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Characteristics of atmosphere - sea ice energy exchange in the Central Arctic

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Abstract. Analysis of an interaction between long-term ice cover and atmosphere in different regions of the Arctic Ocean is conducted. For comparison the energy exchange characteristics in the western and eastern periphery of the Beaufort Gyre, the central part of the Arctic Ocean and in the area to the north of the Kara and Barents seas have been analyzed. The results of calculations based on special observations at Russian drifting station "North Pole-4" and its interpretation using a simple thermodynamic model of sea ice were used. As modern in situ data, meteorological observations at drifting stations "North Pole-35" (2007-2008) and "North Pole-39" (2011-2012) were used. Calculations of turbulent heat fluxes in the region of the drift of the American station "SHEBA" were performed. A good agreement between the calculated fluxes based on the historical data and NP-39 data for the summer period is shown. Monthly mean values and standard deviations of meteorological parameters for winter period are presented on the basis of data from drifting stations "North Pole-35" – "North Pole-40" (2007-2013).

1. Introduction

Measurements of the atmospheric and sea ice parameters at the drifting stations allow obtaining continuous series of in situ data from remote and inaccessible regions of the Arctic Ocean. The first drifting station "North Pole" (NP-1) had been opened in 1937 and worked for nine months. Since 1950, observations on the drifting ice have been regular (NP-2 - NP-31) until 1991. Meteorological parameters of the atmospheric surface layer had been received over more than forty years and were published by the team of Russian and American researchers in 1996 [2]. These datasets have become the basis for number of publications, for example [1]. After the break, meteorological studies at drifting stations NP-32 - NP-40 (Figure 1) were continued from 2003 to 2013. Since 2007 (NP-35) the set of measured meteorological parameters has been significantly expanded. Carefully organized full-scale experiments and the use of modern sensors made a good basis for investigation of the energy exchange between sea ice cover and atmosphere in the Central Arctic.

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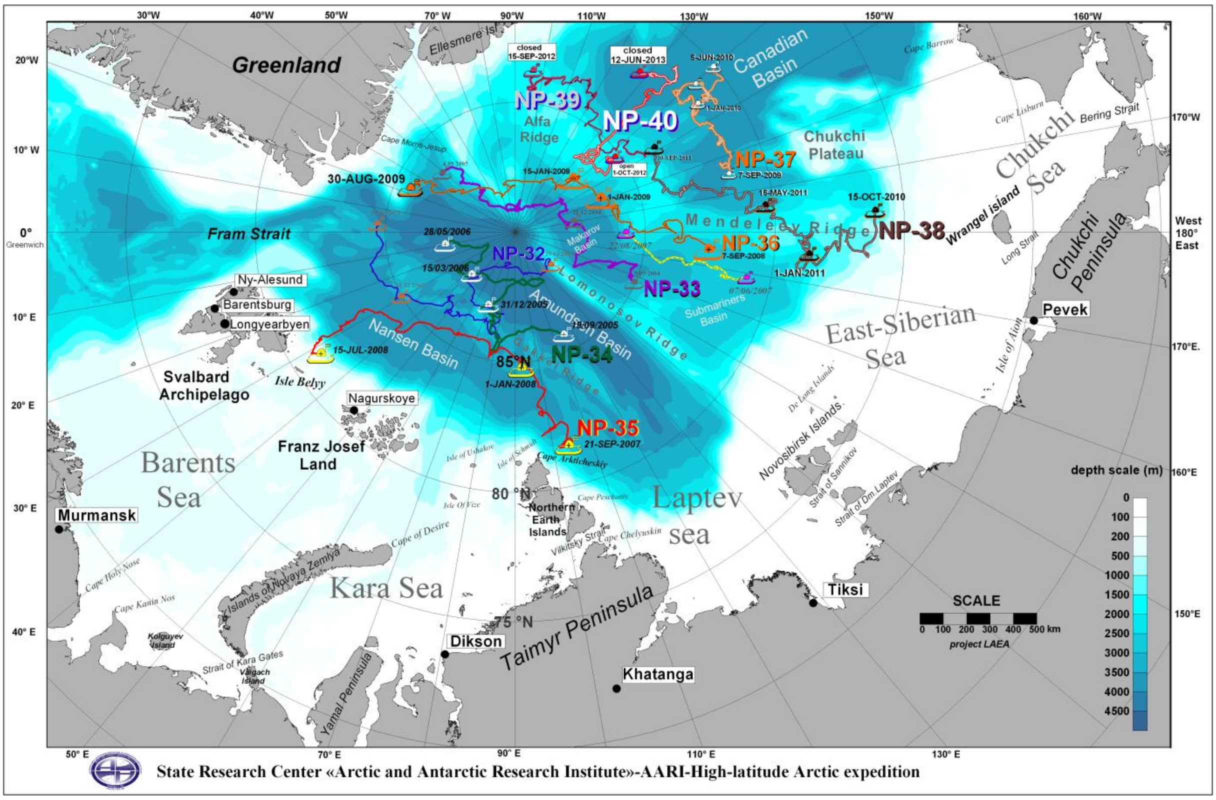

