Factors of natural climate variability contributing to the Early 20th Century Warming in the Arctic

D D Bokuchava 1,2, V A Semenov 1,2

1 Institute of Geography RAS, 119017, Moscow, Staromonetny per-k 29/4
2 A.M.Obukhov Institute of Atmospheric Physics RAS, 119017, Moscow, Pyzhevsky per-k, 3
d.bokuchava@gmail.com

Abstract. The Early 20th century warming (ETCW) in the Northern Polar region was comparable by its average pace to the modern warming, but the mechanism of this climate anomaly remains a matter of debate. The key issue is to assess the contribution of internal variability and external natural and human impacts. Internal variability is one of the most likely mechanisms that may explain a large part of ETCW. This paper provides an overview of the existing mechanisms of internal climate variability responsible for the long-term climate anomaly in the mid-twentieth century.

1. Introduction
The global warming event in 1910 – 1940 is the second strongest positive climate anomaly during the instrumental global temperature record along with the recent warming, separated by a period of the global temperature decline.

Early 20th century climate fluctuations are of particular interest now, because they share some features of modern warming, despite the fact that greenhouse gas concentrations increase was at least 4 times smaller compared to the recent decades. The specific features of both episodes are pronounced surface air temperature (SAT) anomalies in the Northern Hemisphere (NH), particularly enhanced in the northern high latitudes.

The Early 20th century warming (ETCW) reached its peak in 1940-45, with global warming trends comparable to the modern period of 0.47 °C and 0.48 °C for 30-year periods of 1916-45 and 1962-91 respectively (Fig. 1).

The dynamics of temperature changes in the Northern and Southern Hemispheres has significant differences (Fig. 2). The analysis of SAT anomalies evolution for various NH latitudinal zones shows that the highest SAT growth both for ETCW and modern warming periods was observed primarily in the northern Polar region (Fig. 2). The largest amplitude of annual temperature anomaly in the Arctic region (60°-90° N) was 1.7°C (2.2°C for winter season) for the 1940s relative to 1910s. [1].

In the Arctic, ETCW was most pronounced in winter season [2], while the warming of the 1980s-1990s was stronger in spring and autumn [3], with the temperature increase in winter being relatively moderate. At the same time, abnormally warm winter temperatures in the NH high latitudes reached the peak of the 1940s only at the beginning of the 21st century [1] after the relatively cold period of the 1960s and 1970s.
The main cause of the recent warming is considered to be due to the anthropogenic forcing – primarily the carbon dioxide (CO₂) concentration growth causing a greenhouse effect [5]. But the role of CO₂ for ETCW could not be as important since this period precedes the time of the accelerating growth of radiative forcing by greenhouse gases (GHG). This GHG increase after 1950s is also inconsistent with the global SAT decline from 1940s to 1970s.

Numerical experiments with different climate model generations [6,7] show that modern warming is well reproduced when averaged over model ensembles (indicating external influence as major factor). The ETCW amplitude, despite the increasing accuracy of model simulations, still differs significantly in climate models. This may indicate the important role of internal climate variability [2], as well as the uncertainty of results of model experiments due to incorrectly specified forcing.

The majority of studies [8,9] agree that such a strong warming can be explained by a combination of internal climate system variability as quasi-periodic oscillation or random climate fluctuation with increasing global temperature in the background associated with external anthropogenic and natural forcings (increased GHGs emissions and a pause in volcanic eruptions, in particular).

This paper provides an overview of the existing hypotheses that may explain ECTW, describes the main mechanisms of internal climate variability during the twentieth century, in particular in the Arctic region.

2. Arctic Amplification

The range of temperature changes in the Arctic region in the 1st half of the 20th century was approximately three times higher than the changes in the Northern Hemisphere on average [10], and Arctic surface temperature anomalies reached 1.7 °C in the 1930 – 1940s, compared to maximum of 2000 – 1.5 °C [11].

![Figure 1. 30-year moving trends in global surface air temperature (°C / 30 years) according to Berkley dataset [4]](image-url)
Figure 2. Average annual SAT (°C) anomalies in the period 1900-2015, according to Berkley observational dataset (5-year running mean), global (black curve), Northern Hemisphere (blue curve), Southern Hemisphere (orange curve), NH high latitudes (60°-90° N) (red curve), and NH high latitudes without 5-yr running mean smoothing (gray curve).

