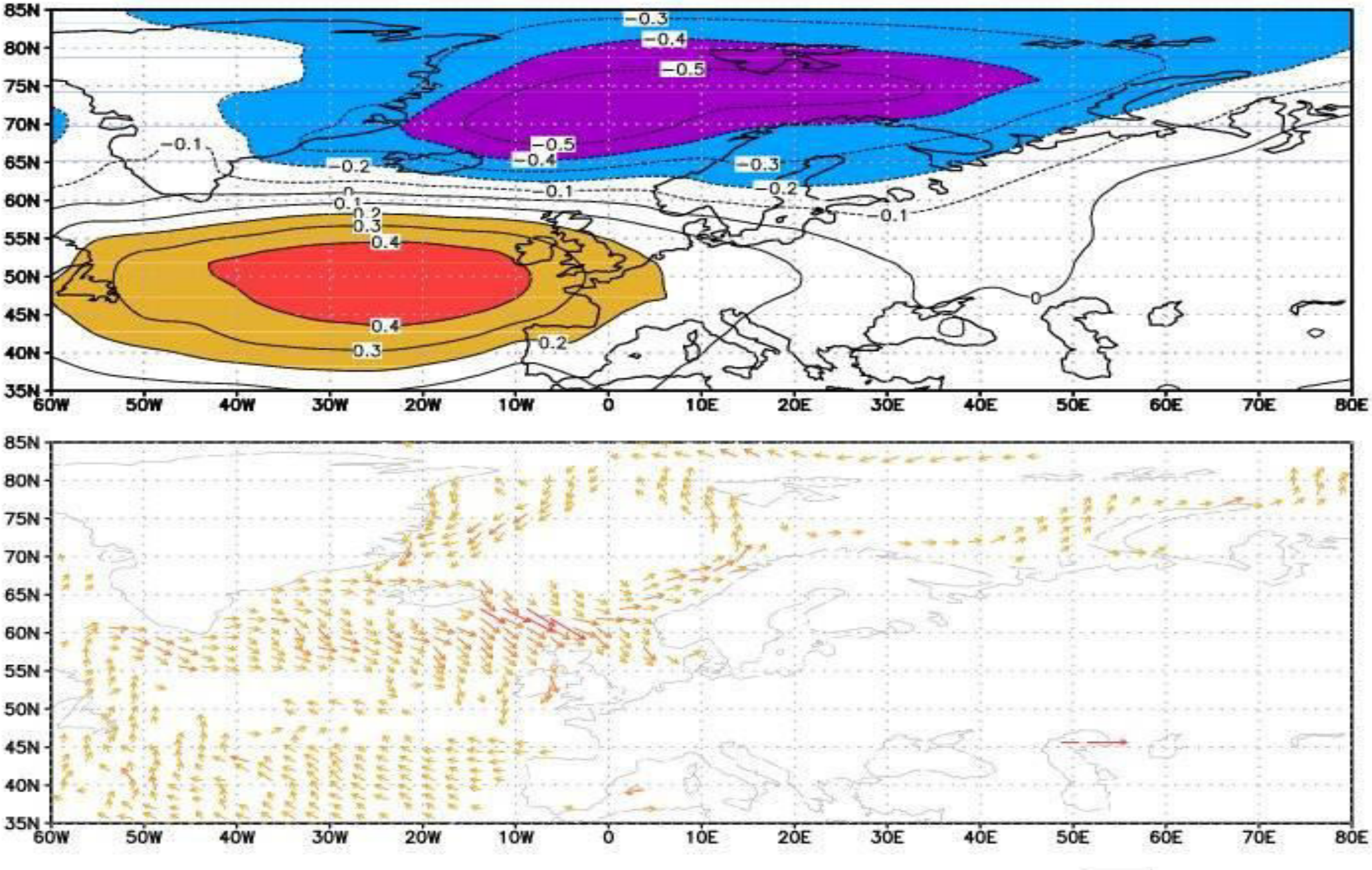


Fig.7. As in Fig.6, but for 2 years before maximum Arctic warming.

During maximum of Arctic warming we also can see positive NAO index, counterclockwise circulation in GIN seas and enhanced Atlantic water inflow to Barentz and Kara seas.