Figure 1. Map of the drift of the North Pole stations in the 21st century.

Calculation of turbulent heat fluxes between the underlying surface and the atmospheric surface layer is one of the key tasks for better understanding of air – sea interaction processes determining the formation and destruction of sea ice cover and for validation of weather and climate models in Polar Regions. The relevance of such approach is confirmed by organization of the International drifting station MOSAiC [http://www.mosaic-expedition.org] in 2019. One of the main tasks of the project is a comprehensive study of physical processes in sea ice cover and atmospheric boundary layer during the ongoing climate change in the Arctic. Our article aims to summarize the data of meteorological observations executed on the drifting stations during the last decade, because of its exceptional value in planning future experimental studies as it was noted at the Workshop on the "Mosaic" project, held in November 2017 in the Arctic and Antarctic Research Institute [http: //www.aari.ru].

2. Characteristics of the Arctic atmospheric surface layer in the 21st century according to drifting stations

In present work we used the data of meteorological measurements executed at the drifting stations NP-35 - NP-40 in 2007 – 2013 years. Atmospheric pressure, wind speed and direction at heights 2 and 10 m, air temperature and humidity at heights of 2 and 8 m, incoming and reflected short-wave radiation, as well as upward and downward fluxes of long-wave radiation were measured with automatic meteorological station (MAWS 110 and MAWS 420 (Vaisala, Finland)). After the control procedures, arrays of 10-minute values have been prepared. Tables 1 (a-f) show the mean values and standard deviations of air temperature and specific humidity at 2 meters, wind speed at 10 m and atmospheric surface pressure, calculated for each month during drift of the stations. Trajectories of drifts as well as beginning and end of works at stations are shown at figure 1.

Table 1 (a). Characteristics of atmospheric surface layer at NP-35

Year	Month	Ta2m (°C)		Ws (ms^{-1})		q2m (kg m^{-3})		Pa (hPa)	
		mean	σ^2	mean	σ^2	mean	σ^2	mean	σ^2
2007	9	-5.4	3.4	4.6	2.1	0.0025	0.0007	1001.8	8.7
2007	10	-10.0	5.3	6.1	3.1	0.0018	0.0007	1003.1	13.5
2007	11	-20.6	5.3	5.7	2.5	0.0007	0.0004	1018.8	7.2
2007	12	-27.4	4.5	5.3	2.1	0.0003	0.0002	1012.7	6.9
2008	1	-30.6	5.1	6.3	2.9	0.0002	0.0002	1007.3	11.6
2008	2	-29.5	4.6	5.2	2.3	0.0003	0.0001	1012.0	9.7
2008	3	-31.6	5.5	4.3	2.0	0.0002	0.0002	1014.8	8.4
2008	4	-19.4	6.7	5.2	2.3	0.0008	0.0005	1022.1	13.9
2008	5	-11.3	4.4	4.0	1.9	0.0015	0.0005	1022.5	8.1
2008	6	-1.6	1.6	5.6	2.6	0.0032	0.0004	1013.4	9.4
2008	7	-0.4	0.6	4.1	1.9	0.0036	0.0001	1010.1	14.5