Internal variability in the Arctic can be enhanced by positive radiation feedbacks [12], including surface albedo - temperature feedback, which can strongly impact the absorption of solar shortwave radiation. This mechanism manifests itself during prolonged warm periods, mainly in autumn, when a growing ice-free ocean surface with low albedo absorbs more solar radiation and warms the upper ocean layer that leads to further sea ice melting [10]. This positive radiation feedback contributes to the faster temperature increase in the Arctic. This phenomenon is now well-known as “Arctic (or Polar) Amplification”.

However, other positive feedbacks also play major roles in the Arctic Amplification. There are positive feedbacks related to long-wave radiation, for instance, an increase of water vapor content and cloud cover leads to a greenhouse effect, which is more pronounced at high latitudes [13], as well as dynamic feedbacks, which imply strengthened oceanic and atmospheric ocean heat transfer to the Arctic in the conditions of the shrinking sea ice extent [14,15].

Arctic Amplification may also be a consequence of non-local mechanisms such as enhanced northward latent heat transfer in the warmer atmosphere [16] Quasi-periodic fluctuations of North Atlantic sea surface temperature (SST) of 60-80 year time scale [17] suggest a possible role of oceanic heat transfer as a driver of long-term SAT anomalies in the Arctic that can be enhanced by positive feedbacks [18].

Thus, the amplitude of SST oscillations in the NH polar latitudes can be a combination of both regional response to global climate change and the formation of internal oscillations in the ocean-atmosphere system.

3. Natural internal factors – ocean-atmosphere system variability

3.1 Atmosphere circulation variability

The main uncertainty of climate change drivers in the 20th century belongs to quantifying relative contributions of internal natural variability and external anthropogenic impact. Noticeable temperature fluctuations in the 1920s and 1940s had already in those times been a subject of scientific interest.
Numerous studies in the first half of the 20th century have showed the important role of atmospheric and ocean circulation in the development of regional climate fluctuations, e.g., [19].

A number of numerical experiments with climate models, e.g., [20] show that atmosphere internal variability and feedbacks between the atmosphere and other components of the climate system (ocean, sea ice, etc.) - can lead to repetition of ETCW amplitude in recent period. A significant part of interannual and long-term SAT anomalies in the Arctic and other regions in the first half of the 20th century can be explained by atmospheric circulation variability [21]. The key regions responsible for the air masses inflow to the Arctic are the North Atlantic sector and the North Pacific Ocean [22]. In the second half of the 20th century, indices of leading atmosphere variability modes such as the North Atlantic oscillation, the Arctic oscillation and the Pacific North American index in combination explained 44% of the Arctic SAT variance [21].

The North Atlantic Oscillation (NAO) and the closely related Arctic Oscillation (AO) is the dominant mode of large-scale winter atmospheric variability in the North Atlantic, characterized by sea level pressure dipole with one center over Greenland (Icelandic minimum) and another center of the opposite sign in the North Atlantic mid latitudes (Azores maximum). NAO controls the strength and direction of westerly winds and the position of storm tracks in the North Atlantic sector, thus crucially impacting the European climate [23].

During the first two decades of the 20th century, the positive phase of NAO was expressed in a stronger than usual zonal circulation over the North Atlantic (Fig. 3). The long-term dominance of these atmospheric circulation pattern led to an advection of heat to the northeastern part of the North Atlantic. However, the NAO transition to the negative phase after 1920s and in general inconsistency between NAO and Arctic SAT variations in the first half of the 20th century do not support a hypothesis of NAO contribution to the ETCW warming [24].

The Pacific North American Oscillation index (PNA) characterizes the pressure gradient between the North Pacific (Aleutian minimum) and the East of North America (Canadian maximum) and is related to fluctuations of North Pacific zonal flow. An important feature of PNA in the context of the ETCW is that both (positive and negative) PNA phases may contribute to atmospheric heat advection to the Arctic. In the 1930s and 1950s, the negative phase (Fig. 3) led to the transfer of warm air masses to the pole across the northwestern Pacific Ocean, and the positive phase of the 1940s forced increased
zonal transfer to the Western coast of Canada and Alaska [8]. PNA is strongly influenced by the Pacific Southern Oscillation (El Nino Southern Oscillation – ENSO) – the positive index phase is associated with the El Nino phenomena, and the negative with La Niña events.