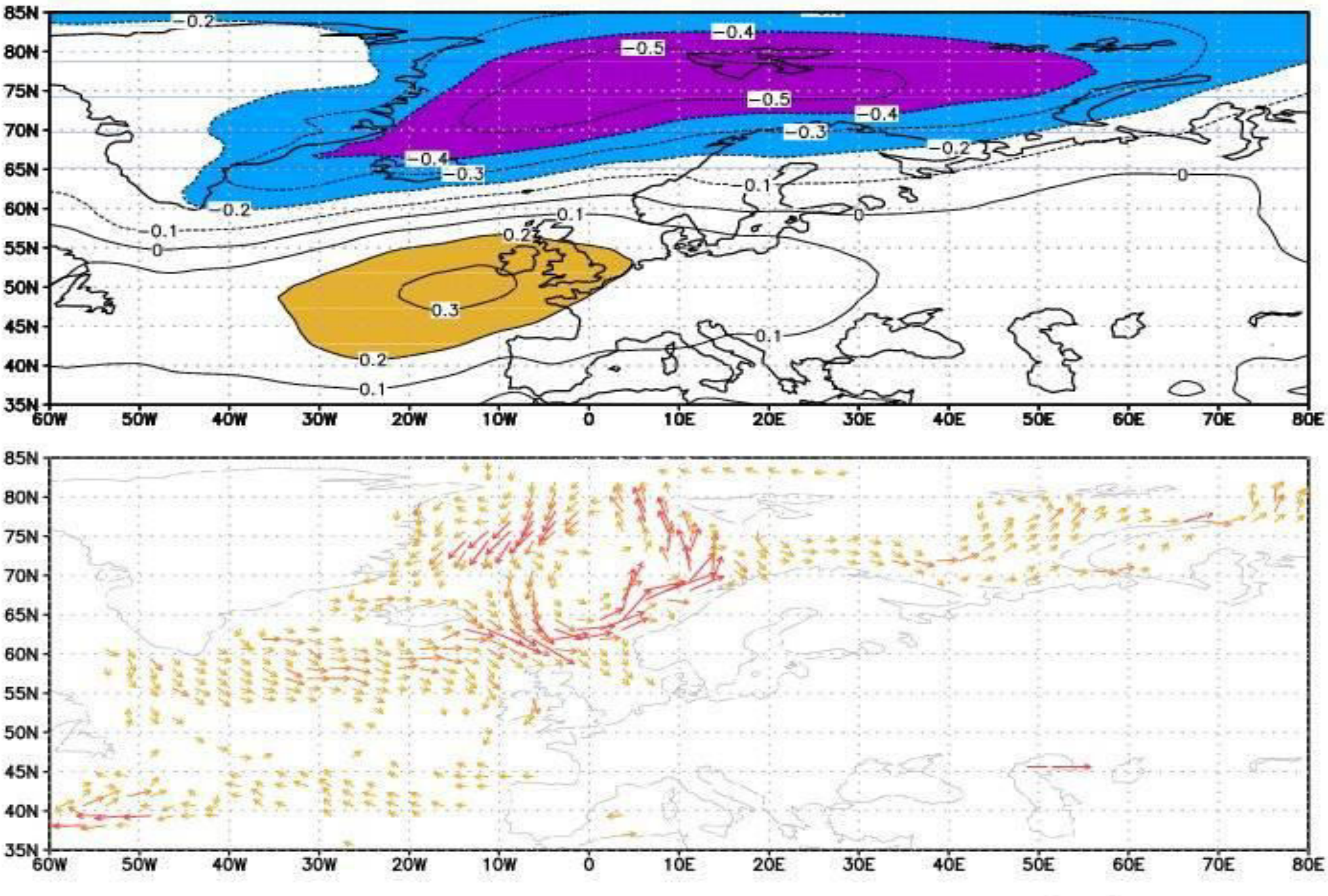


Fig.8. As in Fig.6, but for time of maximum Arctic warming

Two years after maximum of Arctic warming SLP anomalies become small, counterclockwise circulation in GIN seas still persists, Atlantic water inflow to Arctic ocean becomes normal.