Table 1 (b). Characteristics of atmospheric surface layer at NP-36

Year	Month	Ta2m (°C)		Ws (ms^{-1})		q2m (kg m^{-3})		Pa (hPa)	
		mean	σ^2	mean	σ^2	mean	σ^2	mean	σ^2
2008	9	-4.3	2.6	5.8	2.0	0.0027	0.0005	1012.6	7.4
2008	10	-14.7	4.8	7.8	3.0	0.0012	0.0005	1005.0	8.5
2008	11	-20.8	6.0	5.6	2.3	0.0007	0.0004	1015.5	8.4
2008	12	-	-	-	-	-	-	-	-
2009	1	-27.3	6.6	4.8	2.9	0.0004	0.0004	1005.7	13.4
2009	2	-31.9	6.9	4.7	2.2	0.0002	0.0002	1016.8	14.2
2009	3	-35.0	3.8	4.2	2.3	0.0001	0.0001	1024.5	9.4
2009	4	-26.5	6.1	4.8	1.9	0.0004	0.0002	1017.4	7.4
2009	5	-8.6	3.6	5.8	2.3	0.0019	0.0006	1010.4	7.5
2009	6	-2.4	2.0	5.5	2.3	0.0030	0.0004	1018.3	6.3
2009	7	-0.5	1.2	4.5	1.9	0.0035	0.0003	1020.5	5.7
2009	8	-1.9	1.8	3.4	1.3	0.0032	0.0004	1014.6	3.9

Table 1 (c). Characteristics of atmospheric surface layer at NP-37

Year	Month	Ta2m (°C)		Ws (ms^{-1})		q2m (kg m^{-3})		Pa (hPa)	
		mean	σ^2	mean	σ^2	mean	σ^2	mean	σ^2
2009	9	-6.9	4.0	5.0	2.5	0.0022	0.0007	1015.2	9.3
2009	10	-14.1	6.2	4.6	2.0	0.0013	0.0006	1026.5	7.4
2009	11	-23.3	6.8	5.2	1.9	0.0006	0.0004	1007.5	11.0
2009	12	-27.5	5.7	6.1	2.6	0.0004	0.0002	1027.5	14.1
2010	1	-32.0	6.1	6.1	2.7	0.0002	0.0002	1014.6	13.8
2010	2	-31.3	5.5	6.0	2.1	0.0002	0.0001	1028.8	10.8
2010	3	-26.0	5.6	5.8	2.6	0.0004	0.0002	1022.2	11.4
2010	4	-19.0	5.9	4.4	2.1	0.0008	0.0004	1017.4	8.3
2010	5	-8.5	3.5	3.9	2.0	0.0019	0.0006	1029.1	8.3

Table 1 (d). Characteristics of atmospheric surface layer at NP-38

Year	Month	Ta2m (°C)		Ws (ms^{-1})		q2m (kg m^{-3})		Pa (hPa)	
		mean	σ^2	mean	σ^2	mean	σ^2	mean	σ^2
2010	11	-15.6	5.5	4.7	3.4	0.0010	0.0005	1012.3	8.0
2010	12	-25.6	5.4	4.0	3.2	0.0004	0.0002	1025.5	9.9
2011	1	-23.2	5.6	4.4	2.3	0.0005	0.0003	1019.4	14.0
2011	2	-27.3	4.8	4.9	2.9	0.0003	0.0002	1012.4	12.6
2011	3	-25.1	5.4	2.5	1.6	0.0004	0.0003	1010.5	10.4
2011	4	-19.3	7.1	5.2	2.3	0.0008	0.0006	1016.2	11.7
2011	5	-7.8	5.8	5.1	2.0	0.0020	0.0009	1020.8	6.4
2011	6	-1.7	2.0	5.0	2.5	0.0031	0.0005	1020.6	6.7
2011	7	0.4	0.7	4.6	2.0	0.0036	0.0001	1015.3	13.5
2011	8	-0.4	1.2	3.9	2.0	0.0036	0.0003	1017.1	7.4
2011	9	-6.1	4.4	4.3	2.7	0.0024	0.0008	1005.1	7.8

