Evaporation from Arctic sea ice in summer during the International Geophysical Year, 1957-1958

H.K. Froyland, M.S. Town, S.G. Warren

Evaporation from Arctic sea ice in summer during the International Geophysical Year, 1957–1958

Hugo K. Froyland,[1] Norbert Untersteiner,[1] Michael S. Town,[2] and Stephen G. Warren[1]

Received 1 July 2009; revised 20 January 2010; accepted 28 January 2010; published 5 August 2010.

[1] Measurements of pan evaporation were made during the summers of 1957 and 1958 on an ice station drifting between 80° and 86°N. Using weather reports, measurements were either screened for absence of precipitation (to obtain evaporation, *E*) or not screened (to obtain *P*-*E*). Applying the screened data either to the entire month or only to the days without precipitation results in upper and lower limits to *E*. Monthly average values of *E* are positive in June and July, 3–5 and 5–8 mm/month, within the range of prior estimates, but are negative in August and September, indicating net deposition of frost or dew, at variance with prior estimates. The monthly averages of latent heat flux are small, 2–10 W m^{-2}, by comparison to the individual components of net radiation, each on the order of 100–300 W m^{-2}.

Citation: Froyland, H. K., N. Untersteiner, M. S. Town, and S. G. Warren (2010), Evaporation from Arctic sea ice in summer during the International Geophysical Year, 1957–1958, *J. Geophys. Res.*, *115*, D15104, doi:10.1029/2009JD012769.

1. Introduction

[2] Of the various contributors to the energy budget and mass budget of sea ice, the most poorly determined is the flux of water vapor. Because the atmospheric boundary layer in the Arctic often has a stable temperature profile, the ability of models to simulate the near-surface moisture flux is limited [e.g., *Tjernström et al.*, 2005]. The observation of moisture flux requires instrumentation to measure wind and humidity profiles in the near-surface atmospheric layer, or eddy-flux devices to record the turbulent fluctuations of wind and vapor pressure. Eddy-flux devices are difficult to maintain for extended periods on a drifting ice camp, and only one long-term data set of this kind has been reported [*Persson et al.*, 2002].

[3] Here we offer results from a recently recovered data set taken during the International Geophysical Year 1957–1958 at U.S. drifting Station Alpha [*Untersteiner*, 1961]. The drift track of the station is shown in Figure 1. It was manned from April 1956 to November 1958. The scientific studies conducted at Station Alpha covered a wide range of disciplines, including the heat and mass budgets of sea ice. To augment the basic observations of radiation, wind, wind profiles (for limited intervals) and ice temperature and thickness, "evaporation pan" measurements were taken during the months of June to September of 1957 and 1958. Standard meteorological measurements were made consistently for nearly the entire period the station was manned (Figure 2). A frequency distribution of weather types is shown in Figure 3.

[1]Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.

[2]Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, UJF, Saint Martin d'Hères, France.

0148-0227/10/2009JD012769

2. Methods

[4] The evaporation measurements were made by filling two Plexiglas pans, 700 cm^2 in area and 5 cm in depth, with granular ice and placing them outside, flush with the ice surface (Figure 4). The pans were weighed in an unheated hut at 12 h intervals. The necessity of carrying the pans to a windproof shelter for weighing limited the feasible size of pan. Similar experiments designed to measure sublimation of Antarctic snow used areas smaller by a factor of 4 [*Fujii and Kusunoki*, 1982] or larger by a factor of 2.5 [*Fujita and Abe*, 2006]. The exposure time was used to convert the mass changes to latent heat fluxes in W m^{-2}; the measurements are given in both units in Figure 5. The latent heat of evaporation was used for the conversion during June, July, and August, but the latent heat of sublimation was used in September because the surface temperature was usually below freezing in that month. These choices are of little consequence, since they differ by only 12%, and other sources of error are larger. In the remainder of the paper, we often use the shorthand term "evaporation" where we mean "evaporation or sublimation or both."

[5] The pans were not sheltered from above, so it was possible for precipitation to enter the pan, and blowing snow to enter or exit the pan. This resulted in large changes of mass (usually mass gains) over some 12 h periods, causing the monthly averages to indicate a substantial deposition, even during summer. The averages of all observations in Figure 5 therefore represent the net precipitation minus evaporation (*P*-*E*).

