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Meteorological conditions in the Arctic Ocean in spring and summer 2007 as recorded on the drifting ice station Tara

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[1] Meteorological observations were made at the drifting ice station Tara in the central Arctic Ocean from 23 March to 19 September 2007, constituting a unique data set from the season preceding the record-low sea ice extent. Comparisons of the Tara data with observations at the Russian drifting ice stations in 1937–1938 and 1950–1991 and at SHEBA in 1998 indicated that at Tara and SHEBA the atmospheric transmissivity for shortwave radiation was smaller than at the Russian stations, suggesting a higher cloud fraction or optical thickness. Compared to the mean conditions at the Russian stations, at Tara the melting season was twice as long and in April the 2-m air temperature was 7.0°C higher, but in July the 2-m temperature difference disappeared. The Tara tethersonde sounding data suggest that the air temperature at the altitudes of 200–1000 m was approximately 1°C higher than the mean of 1954–1985. **Citation:** Vihma, T., J. Jaagus, E. Jakobson, and T. Palo (2008), Meteorological conditions in the Arctic Ocean in spring and summer 2007 as recorded on the drifting ice station Tara, *Geophys. Res. Lett.*, *35*, L18706, doi:10.1029/2008GL034681.

1. Introduction

[2] The Arctic climate is rapidly changing, as diagnosed from increasing atmospheric and ocean temperatures, declining snow cover, retreating and thinning summer sea ice, and melting glaciers [*Arctic Climate Impact Assessment*, 2005]. A record low sea ice extent (since 1979 when reliable data became available) was reached in September 2005 and again in 2007 [*Comiso et al.*, 2008].

[3] Trying to understand the atmospheric factors controlling the sea ice decline, we unfortunately mostly have to rely on large-scale model results, remote sensing data, and observations from coastal and archipelago stations. Retrieval of atmospheric variables from remote sensing data is hampered in the Arctic due to the high cloud coverage and difficulties in distinguishing the signals originating from the atmosphere and ice/snow surface. The atmospheric model forecasts, analyses, and re-analyses include large errors, in particular in the near-surface wind, air temperature, air humidity, precipitation, as well as the radiative and turbulent surface fluxes [*Curry et al.*, 2002; *Tjernström et al.*, 2005]. Unfortunately, these are the meteorological variables that most directly control the sea ice growth, melt and drift. Although strongly needed, in situ meteorological observations in the Arctic Ocean have always been sparse. Since 1930s, meteorological measurements have been made on 35 Russian "North Pole" drifting stations (hereafter called as "NP stations"). Since 1979, the International Arctic Buoy Programme (IABP) has yielded regular observations on the atmospheric pressure and surface air temperature. Meteorological data have also been collected by ship cruises, aircraft experiments, and western drifting stations. The most extensive field campaign has been the Surface Heat Budget of the Arctic Ocean (SHEBA) [*Uttal et al.*, 2002] in 1997–1998.

[4] In 2006–2007 meteorological, oceanographic and sea ice measurements were made at the drifting ice station Tara [*Gascard et al.*, 2008]. The Tara expedition was a part of the European Union project DAMOCLES (Developing Arctic Modeling and Observation Capabilities for Long-Term Environmental Studies). Except for automatic buoy measurements and shorter ship cruises, the Tara expedition yielded the only in situ meteorological observations from the central Arctic in summer 2007. The previous Russian drifting station, NP-34, had finished its operations on 25 May 2006, while NP-35 started on 21 September 2007.

[5] The purpose of this paper is to present the Tara observations on meteorological conditions over the Arctic Ocean in late March through September 2007. Attention is paid to the air temperature, humidity, wind speed, as well as the shortwave and longwave radiation. These are compared against observations at SHEBA and the NP stations. The comparisons provide quantitative information on the weather conditions in the period preceding the record low sea ice cover.

2. Field Observations

[6] Observations on the near-surface air temperature, humidity and wind were made at 31 NP stations in 1937–1938 and from 1950 to 1991 [*Arctic Climatology Project*, 2000]. Downward and reflected solar radiation and net radiation (shortwave and longwave) were measured at 15 ice stations from 1968 to 1991, but longwave radiation was not measured separately. Rawinsonde soundings of the vertical profiles of wind, temperature and humidity were made at 19 ice stations in 1954 to 1990. The data from NP-32 – NP-35 in 2003–2008 were not available for this study. The SHEBA observations utilized are the near-surface measurements on the wind, air temperature, air humidity, the shortwave and longwave radiative fluxes, and rawinsonde soundings.