Table 1 (e). Characteristics of atmospheric surface layer at NP-39

Year	Month	Ta2m (°C)		Ws (ms^{-1})		q2m (kg m^{-3})		Pa (hPa)	
		mean	σ^2	mean	σ^2	mean	σ^2	mean	σ^2
2011	9	-4.9	2.7	5.0	2.1	0.0025	0.0005	1011.0	5.7
2011	10	-15.6	5.4	4.4	3.2	0.0011	0.0005	1011.7	11.6
2011	11	-24.2	5.4	4.6	2.5	0.0005	0.0003	1010.1	9.2
2011	12	-28.5	6.0	4.3	2.9	0.0003	0.0002	1007.4	8.7
2012	1	-27.7	8.1	4.9	3.0	0.0004	0.0004	1013.4	9.7
2012	2	-31.5	5.5	4.4	1.9	0.0002	0.0001	1016.0	6.9
2012	3	-33.3	5.9	4.6	1.9	0.0002	0.0002	1017.8	10.7
2012	4	-24.3	4.8	3.5	1.3	0.0004	0.0002	1027.9	5.9
2012	5	-10.4	6.0	3.7	2.1	0.0016	0.0008	1023.8	6.8
2012	6	-0.7	1.2	4.4	2.1	0.0033	0.0004	1020.3	11.8
2012	7	0.3	0.6	4.2	2.2	0.0037	0.0002	1015.9	8.3
2012	8	-1.4	1.7	4.5	2.5	0.0032	0.0005	1013.3	10.6

Table 1 (f). Characteristics of atmospheric surface layer at NP-40

Year	Month	Ta2m (°C)		Ws (ms^{-1})		q2m (kg m^{-3})		Pa (hPa)	
		mean	σ^2	mean	σ^2	mean	σ^2	mean	σ^2
2012	10	-18.5	4.7	4.4	3.3	0.0008	0.0003	1017.8	11.7
2012	11	-23.5	6.9	5.3	3.6	0.0006	0.0004	1013.9	12.1
2012	12	-30.2	6.0	2.7	1.7	0.0003	0.0002	1020.8	8.2
2013	1	-27.5	5.4	7.6	3.3	0.0003	0.0002	1028.4	11.8
2013	2	-36.4	4.7	3.6	1.8	0.0001	0.0001	1021.9	10.3
2013	3	-30.0	7.5	4.2	2.7	0.0003	0.0003	1037.6	7.2
2013	4	-23.0	4.0	4.8	2.2	0.0005	0.0002	1023.9	13.7
2013	5	-11.6	5.1	5.5	2.8	0.0014	0.0007	1017.9	4.8
2013	6	-6.6	2.1	5.3	2.7	0.0020	0.0004	1001.2	10.3

The analysis of presented data gives possibility to characterize typical meteorological conditions in the Central Arctic during last decade as follows. Since June to September there is a warm period with temperatures, varying from 0.4 to -7 °C with standard deviations from 0.4°C in July to 4.0°C in September. From October to May, the temperature variability increases at all stations and ranges from 3.5°C to 8.1°C. The lowest monthly mean air temperature -36.4°C had been observed in February 2013 at NP-40. The warmest winter was at NP-38 with average temperatures from -23 to -27 °C.

Since November to April the specific humidity has the minimum values in the annual cycle. Maximum is in June-August. During both periods specific humidity is nearly constant. The most variations of the specific humidity were observed in September-October and May, during periods of beginning freezing and melting of sea ice cover.

The average wind speed varies from 2.5 to 7.8 ms^{-1} and does not have a pronounced annual cycle. The standard deviation of wind speed at all stations equals approximately to half of the mean monthly values and slightly decreases from winter to summer.

The annual cycle of atmospheric pressure at each station has one to three expressed maxima and minima, characterizing the individual synoptic conditions in the region of station drift and associated with the baric systems. The intra-annual differences in the average monthly atmospheric pressure at stations NP-35-NP-39 are about 20 hPa, at the NP-40 station the difference reaches 36.4 hPa (1037.6 hPa on March and 1001.2 hPa on June).

Figure 2 shows the frequencies of occurence air temperature, specific humidity, wind speed and atmospheric surface pressure averaged over 10 minutes from measurements at drifting stations NP-35 – NP-40 in winter (December-March), the most complicate period for field observations.