[6] Evaporation could not be measured directly if precipitation was occurring in the same 12 h period. To estimate monthly average evaporation, two extreme assumptions were used: (a) evaporation measurements made during 12 h periods without precipitation are representative of all measurement periods, including those with precipitation, or (b) evaporation

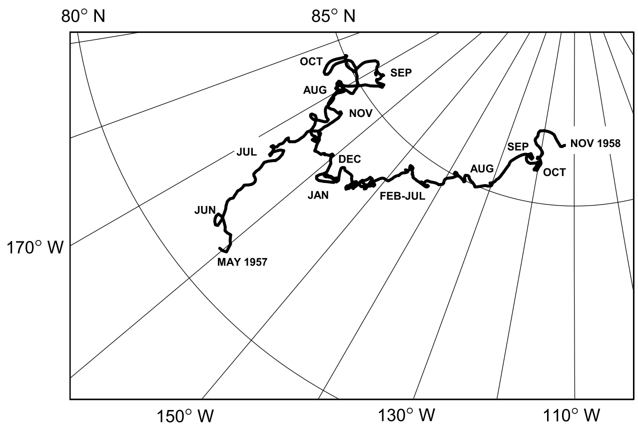

Figure 1. The drifting path of U.S. Station Alpha from April 1957 to November 1958. From *Untersteiner* [1961].

measurements made during periods without precipitation apply only to those periods; evaporation was zero on days with precipitation. We also had to account for periods missing present-weather observations, so we formed monthly averages of precipitation frequency from the available present-weather observations. Sometimes precipitation was not noted in the weather report because it was difficult to distinguish between fog and drizzle; in these cases precipitation would have been very light.

[7] Using present-weather observations reported every 6 hours as part of the routine weather report, pan measurements that occurred during precipitation could be identified; they were removed to form monthly averages by Method *a* (Table 1). Monthly averages were also calculated by Method *b* (Table 1), under the assumption that the evaporation/sublimation rate was zero during times of precipitation. The number of 12 h periods without precipitation in each month was determined from the present-weather observations. For the measurement periods without precipitation the amount of evaporation was taken to be the daily evaporation rate from the unweighted averages; for the rest of the measurement periods the evaporation rate was taken as zero. The resulting monthly averages using the two assumptions are shown in Figure 6.

[8] The total number of pan measurements made in summer months was 258, of which 88 remained after removing the measurements that could have been affected by precipitation. The number of evaporation measurements in each month was as follows: June (20), July (25), August (27), September (16). While this system eliminated many of the large depositional values, there were many evaporation measurements that indicated a net loss of mass over the exposure period, but since some precipitation was also occurring we had to exclude those measurements from the evaporation budget estimates. For July 1957, we were unable to recover any present-weather observations, forcing us to reject the entire month of evaporation measurements.

[9] There are several sources of error. An error of 1–2 g could be caused by incompletely wiping the outside surfaces of the pan. Large errors (spillage) may have occurred while carrying the pan to the shelter where the scale was located; this is the likely explanation for the few cases where the two pans disagreed markedly in their mass loss. After applying all filter criteria, the mean absolute mass difference between the two pans was 3.9 g; this implies that the uncertainty of an individual measurement is 7.0 g (one standard deviation). The uncertainty of the monthly average is then the standard error of the mean, determined by uncertainty of an individual observation together with the number of observations in a month. It is about 1 W m^{-2} or 1 mm/month (Table 1).