[7] The Tara drift started on 3 September 2006. Some meteorological measurements were made from September 2006 to April 2007. The continuous measurements, carried

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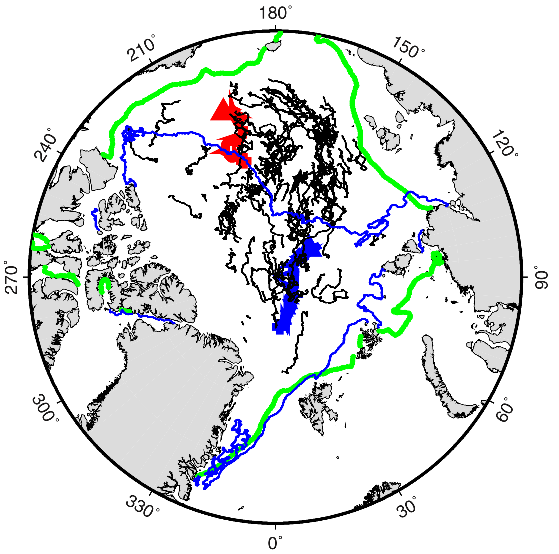

Figure 1. The drift trajectories of Tara (blue), SHEBA (red), and the NP stations (black) for the period of 23 March–19 September. The triangles mark the beginning and the crosses the end of the Tara and SHEBA trajectories. The sea ice edge on 17 September 2007 is shown as a thin blue line, and the mean September sea ice edge in 1979–1983 as a green line. The ice edge coordinates are based on the AMSR-E ASI algoritm [*Spreen et al.*, 2008].

out by TP and EJ, started on 23 March–2 April and ended on 19 September 2007. We will only address data from this period. The drift trajectories of Tara, SHEBA and the NP stations are presented in Figure 1.

[8] The air temperature and wind speed were measured at a 10-m-high weather mast (Aanderaa AWS 2700) at the heights of 1, 2, 5 and 10 m, the air relative humidity at 2 m and wind direction at 10 m. The upward and downward shortwave radiation was measured by a pair of Eppley PSP pyranometers, and the upward and downward longwave radiation by a pair of Eppley PIR pyrgeometers. A Vaisala DigiCORA Tethersonde System was used to measure the vertical profiles of the air temperature, relative humidity, wind speed, and wind direction up to the height of 2 km; the average top height of the soundings was 1240 m. In the period from 25 April to 31 August (129 days), there were 39 sounding days with a total of 95 soundings. Soundings could only be made under wind speeds lower than 15 m/s.

3. Meteorological Conditions at Tara Compared to SHEBA and the NP Stations

3.1. Near-Surface Conditions

[9] The diurnal mean values of near-surface meteorological variables are presented in Figure 2. For the NP stations, the diurnal means are averaged over the 31 stations (15 for the radiative fluxes). As most NP stations operated for more than a year, each diurnal mean is based on 64–79 diurnal data sets (39–44 for the radiative fluxes), and their standard deviation is presented for each day (Figure 2). In the following, spring is defined as the period from 23 March (or 2 April) to 8 June, summer as 9 June to 31 August (the period with the 2-m air temperature above −1°C at Tara), and fall as 1 to 19 September.

[10] Due to the differences in the station latitudes (Figure 1), until mid-April and from the end of August onwards, the intensity of the diurnal mean incident solar radiation at the top of the atmosphere (TOA) was lowest at Tara and highest at SHEBA. The maximum difference occurred on 23 March: 49 $\mathrm{Wm^{-2}}$ at Tara compared to 125 $\mathrm{Wm^{-2}}$ at SHEBA. In mid-summer, when the length of the day dominated, the situation was vice versa but the difference between Tara and SHEBA did not exceed 14 $\mathrm{Wm^{-2}}$ (3%).

[11] At Tara, SHEBA, and the NP stations, the downward solar radiation at the ice surface peaks close to the summer solstice (Figure 2a). Then the values decrease faster than they increase before the peak. The fast decrease is due to the increase in cloudiness. Filtering out the synoptic-scale fluctuations, the Tara and SHEBA data qualitatively follow the seasonal cycle of the NP data but decrease even faster towards the end of our study period. The high values at the NP stations in March–April and August–September cannot be explained by the latitude: the mean latitude of the NP stations was between those of Tara and SHEBA. The atmospheric transmissivity for shortwave radiation (the ratio of the surface to TOA solar radiation) is, however, clearly higher at the NP stations: the mean value is 0.54, while it is 0.50 for Tara and 0.49 for SHEBA (Figure 2b). The differences from the NP stations are statistically significant at 99% confidence level (S99%). Excluding the summer period, the mean values differed even more: 0.56 for the NP stations, 0.49 for Tara and 0.46 for SHEBA. This suggests a lower cloud fraction or optically thinner clouds at the NP stations compared to Tara and SHEBA. The limited cloud observations available were not enough to tell which factor was more important.