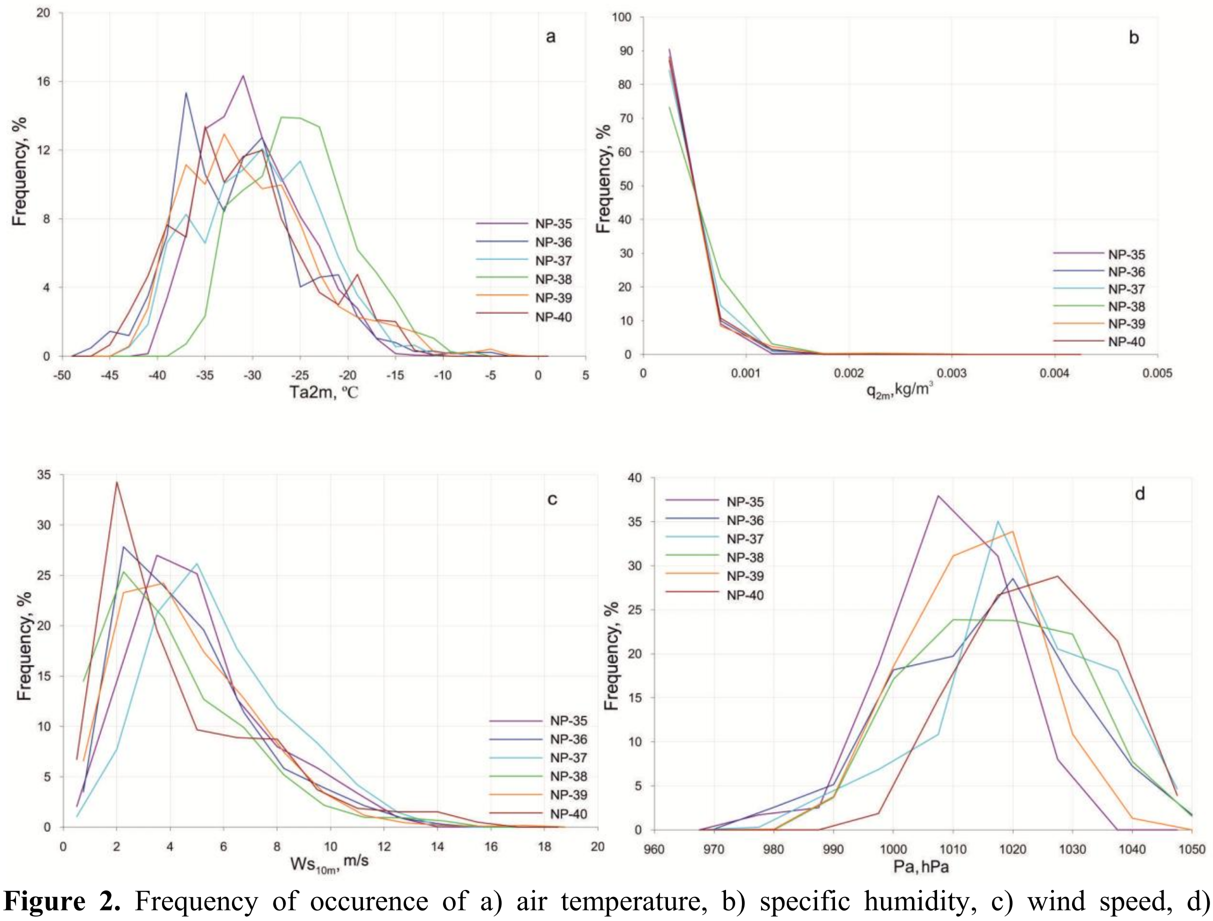

Figure 2. Frequency of occurence of a) air temperature, b) specific humidity, c) wind speed, d) atmospheric pressure at drifting stations NP-35 – NP-40 in December - March.

According to presented frequency distributions of 10-minute values, the meteorological conditions for work in the winter can be quite severe: air temperature at a height of two meters in rare cases could reach -47.3°C (NP-36), and wind speed at altitude ten meters may be 18.3 ms^{-1} (NP-39).

3. Preliminary analysis of the characteristics of sea ice-atmosphere interaction in the Arctic Ocean according to historical and modern data

In this part the analysis of multiyear sea ice cover - atmosphere interaction in different regions of the Arctic Ocean is presented. For comparison of past and recent values of surface heat balance components the results of calculations, based on unique special observations at NP-4, published in [3] and the same, calculated with the simple thermodynamic model of sea ice and published in [1] are used. Calculations of turbulent heat fluxes in the region of SHEBA drift [4] were executed on the basis of the Hourly Observation Data Archive, courtesy of E. Andreas. The last data were also had been used to validate the new version of the method for calculation of turbulent heat fluxes, developed in AARI [5].