It is also important to mention indices of regional atmospheric variability patterns reflecting anomalies of geopotential height and sea level pressure in the North Atlantic and Pacific ocean – Eurasia – East Atlantic (East Atlantic – EA), East Atlantic – Western Russia (East Atlantic – Western Russia – EAWR), Scandinavian (Scandinavian – SCAND) [26], Barents Oscillation (Barents Oscillation – BO) [27] and others linked to the atmospheric heat transport to the high latitudes at regional scales. They may significantly impact Arctic climate on a time scale from interannual to decadal. Such regional atmospheric variability may contribute to the Arctic SAT anomalies, but the related SAT variations are much smaller compared to those caused by NAO or PNA and the associated variability has higher frequency time scale.

Atmospheric circulation in the mid-latitudes of the Pacific Ocean may also depend on fluctuations of the Pacific trade winds [28]. The trade winds weakening is manifested in the SAT growth in Pacific mid-latitudes, which coincides on the time scale with the warming of 1910-1940s in the high Arctic latitudes and in the lowering of temperatures during the cooling period between 1940s and 1970s when the strength of the trade winds had been increasing.

Analysis of tropospheric circulation shows that the internal atmosphere dynamics may have an impact on the Arctic SAT in the first half of the 20th century, suggesting significant contribution of both the Atlantic and Pacific sectors to the transport of warm southern air masses into the Arctic [29]. This, however, cannot explain the entire amplitude of ETCW [8] and should be complemented by other factors of external or internal variability. The results of six ensemble simulations with the coupled ocean-atmosphere climate model [9] suggest that the ETCW could be a joint result of large internal multidecadal fluctuation and anthropogenic forcing.

3.2 Ocean circulation variability
Arctic Amplification in the 20th century, including ETCW period can be associated not only with an increase of atmospheric heat transport, but also with an enhancement of ocean heat inflow in the North Atlantic to the extratropical latitudes of the NH from its equatorial part [30].

An analysis of climate model simulations shows that ETCW in the Arctic may be a result of increased oceanic inflow from the North Atlantic to the Barents sea with a corresponding retreat of sea ice [1], and also points to relationship link between inter-decadal temperature variability in the Arctic and thermohaline circulation in the North Atlantic [30]. Thermohaline circulation also often called the ocean conveyor is driven by temperature and salinity gradients that determine the density of sea water. It is largely responsible for heat transport between ocean basins and, in particular for the northward oceanic heat transport in the North Atlantic. Quasi-periodic variations of this heat transport may lead to global climate anomalies [31,32].

Instrumental data show that SST variability in the North Atlantic during the 20th century was dominated by cyclic fluctuations on time scales of 50-80 years, showing two warm periods in the 1930s-1940s and at the end of the 20th century and two cold periods in the beginning of the century and in the 1960s-1970s. SST oscillations in the North Atlantic are called Atlantic Multidecadal Oscillation (AMO). The observational data also indicate AMO-like cycles in the Arctic SAT (Fig. 4).

Paleo-reconstructions of AMO [33] demonstrate that strong, low-frequency (60-100 years) SST variability is a robust feature of the North Atlantic climate over the past five centuries. There are also indications of a significant correlation between Arctic sea ice area and AMO index including a sharp change during ECTW period [34].

There is another pronounced internal climate variability that may act synchronously with AMO. This is the Pacific Decadal Oscillation (PDO), which reflects a variability of the Pacific SSTs north of 20° N and gas 20-40 years periodicity [35]. PDO might have played an equally important role in the heat advection to the Arctic in the middle of the century. Several current studies [36,29] suggest the
synchronous phase shift of AMO and PDO largely contributed to the accelerated Arctic warming, both the ongoing and ETCW.