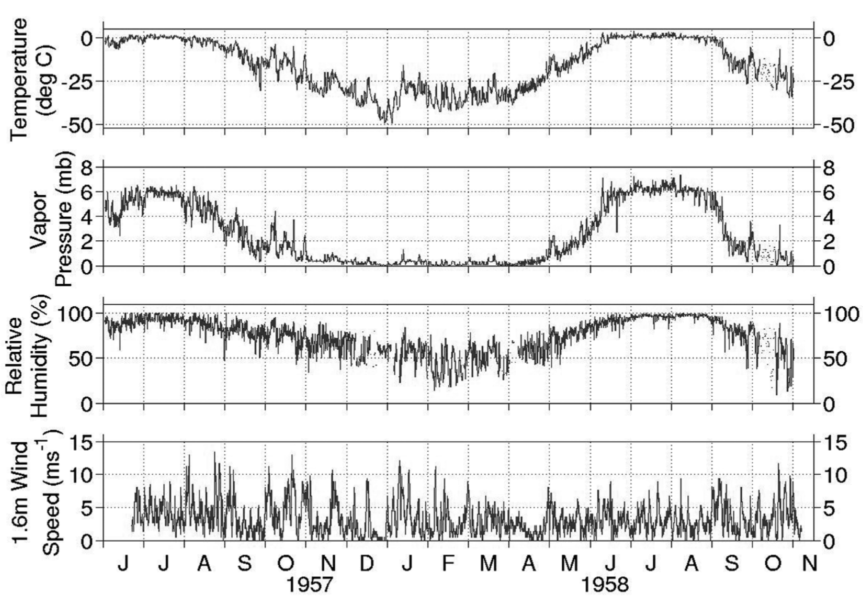

Figure 2. Time series of meteorological variables from June 1957 through November 1958. The variables plotted are temperature, vapor pressure, relative humidity with respect to water, and wind speed at a height of 1.6 m. The sampling interval was 1 h for wind measurements and 3 h for temperature, vapor pressure, and relative humidity.

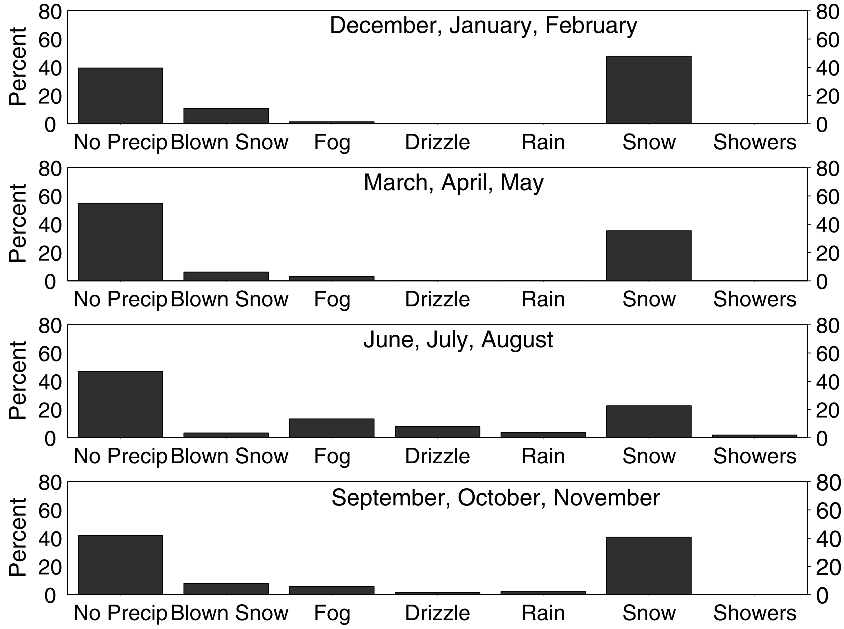

Figure 3. Frequency of occurrence of weather types, from the present-weather code reported every 6 h. The data from April 1957 to November 1958 were grouped into four seasons, irrespective of year. Number of observations was 347, 452, 570, and 579 for DJF, MAM, JJA, and SON, respectively.

[10] Drifting snow might cause additional errors, but was not a significant concern for this data set, because there was practically no drifting snow during summer; the pan measurements had to be terminated when drifting began in September. The average wind speed was 2.4 m/s, well below the threshold for blowing snow, which is ~6 m/s. Rejecting observations made during high wind (>5 m/s) resulted in monthly averages that differed from the values in Table 1 by 10%, 2%, 2%, and 0% for June, July, August, and September, respectively.

3. Results

3.1. This Work

[11] The monthly evaporation averages from this work are presented in Table 1 along with other published sources. For June and July our averages agree with published estimates on the sign of *E*, indicating net evaporation, but the magnitudes we obtain are smaller: we obtain 3–5 mm/month in June and 5–8 mm/month in July, compared to 10.3 and 7.3 mm/month, respectively, for the means of the published estimates. The monthly averages from this work for August and September indicate there is net deposition in these months, at the rates of 2–5 mm/month in August and 2–4 mm/month in September, exceeding the estimated uncertainty of 1.2–1.5 mm/month. By contrast, the published estimates for August and September indicate net evaporation.