For comparison the energy exchange characteristics in the western and eastern peripheries of the Beaufort Gyre (NP-39 and SHEBA), the central part of the Arctic Ocean (NP-4), and in the area to the north of the Kara and Barents seas (NP-35) have been analyzed. The modern in situ data of meteorological observations (atmospheric pressure, wind speed at 2 and 10 meters, air temperature and humidity at 2 and 8 meters, short-wave and long-wave incoming and reflected radiation) of 1-minute discreteness at stations NP-35 (2007-2008) and NP-39 (2011-2012), averaged for each 10 minutes were used. To calculate turbulent sensible (H) and latent (LE) heat fluxes, we used the scheme based on the Monin-Obukhov similarity theory, described in detail in [6]. Taken in account that additional analysis of the data showed too large errors in wind speed data, for the calculations a modification of the scheme, used temperature and humidity at two levels and wind speed at 10 m, was applied.

For the conditions of unstable stratification, the stability function proposed in [7,8,9] was used. Stability functions obtained from the data of SHEBA were used for the conditions of stable stratification [10]. The system of equations was solved using an iterative procedure by Monin-Obukhov parameter L.

In a number of cases the parameter of atmospheric surface layer stratification (DZITA) had a large absolute value, exceeding the limits for which the parameterizations were developed. However, as it can be seen from the histograms (Figure 3), the number of such cases for each of the annual measurement cycles is less than 10%.

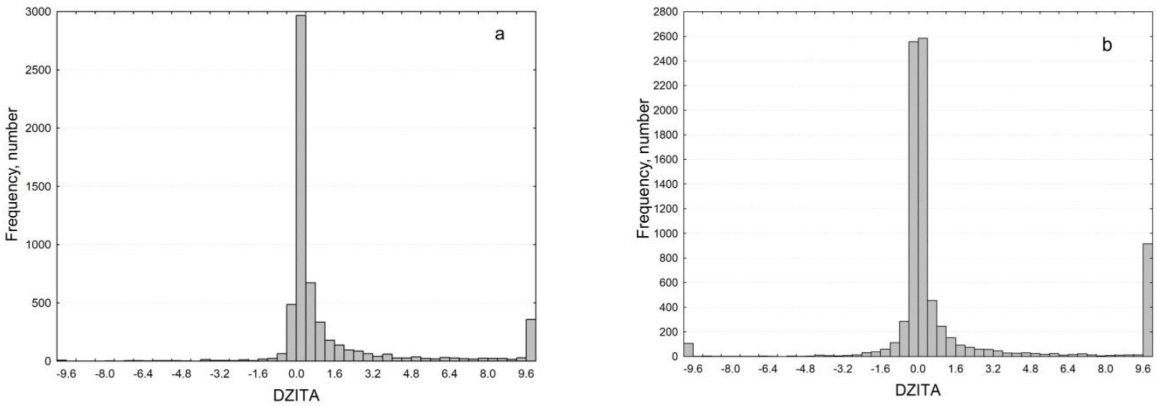

Figure 3. Histograms of the stability parameter of the atmospheric surface layer (DZITA) according to the annual measurement cycles at the drifting stations "North Pole -35" (a) and "North Pole-39" (b).

Figure 4 shows monthly mean values of snow/ice cover heat balance components from [3] - the index H, [1] - the index LM, and calculated with data of the drifting stations North Pole - 35, 39 and

SHEBA. In the calculations of H, LE, R, fluxes are considered positive in direction from surface to atmosphere (R is total surface radiation balance). The heat flux to the surface (EH) is calculated as

$$EH = -R - H - LE$$

The positive direction of EH is from the atmosphere to the underlying surface.