Figure 4. Winter Arctic (60°-90°N) SAT anomalies according to Berkley dataset (5-year running mean, black curve); AMO index (pink curve), PDO index (blue curve) according to HadiSST2.0 dataset [37]

The issue of PDO and AMO role in the Arctic climate changes remains controversial. Some results of model simulations, e.g., [38] show that PDO (unlike AMO) does not significantly contribute to global SAT changes in the 20th century. Other studies, e.g., [39] argue that PDO alone was a key factor in the Arctic warming during mid-twentieth century. PDO shifted into a positive phase in that time with the deepening of the Aleutian low and enhancing advection of warm air masses to the Arctic in the Pacific sector. Furthermore, these experiments have shown that changes in Pacific SSTs could weaken the polar vortex leading to air descent and adiabatic heating of the lower troposphere in the Arctic. This mechanism is supported by the findings by [40] that identify Pacific Ocean tropical latitudes as a key region long-term climate variations in the last century, particularly in the 1910s-1940s.

The difference between PDO and AMO influence may be related to their different variability time scales. Pacific Ocean affects the observed SAT variability of NH at the inter-decadal time scale (Fig. 4), while changes in the Atlantic SSTs are represented by 60-70-year cycles [41]. Thus, these modes can enhance or compensate each other depending on the time period.

Recent studies for the modern warming period argue that the combination of a sharply negative PDO phase contrary to a moderately positive AMO phase is able to compensate and even slowdown the anthropogenic warming in the early 21st century in the NH [41]. This is due to a corresponding weakening of the temperature difference between the equator and the pole and, a decrease of the NH westerlies. At the same time, in some model experiments [42] changes in global warming rates within 20th century still persist after removing the AMO and PDO factors and the contribution of two ocean basins internal variability to the global warming in the second half of the 20th century is estimated to be less than 10%.

4. Conclusions
Understanding the mechanisms of ETCW and subsequent cooling is a key to determine the relative contribution of internal natural variability to global climate change on multi-decadal time scale. Studies of climate changes in high latitudes in the mid-twentieth century allows us to identify a
number of possible mechanisms involving natural variability and positive feedbacks in the Arctic climate system that may partially explain ETCW.

Based on the recent literature it can be concluded that internal oceanic variability, together with additional impact of natural atmospheric circulation variations are important factors for ETCW. Recently, a number of results indicating the Pacific Ocean as a source of multidecadal fluctuations both on a global scale and in high latitudes has increased. However, assessment of a relative contribution to ETCW in the Atlantic and Pacific sectors remains uncertain.

Climate model simulations [9,43,44] argue that the internal variability of the ocean-atmosphere system cannot explain the entire amplitude of temperature fluctuations in the first half of the 20th century as a single factor, and must act in combination with external forcings (solar and volcanic activity), positive feedbacks in the Arctic climate system, and anthropogenic factors. Quantifying the contribution of each factor still remains a matter of debate.

The research was performed with the financial support of Ministry of Science and Higher Education of the Russian Federation (№ 05.616.21.0109 (075-15-2019-1487) (RFMEF161619X0109)).