[12] We show the evolution of the surface albedo only from 12 May onwards (Figure 2c); before it the quality of Tara data was not good. Albedo differences between the stations were not statistically significant. The variability was large in the melting season, as seen as the increased standard deviation of the NP station data.

[13] The downward longwave radiation was not measured at the NP stations, but we calculated it as a residual of the net radiation, downward solar radiation, reflected solar radiation, and upward longwave radiation. In estimating the last one, we assumed that the surface temperature was 0.3°C lower than the 2-m air temperature: the number is based on SHEBA data. The results (Figure 2d) suggest largest downward longwave radiation at SHEBA (mean value for the study period 269 $\mathrm{W/m^2}$), second largest at Tara (249 $\mathrm{W/m^2}$), and smallest at the NP stations (240 $\mathrm{W/m^2}$). An inaccuracy of 1°C in the surface temperature generates an inaccuracy of 4 $\mathrm{W/m^2}$ in the downward longwave radiation. The inaccuracy of the radiation sensors, in particular the net radiometers applied in 1968–1991, may, however, be larger. Hence, bearing in mind the low latitude of SHEBA, we cannot conclude on an increase in the downward longwave radiation. The seasonal evolution of net radiation (Figure 2e) was qualitatively similar at Tara, SHEBA, and the NP stations, except that at SHEBA the July peak was more pronounced and at Tara a strong peak occurred in early May.

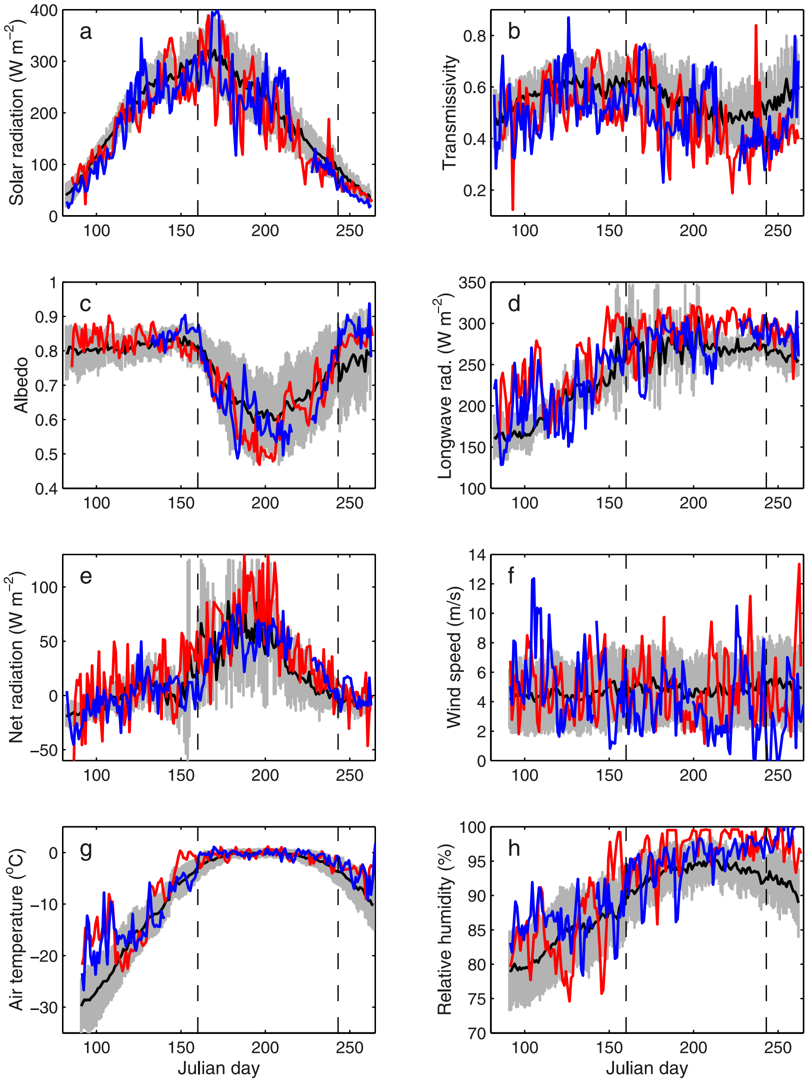

Figure 2. Time series of diurnal means of meteorological observations at Tara in 2007 (blue), at SHEBA in 1998 (red), and at the NP stations (black): (a) downward solar radiation, (b) atmospheric transmissivity for shortwave radiation, (c) surface albedo, (d) downward longwave radiation, (e) net radiation, (f) 10-m wind speed, (g) 2-m air temperature, and (h) 2-m relative humidity (with respect to water). The standard deviation of the NP station data (originating from spatial and inter-annual variations) is marked by grey error bars for each day. The dashed vertical lines separate the spring, summer, and fall as defined in the text.