[12] We estimate monthly average precipitation (*P*) by adding evaporation (*E*) from Figure 6 to the *P*-*E* values in Figure 5. Tables 2 and 3 compare our values to other published estimates for *P* and *P*-*E*, respectively. The monthly totals of *P* for June and July are similar to other estimates, while August and September are smaller than what others found. The low estimates for August and September are consistent with the negative *E* values in our evaporation estimate.

3.2. Discussion of Other Estimates

[13] The values listed in Tables 1 and 2 come from a variety of methods. The primary methods for estimating latent heat flux over Arctic sea ice in existing sources were (1) to take direct measurements, (2) to use an equation based on horizontal wind speed applied to humidity, or (3) to employ an atmospheric model forced by meteorological measurements.

Figure 4. A pan filled with crushed ice was used to take sublimation/evaporation measurements. The pan is about 700 cm^2 in area and about 5 cm deep, made of Plexiglas. The pans were placed so that the top of the rim was flush with the snow or ice surface, and weighed before and after a 12 h exposure.

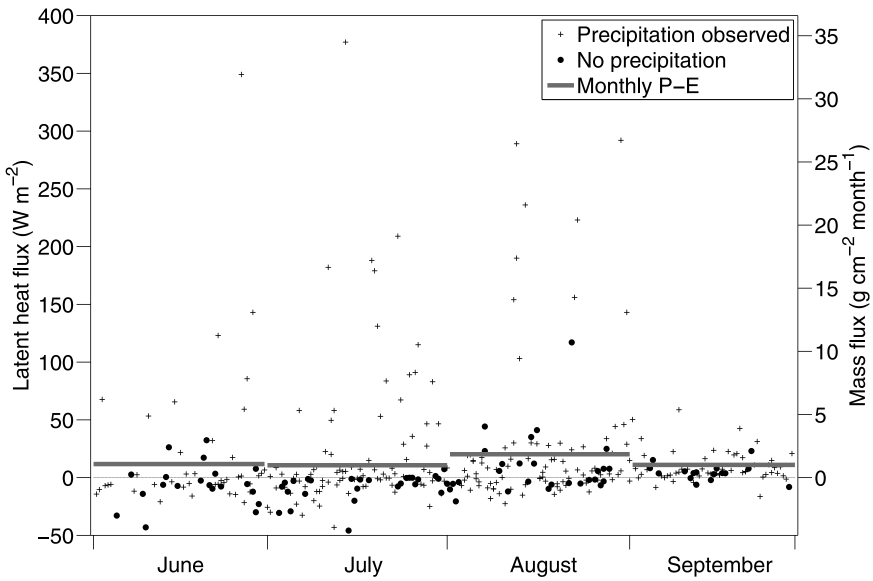

Figure 5. All 12 h pan measurements and monthly averages of the moisture budget during the summers of 1957 and 1958. The pluses indicate that precipitation was reported during a pan measurement; these values are not included in the monthly evaporation averages. The solid circles indicate that no precipitation was observed during a pan measurement. Positive values indicate precipitation or deposition; negative values indicate net sublimation/evaporation. The solid bars represent the monthly mean moisture flux.

[14] The values of *Radionov et al*. [1997] were measured with a two-tier Plexiglas tray; the upper tray had a perforated bottom that allowed the water to drain into the lower tray. The trays were weighed before and after an exposure of 2–6 h. Measurements using that device were made in 1958 on station North Pole 6 (NP-6) and in 1976 on station NP-22.

[15] Doronin (cited by *Fletcher* [1965]), *Badgley* [1966] and *Khrol et al.* [1996] used available meteorological observations from NP stations to calculate the latent heat fluxes using a "bulk" transfer formula, based on the difference in water vapor mixing ratios at two levels. *Lindsay* [1998] calculated the latent heat flux using the 2 m relative humidity measured at NP stations and a surface humidity estimated from the modeled skin surface temperature at saturation. *Jordan et al*. [1999] used SNTHERM, a one-dimensional energy and mass balance model to determine latent heat fluxes from data collected at Station NP-4.

[16] The SHEBA estimates [*Persson et al.*, 2002] are either eddy-covariance measurements or bulk estimates, depending on the level of data acquisition at the time of the observation. Eddy covariance data were obtained using a single fast response hygrometer at a height of 8.1 m and a sonic anemometer at 8.9 m. The months of June and July had data recovery rates of about 75%, while August and September had much lower rates, about 35% and 25% respectively.