References
[1] Bengtsson L, Semenov V, Johannessen O 2004 *Journal of Climate* 17(20) 4045-4057
[2] Johannessen O, Bengtsson ., Miles M, Kuzmina S, Semenov V, Alekseev G, Nagurnyi A, Zakharov V, Bobylev L, Pettersson L, Hasselmann K, Cattle H 2004 *Tellus A: Dynamic Meteorology and Oceanography* 56(4) 328-341
[3] Polyakov I, Bekryaev R, Alekseev G, Bhatt U, Colony R, Johnson M, Makshtas A, Walsh D 2003 *Journal of Climate* 16(12) 2067-2077
[4] Rohde R, Muller R.A, Jacobsen R, Muller E, Perlmutter S, Rosenfeld A, Wurtele J, Groom D, Wickham C 2013 *Geoinform Geostat: An Overview* 1:1 72
[5] Serreze M and Francis J 2006 *Climatic change* 76(3-4) 241-264
[6] IPCC, 2013: Climate Change 2013: Stocker T, Qin D, Plattner G-K, Tignor M, Allen S, Boschung J, Nauels A, Xia Y, Bex V, Midgley P (eds.) *Cambridge University Press*
[7] IPCC, 2007: Climate Change 2007: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avert K, Tignor M, Miller H (eds.) *Cambridge University Press*
[8] Hegerl G, Brönnimann S, Schurer A, Cowan T 2018 *Wiley Interdisciplinary Reviews: Climate Change* 9(4) e522
[9] Delworth T and Knutson T 2005 *Science* 287(5461) 2246-2250
[10] Bekryaev R, Polyakov I, Alexeev V 2010 *Journal of Climate* 23(14) 3888-3906
[11] Polyakov I, Alexeev G, Bekryaev R, Bhatt U, Colony R, Johnson M, Karcklin V, Makshtas A, Walsh D, Yulin A 2002 *Geophysical research letters* 29(18) 25-1
[12] Pithan F and Mauritsen T 2014 *Nature Geoscience* 7(3) 181
[13] Graversen R and Wang M 2009 *Climate Dynamics* 33(5) 629-643
[14] Alexeev V, Walsh J, Ivanov V, Semenov V, Smirnov A 2017 *Env. Res. Lett* 12(2017) 084011
[15] Ivanov V, Alexeev V, Koldunov N, Repina I, Sandø A, Smedsrud L, Smirnov A 2016 *Journal of Physical Oceanography* 46(5) 1437-1456
[16] Caballero R and Langen P 2005 *Geophysical Research Letters* 32(2)
[17] Schlesinger M and Ramankutty N 1994 *Nature* 367(6465) 723
[18] Semenov V 2008 *Dokl. Earth Sci* 418(1) 91–94
[19] Wiebe V 1937 *Soviet Arctic* 1 1-7
[20] Wang M, Overland J, Kattsov V, Walsh J, Zhang X, Pavlova T 2007 *Journal of Climate* 20(6) 1093-1107
[21] Wood K and Overland J 2010 *International Journal of Climatology* 30(9) 1269-1279
[22] Alexeev G, Kuzmina S, Bobylev L, Urazgildeeva A, Gnutiu N 2019 *International Journal of Climatology* 39(8) 3582-3592
[23] Ambaum M, Hoskins B, Stephenson D 2001 *Journal of Climate* 14(16) 3495-3507
[24] Semenov V 2007 *Izvestiya, Atmospheric and Oceanic Physics* 43(6) 687–695
[25] Allan R and Ansell T 2006 *Journal of Climate* 19(22) 5816-5842
[26] Barnston A and Livezey R 1987 *Monthly weather review* 115(6) 1083-1126
[27] Chen H, Zhang Q, Körnich H, Chen D 2013 *Geophysical Research Letters* 40(11) 2856-2861
[28] Thompson D, Cole J, Shen G, Tudhope A, Meehl G 2015 *Nature Geoscience* 8(2) 117
[29] Wegmann M, Brönnimann S, Compo G 2017 *Climate dynamics* 48(7-8) 2405-2418
[30] Alekseev G, Kuzmina S, Urazgildeeva A, Bobylev L 2016 *Fundamental and Applied Climatology* 1 43-63
[31] Delworth T and Mann M 2000 *Climate Dynamics* 16(9) 661-676
[32] Semenov V, Latif M, Dommenget D, Keenlyside N, Streizh A, Martin T, Park W 2010 *J. Clim* 23 5668–5677
[33] Gray S, Graumlich L, Betancourt J, Pederson G 2004 *Geophysical Research Letters* 31(12)
[34] Miles M, Divine D, Furevik T, Jansen E, Moros M, Ogilvie A 2014 *Geophysical Research Letters* 41(2) 463-469
[35] Mantua N, Hare S, Zhang Y, Wallace J, Francis R 1997 *Bulletin of the american Meteorological Society* 78(6) 1069-1080
[36] Tokinaga H, Xie S, Mukougawa H 2017 *Proceedings of the National Academy of Sciences* 114(24) 6227-6232
[37] Titchner H and Rayner N 2014 *Journal of Geophysical Research: Atmospheres* 119(6) 2864-2889
[38] Chylek P, Klett J, Dubey M, Hengartner N 2016 *Climate Dynamics* 47(9-10) 3271-3279
[39] Svendsen L, Keenlyside N, Bethke I, Gao Y, Omrani N 2018 *Nature Climate Change* 1
[40] Kosaka Y and Xie S 2016 *Nature Geoscience* 9(9) 669
[41] Steinman B, Mann M, Miller S 2015 *Science* 347(6225) 988-991
[42] Stolpe M, Medhaug I, Knutti R 2017 *Journal of Climate* 30(16) 6279-6295
[43] Shiogama H, Nagashima T, Yokohata T, Crooks S, Nozawa T 2006 *Geophysical Research Letters* 33(9)
[44] Yamanouchi T 2011 *Polar Science* 5(1) 53-71