[14] The 10-m wind speed averaged over the study period was 4.2 m/s at Tara and 4.8 m/s at the NP stations (difference S99%), while in summer, the mean values were 3.8 and 4.9 m/s, respectively (S99%). The seasonal evolution was different (Figure 2f): at the NP stations the winds increased towards the end of the study period, while the trend was opposite at Tara. In summer and fall, the SHEBA observations were closer to the NP than the Tara data. The Tara drift was approximately three times faster than that of Nansen's Fram [*Gascard et al.*, 2008]. Although the wind speeds were low, we found that the tailwind component favored fast drift. On the basis of the operational analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF), during years 1998–2007 in April–September the tailwind component along the Tara trajectory has been stronger only in 2005.

[15] April was 7.0° warmer at Tara than at the NP stations on average (Figure 2g, difference S99%). This is in line with the analysis of *Comiso et al.* [2008] based on the snow/ice surface temperature derived from NOAA's Advanced Very High Resolution Radiometer (AVHRR). The summer (as defined above) started on average on 29 June at the NP stations, on 9 June at Tara, and on 30 May at SHEBA. The summer ended approximately on 4 August at the NP stations and much later, in the last week of August, at Tara and SHEBA. During the Tara summer period the mean 2-m air temperature was 0.6°C higher at Tara than at the NP stations (difference S99%), but this was only due to the shorter melting season at the latter. In July, with melting also at the NP stations, the mean 2-m air temperature was −0.2°C both at Tara and the NP stations.

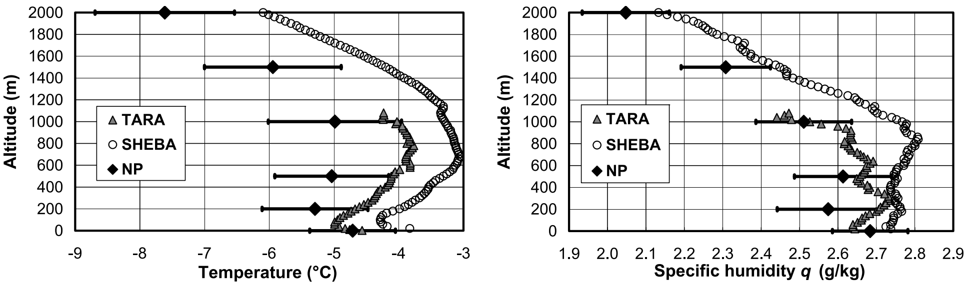

Figure 3. Mean vertical profiles of the air temperature and specific humidity in the period from 25 April to 31 August as observed at Tara in 2007, at SHEBA in 1998, and at the NP stations in 1954–1985. The error bars denote the standard deviation of the NP station data.

[16] The mean relative humidity was 92.5% both at Tara and SHEBA and 88.8% at the NP stations (difference S99%, Figure 2h). In all stations, the date when the relative humidity first exceeds 93–95% coincides with the air temperature reaching 0°C. The results from all stations support the idea of *Andreas et al.* [2002] that the near-surface relative humidity over the ice-covered Arctic Ocean is near saturation with the respect to the ice phase. At Tara the mean relative humidity with respect to ice was 98% (not shown).

3.2. Vertical Profiles

[17] The vertical profiles of the air temperature and humidity at Tara, SHEBA, and the NP stations were compared on the basis of the sounding data. The tethersonde soundings at Tara and the rawinsonde soundings at SHEBA and the NP stations were applied. The comparisons were made for the period of sounding data gathered at Tara: from 25 April to 31 August. To calculate a representative mean profile for the period, it is essential that the data are uniformly distributed in time. Hence, from the Tara data, weekly averages were first calculated, and the mean profile for the whole period was based on their average. From the NP station data, only the station seasons with continuous sounding activity from 25 April to 31 August were included in the calculation of the mean profile. This yielded 30 station seasons in 1954–1985. In SHEBA, the daily 11 and 23 UTC soundings were included in the analyses.