[17] Precipitation was measured at all the NP stations with a gauge about 2 m above the surface, and such data were the basis for analyses by *Radionov et al*. [1997], *Khrol et al.* [1996], *Vowinckel and Orvig* [1970], *Colony et al*. [1998], and *Yang* [1999]. *Colony et al*. [1998] estimated monthly precipitation using daily observations with a correction for wetting losses. *Yang* [1999] removed biases from the NP data set caused by trace precipitation, wetting losses, and wind-induced undercatch. *Jaeger* [1976] and *Legates and Willmott* [1990] estimated precipitation throughout the world oceans by correlating ship-based present-weather reports (drizzle, rain, snow) to precipitation measurements at land

Table 1. Monthly Evaporation Averages Compared to Those From Other Sources[a]

Source	June	July	August	September	Method
This work, Method a	5.1 ± 1.4	8.3 ± 1.2	−4.6 ± 1.2	−4.2 ± 1.5	Days without precipitation represent all days
This work, Method b	3.2	5.3	−2.5	−1.9	Evaporation assumed zero on days with precipitation
Radionov et al. [1997]	10.1	9.2	5.7	4.1	Pan measurements NP-6 (Method a)
Radionov et al. [1997]	13.0	10.0	3.0	4.0	Pan measurements NP-22 (Method b)
Radionov et al. [1997]	14.0	11.0	7.0	3.0	Bulk calculation (Method c)
Persson et al. [2002]	6.2	1.0	1.7	0.5	Bulk flux calculation, SHEBA
Jordan et al. [1999]	15.8	8.2	8.5	2.3	Bulk flux calculation, NP stations
Lindsay [1998]	9.4	6.2	6.3	3.6	Bulk calculation, NP-4
Khrol et al. [1996]	11.0	7.0	8.0	4.0	Bulk calculation, NP stations
Badgley [1966]	8.3	4.4	0.6	−3.3	Bulk calculation, NP stations and Station Alpha
Doronin, quoted by *Fletcher* [1965]	10.3	9.5	9.8	5.8	Bulk calculation, NP stations

[a]Evaporation (E) averages are in mm/month.

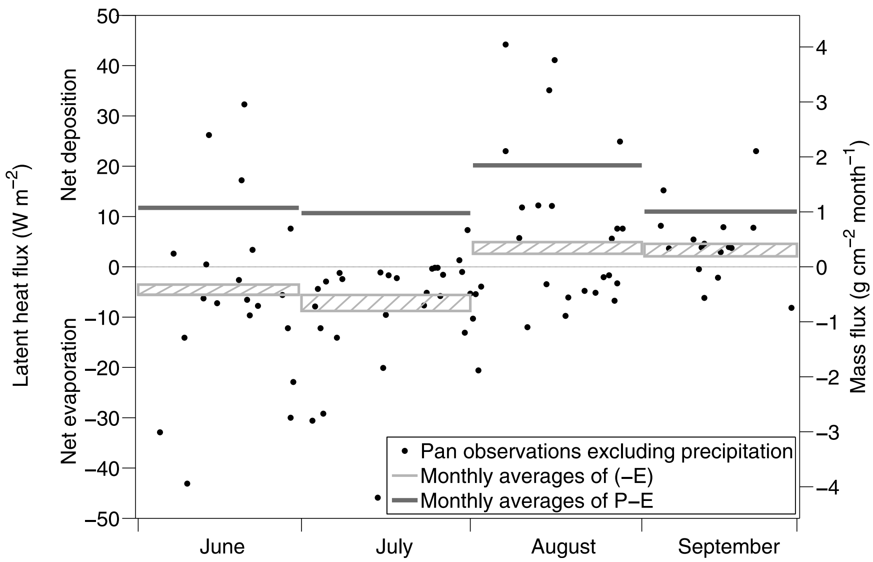

Figure 6. Pan observations made in the absence of precipitation, along with monthly averages of evaporation (boxes) and *P-E* monthly averages (bars), based on data from both 1957 and 1958. The shaded boxes indicate the range between the monthly averages computed by methods a and b. The averages from method a, assuming that evaporation on days without precipitation can represent all days, are the side of the box of greater magnitude for all months. One outlier (117 W m^{-2} in August) (see Figure 5) is beyond the range of this plot. We think the outlier is spurious, so we excluded it from the August average.

stations. A similar method was used by *Khrol et al.* [1996] for the NP data set.