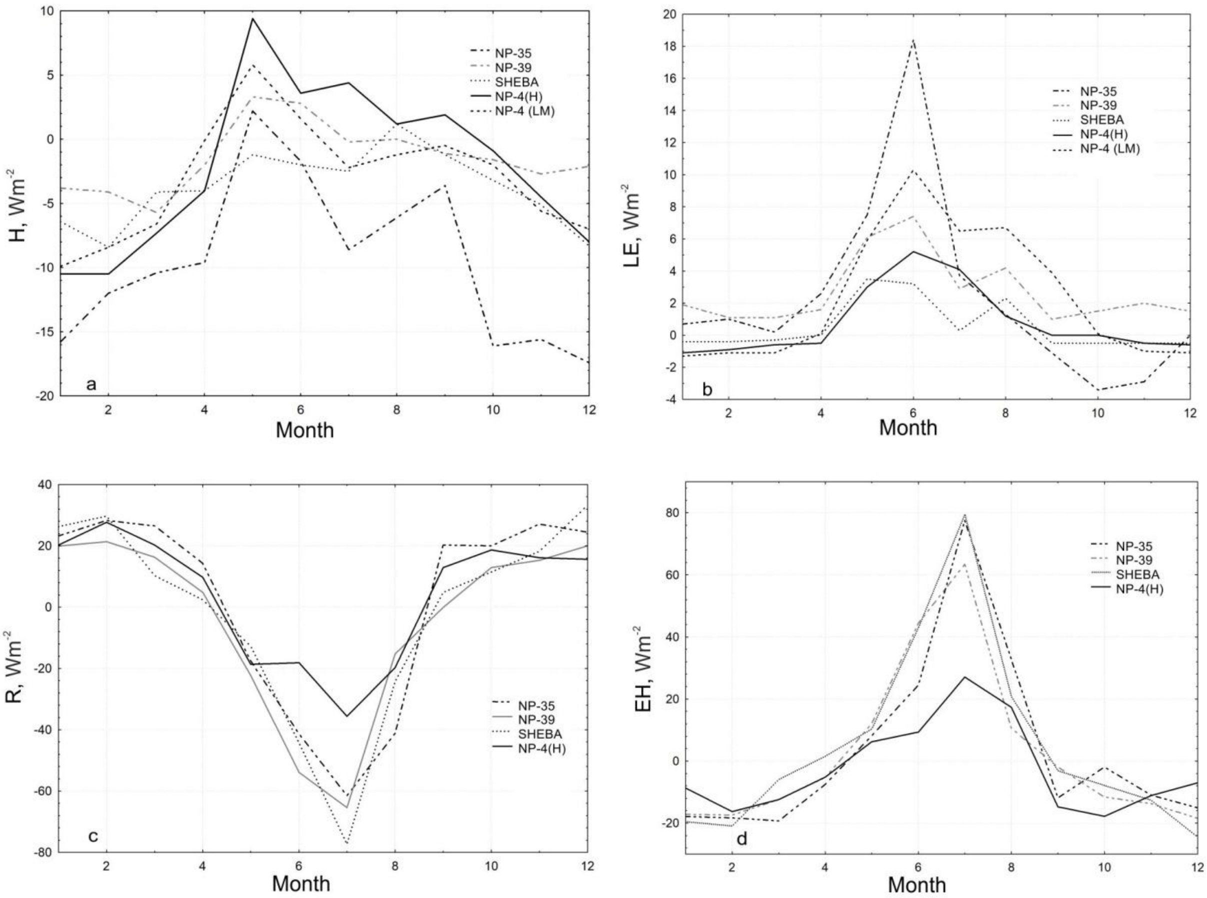

Figure 4. Characteristics of the surface heat balance according to the data of drifting stations.

In [1] turbulent heat fluxes had been calculated from standard meteorological measurements by model assuming fixed sea ice thickness of 3 meters. It could be the reason of rather large difference with values from profile measurements, presented in [3]. Same time a rather good agreement between the calculated fluxes based on the historical data and NP-39 data for the summer period is evident. The decrease in the value of heat flux to the ice cover according to NP-39 can be associated with a decrease in the ice thickness in the first decade of the 21st century. Also it can be assumed that the difference in the latent heat flux LE presented in Figure 4 is determined by drift of NP-35 close to the marginal seas of the Arctic Ocean (see Figure 1).

The most interesting is a large difference in the amount of heat flux to the surface (EH) during the summer period in 1950th and 2000th mainly due to the small values of the radiation balance according to [3] data. The reasons could be the changes in cloudiness [11], as well as due to large albedo at NP-4 (0.75) in July, compared to 0.65 at NP-35 and NP- 39, and 0.56 according to SHEBA.

Figure 5 shows the hourly mean values of turbulent heat fluxes at NP-35 and NP-39 in October, together with the hourly mean values of air temperature and wind speed, measured on these stations. For this month the average monthly values of the turbulent fluxes at all stations with the exception of NP-35 were very similar. The maximum negative turbulent heat fluxes occurred at NP-35 during the periods of maximum air temperatures and wind speeds. The difference in values reached more than 20° C and 10 ms^{-1} compare with similar at NP - 39. The duration and frequency of abrupt changes in these meteorological parameters could be caused by the invasion of air masses of continental origin in the region of NP-35 drift and amplification of anticyclonic circulation in the area of NP-39.