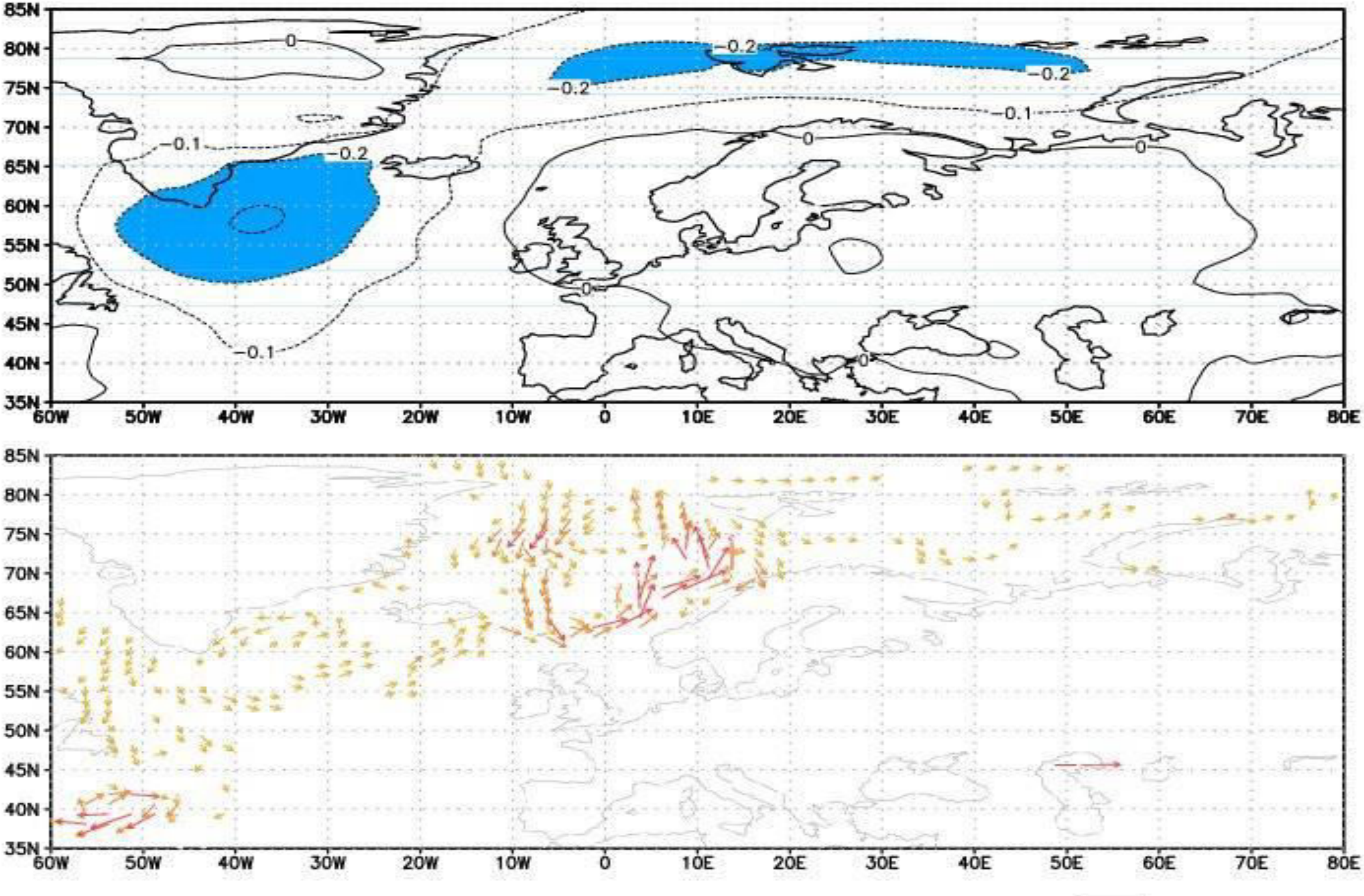


Fig.9. As in Fig.6, but for 2 years after maximum Arctic warming.

Figure 10 shows that heating rate of oceanic water by resolved advection is 1 year ahead of temperature, heating by fluxes from the atmosphere minimum happens 1 year after temperature maximum. NAO index maximum appears 1 year before temperature maximum