[18] The differences among the various data sets are particularly large for precipitation (Table 2). As has been noted by others, snow precipitation is notoriously difficult to measure. Given that the estimates in Table 2 come from a diversity of studies, comparing areal means to single stations, long-term data to short-term data, and different methods of analyses, it is not surprising to see the large spread of estimates.

4. Conclusions

[19] Net evaporation occurred in June and July, at the rate of 3–8 mm/month, and net deposition occurred in August and September. The corresponding values of latent heat flux, with magnitudes less than 10 W m^{-2} in all months, are small compared to the individual components of net radiation, each on the order of 100–300 W m^{-2} [*Intrieri et al.*, 2002].

[20] The monthly averages of latent heat flux in general display more positive values than those of prior publications (note: latent heat flux will have an opposite sign as the evaporation/deposition values presented in Table 1). In other words, latent heat fluxes indicate small evaporation values or relatively large deposition values in the four months presented here. The cause may possibly be attributed to climatic variation of atmospheric conditions during the past 50 years. As outlined by *Maykut and Untersteiner* [1971], the thickness of sea ice can greatly affect heat fluxes, including latent heat. However, we are reluctant to attribute the difference to climatic change, because of the numerous sources of error in the various methods used to estimate evaporation. A possible contributor to the discrepancy is our method used to filter the data set, removing the evaporation

Table 2. Monthly Precipitation Averages[a]

Source	June	July	August	September	Method
This work	15.8	18.4	14.5	5.9	From *P-E*, using *E* from pan measurement, Method a
This work	14.0	15.4	16.6	8.1	From *P-E*, using *E* from pan measurement, Method b
Sturm et al. [2002]	13.4	35.2	28.1	12.9	Nipher shielded gauge system (corrected)
	7.0	23.3	13.0	6.4	Nipher shielded gauge system (measured)
Serreze and Hurst [2000]	32	35	28	24	NCEP Reanalysis using NP stations and *Legates and Willmott* [1990]
Serreze and Hurst [2000]	18	22	24	25	ERA Reanalysis using NP stations and *Legates and Willmott* [1990]
Yang [1999]	17.2	27.5	29.0	31.5	NP stations, with bias corrections
Colony et al. [1998]	12.0	22.0	20.0	19.5	Gauge measurements, NP stations
Radionov et al. [1997]	15.0	24.0	25.0	23.0	Gauge measurements, NP stations
Khrol et al. [1996]	11.0	18.0	20.0	18.0	Frequency distribution of precipitation, NP stations
Jaeger [1976], 85°–90°N	4.5	5.2	6.9	18.6	Frequency distribution of precipitation types (rain, drizzle, snow)
Jaeger [1976], 75°–85°N	14.0	19.3	22.2	24.4	
Vowinckel and Orvig [1970]	7.1	17.7	16.8	11.5	NP stations and Station Alpha

[a]Precipitation (*P*) averages are in mm/month.

Table 3. Monthly Averages of P-E From Different Sources[a]

Source	June	July	August	September	Method
This work	10.7 ± 0.9	10.1 ± 0.9	19.1 ± 0.6	10.1 ± 0.7	Pan measurement
Radionov et al. [1997]	2.6	13.9	19.8	19.3	from Tables 1 and 2
Khrol et al. [1996]	0	11	12	14	NP stations, frequency distribution of precipitation types

[a]Monthly averages are in mm/month.

measurements that were made during precipitation or other weather that would inhibit a reliable measurement. Assuming the present-weather data were accurate, this system should have accounted for all the positive 12 h fluxes in the data analyzed here that were too large to have been caused by condensation/deposition. The fact that some large positive fluxes remained indicates that there are some inconsistencies with either the measurement system or the present-weather reports.

[21] **Acknowledgments.** William J. Campbell and Arnold M. Hanson assisted with the data collection, and Franklin I. Badgley performed some of the initial analysis. We thank Ryan Eastman for obtaining the weather reports from Station Alpha, and Thomas Grenfell for translating Khrol's atlas from Russian into English. We thank Richard Brandt for drafting Figure 1. Three reviewers provided helpful comments. The research was supported by the NASA Space grant, by NSF grant ARC-06-12636, and by the Centre National d'Etudes Spatiales (CNES) as part of the THORPEX/IPY CONORDIASI program.