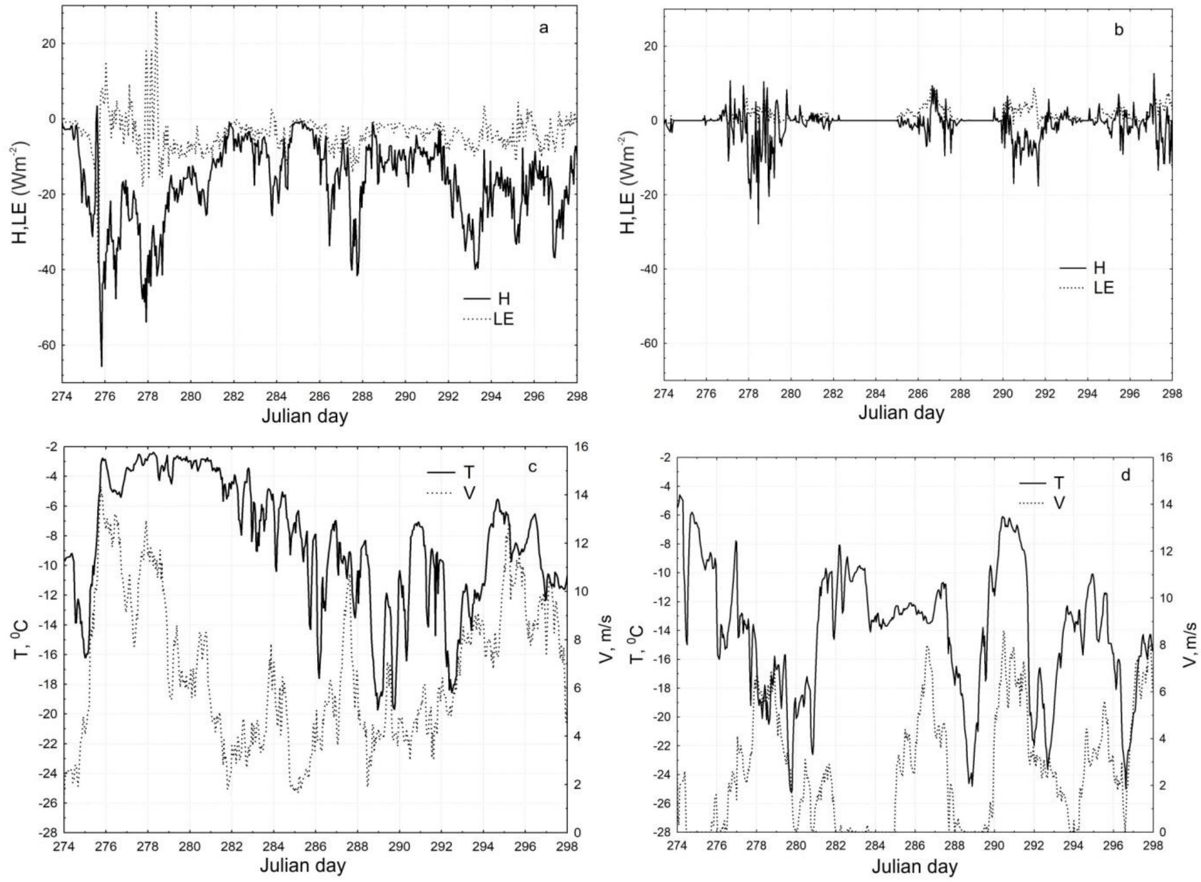

Figure 5. Turbulent fluxes of sensible and latent heat, air temperature and wind speed on October according to measurements on the drifting stations "North Pole-35" (a, c) and "North Pole-39" (b, d).

Of course, it is only a preliminary conclusion. To confirm it, more thorough analysis of all available observational data and mathematical modeling of the "atmospheric boundary layer - snow-ice cover" system, is needed. Nevertheless, the revealed intensification of the processes of turbulent energy exchange during the passage of intense cyclones must be borne in mind, especially when analyzing climate changes with monthly averaged values and extrapolating them to large areas of the Arctic Ocean.

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