[18] The Tara mean profiles were calculated only up to the altitude of 1080 m; too few soundings reached higher. Due to problems in operating the tethersonde under wind speeds exceeding 15 m/s, the Tara data set is not a representative sample of the wind profile. We compared the tethersonde-based 2 m air temperature and relative humidity to the weather mast observations from the whole period of 25 April–31 August. The mean relative humidities based on the soundings and the weather mast were equal within 0.1%, but the 2 m air temperature based on the soundings was 0.35°C lower than that based on the weather mast. Hence, to allow unbiased comparisons, only cases with wind speed less than 15 m/s were included in the calculation of the SHEBA and NP station mean profiles.

[19] The mean profiles showed a temperature inversion at all stations (Figure 3). It had its base height at 70 m at Tara and 100 m at SHEBA, while the coarse vertical resolution prevents conclusions on the NP data. The inversion top was at 600–800 m both at Tara and SHEBA. At SHEBA, also the mean profile of the specific humidity included a weak inversion with the highest values measured at the height of 840 m. Throughout the lowermost 2 km the highest temperature and specific humidity were observed at SHEBA. This is related to the southernmost location of SHEBA. Throughout the lowermost 1 km the lowest temperatures were observed at the NP stations, although the mean latitude of Tara was higher. The specific humidity at Tara and the NP stations was on average close to each other, but the shape of the profile was different in the lowermost 300–400 m.

[20] Although the central location of the Tara trajectory was more northern (87.6°N, 63.8°E) than that of the NP stations (82.7°N, 173.0°E), Tara was drifting towards the Fram Strait, which is an important pathway for cyclones entering to the Arctic Ocean. Hence, it was necessary to study if the spatial differences can explain the observed differences in the temperature profiles. We calculated the seasonal (25 April to 31 August) mean air temperature and specific humidity fields on the basis of the operational analyses and re-analyses (ERA-40 and ERA-Interim) of the ECMWF. The results indicated that in the lowermost 1 km at the central location of Tara the temperature was on average 0.5°C lower and the specific humidity 0.2 g/kg lower than simultaneously at the central location of the NP stations. The gridded data set of the *Arctic Climatology Project* [2000], based on the IABP buoy and NP station observations, yields approximately similar results for the 2-m air temperature. Hence, the observed difference between Tara and the NP stations must be due to a temporal change, with a strong warming at least at the altitudes of 200–1000 m. The humidity data do not show analogous change in a thick layer, but the differences are large in the lowermost 300 m. It remains unclear, if the differences are larger than the accuracy of humidity measurements by rawinsondes in freezing conditions since 1950s.

4. Conclusions

[21] As SHEBA located further south, the most interesting comparisons were those between Tara and the NP stations. The observations indicated that the melting season in the Arctic Ocean was at least twice as long at Tara in 2007 than at the NP stations on average. This was preceded by a warm spring: 2-m air temperature in April 2007 was 7.0°C higher than the NP station mean. The July mean 2-m air temperature was equal (-0.2°C) at Tara and the NP stations. This is related to the fact that the surface and 2–m air temperatures are closely coupled via the sensible heat flux and longwave radiation [*Vihma and Pirazzini*,

2005]. If the air temperature tends to rise above 0°C, the heat will be used in melting snow and ice. If the air temperature tends to drop well below 0°C, the leads and melt ponds start to freeze, and the release of the latent heat will reduce the decrease of the air temperature. Hence the near-surface air temperature remains close to 0°C throughout the melting season, and is not a sensitive indicator for the climate change in the central Arctic, while the length of the melting season is a better indicator.

[22] The Tara and SHEBA data on the atmospheric transmissivity for shortwave radiation suggested that the cloud fraction or thickness, or both, were higher in 1998 and 2007 than at the time of the NP stations with radiation measurements (1968–1991). As the cloud radiative forcing in the central Arctic is negative only for a few weeks in midsummer [*Intrieri et al.*, 2002], the results are in accordance with the observed increase in the length of the melting season.

[23] In summer 2007 at Tara, at least at the altitudes of approximately 200–1000 m, the Arctic atmosphere was warmer than at the NP stations in 1954–1985: at the height of 500 m the difference was 0.9°C. Taking into account the mean spatial temperature gradient between the locations of Tara and the NP stations, the temporal change has probably exceeded 1°C. On the basis of the ERA-40 re-analysis, *Graversen et al.* [2008] concluded that in summers 1979–2001 the maximum climate warming in the Arctic has taken place at the altitudes of approximately 2–4 km. In the lowermost 1 km, *Graversen et al.* [2008, Figure 1c] found a summer warming of 0.1–0.3°C per decade. Accordingly, both their and our study suggest that the major Arctic warming in summer has taken place well above the ice surface. This urgently calls for more observations on the vertical structure of the atmosphere over the Arctic Ocean.

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