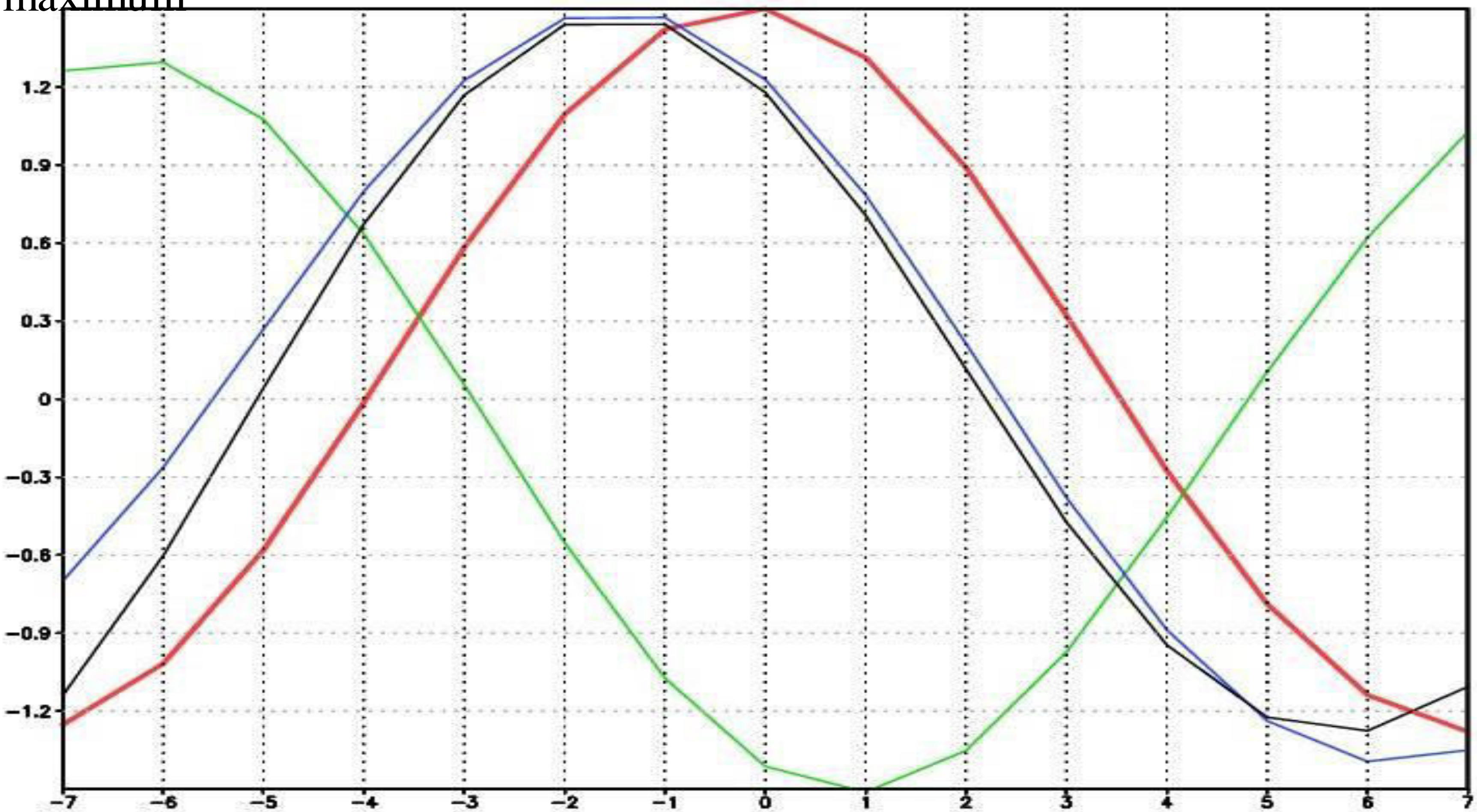


Fig.10. Composites of surface temperature (red), water heating rate because of fluxes from the atmosphere (green), water heating rate because of resolved advection (blue) in region 70-82N, 0E-80E for time shifts from -7 to +7 years from Arctic warming . NAO index is drawn by black. All values are normalized by RMSD.

Table 2 shows results of analysis of energy generation and phase evolution of 15-year oscillation in Arctic. Anomalies of temperature and salinity are generated mainly by oceanic advection. Absorption of Solar radiation also gives positive feedback for temperature. Oceanic currents responsible for anomalous advection are generated by surface wind stress. Phase change of temperature oscillation is produced by oceanic advection and surface fluxes equally.

Table 2. The impact of different terms to energy generation *G* and phase change *P* to temperature (*T*), salinity (*S*) and horizontal currents (*U*, *V*) 15-year oscillation in Arctic in region 70-82N, 0E-80E, 0-100m. Notation of terms as in Table 1.

		FT_{ADV}	FT_{VD}	FT_{IS}	FT_{RAD}
T	G, $10^{-10}K^2/c$ P	4.48 0.44	-5.29 0.46	-1.21 0.01	2.27 0.01
		FS_{ADV}	FS_{VD}	FS_{IS}	
S	G, $10^{-12}‰^2/c$ P	6.1 0.77	-5.9 0.17	0.1 0.00	
		FU_{ADV}, FV_{ADV}	FU_{VD}, FV_{VD}	FU_{HD}, FV_{HD}	FU_{PC}, FV_{PC}
U,V	G, $10^{-10}м^2/c^3$	-0.8	12.6	-10.8	-1.1

Summary

1. Interdecadal natural climate oscillation in Arctic was studied on the basis of 1200 years of piControl run with climate model INM-CM5-0. It was found that EOF-1 of 5-year mean surface temperature is localized in Arctic, and there are 60 year and 15 year oscillations of Arctic climate. Technique of oscillation energy generation and phase change is applied for studying the mechanisms of oscillations.

2. Analysis of 60-year oscillation show that before Arctic warming we have negative salinity anomalies near Arctic coasts and continental slopes from the surface to 1000 meters depth. This leads to low density and counterclockwise currents in the upper Arctic ocean that enhance Atlantic water inflow to Arctic. But increased Atlantic water inflow produces positive salinity anomalies near coasts and sloped that leads decrease of Atlantic water inflow and cooling phase.

3. For 15-year oscillation, temperature, salinity and current anomalies are produced mainly in the upper 100-200 meter upper layer. Positive NAO produces wind surface currents that increase heat transport from Atlantic to Arctic and leads to Arctic warming. But after temperature maximum NAO phase changes sign that leads to change of oscillation phase.

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