References

Badgley, F. I. (1966), Heat budget at the surface of the Arctic Ocean, in *Proceedings from the Symposium on the Arctic Heat Budget and Atmospheric Circulation*, *Res. Mem. RM-5233-NSF*, edited by J. O. Fletcher, pp. 267–278, Rand Corp., Santa Monica, Calif.

Colony, R., V. Radionov, and F. J. Tanis (1998), Measurements of precipitation and snow pack at Russian North Pole drifting stations, *Polar Rec.*, *34*, 3–14, doi:10.1017/S0032247400014923.

Fletcher, J. O. (1965), The heat budget of the Arctic Basin and its relation to climate, *Tech. Rep. R-444-PR*, Rand Corp., Santa Monica, Calif.

Fujii, Y., and K. Kusunoki (1982), The role of sublimation and condensation in the formation of ice sheet surface at Mizuho Station, Antarctica, *J. Geophys. Res.*, *87*, 4293–4300, doi:10.1029/JC087iC06p04293.

Fujita, K., and O. Abe (2006), Stable isotopes in daily precipitation at Dome Fuji, East Antarctica, *Geophys. Res. Lett.*, *33*, L18503, doi:10.1029/2006GL026936.

Intrieri, J. M., C. W. Fairall, M. D. Shupe, P. O. G. Persson, E. L. Andreas, P. S. Guest, and R. E. Moritz (2002), An annual cycle of Arctic surface cloud forcing at SHEBA, *J. Geophys. Res.*, *107*(C10), 8039, doi:10.1029/2000JC000439.

Jaeger, L. (1976), *Monatskarten des Niederschlags für die ganze Erde, Ber. Dtsch. Wetterdienstes*, vol. 18, 38 pp., Im Selbstverlag des Dtsch. Wetterdienstes, Offenbach, Ger.

Jordan, R. E., E. L. Andreas, and A. P. Makshtas (1999), Heat budget of snow-covered sea ice at North Pole 4, *J. Geophys. Res.*, *104*, 7785–7806, doi:10.1029/1999JC900011.

Khrol, V., N. Bryazgin, and L. Burova (1996), *Atlas of the Water Balance of the Northern Polar Area*, 97 pp., Gidrometeoizdat, Saint Petersburg, Russia.

Legates, D. R., and C. J. Willmott (1990), Mean seasonal and spatial variability in gauge-corrected, global precipitation, *Int. J. Climatol.*, *10*, 111–127, doi:10.1002/joc.3370100202.

Lindsay, R. W. (1998), Temporal variability of the energy balance of thick arctic pack ice, *J. Clim.*, *11*, 313–333, doi:10.1175/1520-0442(1998)011<0313:TVOTEB>2.0.CO;2.

Maykut, G. A., and N. Untersteiner (1971), Some results from a time-dependent thermodynamic model of sea ice, *J. Geophys. Res.*, *76*, 1550–1575, doi:10.1029/JC076i006p01550.

Persson, P. O. G., C. W. Fairall, E. L. Andreas, P. S. Guest, and D. K. Perovich (2002), Measurements near the Atmospheric Surface Flux Group tower at SHEBA: Near-surface conditions and surface energy budget, *J. Geophys. Res.*, *107*(C10), 8045, doi:10.1029/2000JC000705.

Radionov, V. F., N. Bryazgin, and E. I. Alexandrov (1997), The snow cover of the Arctic Basin, *Tech. Rep. APL-UW 9701*, chap. 2 and 3, Appl. Phys. Lab., Univ. of Washington, Seattle.

Serreze, M. C., and C. M. Hurst (2000), Representation of mean arctic precipitation from NCEP-NCAR and ERA reanalyses, *J. Clim.*, *13*, 182–201, doi:10.1175/1520-0442(2000)013<0182:ROMAPF>2.0.CO;2.

Sturm, M., J. Holmgren, and D. K. Perovich (2002), Winter snow cover on the sea ice of the Arctic Ocean at the Surface Heat Budget of the Arctic Ocean (SHEBA): Temporal evolution and spatial variability, *J. Geophys. Res.*, *107*(C10), 8047, doi:10.1029/2000JC000400.

Tjernström, M., et al. (2005), Modeling the arctic boundary layer: An evaluation of six ARCMIP regional-scale models using data from the SHEBA project, *Boundary Layer Meteorol.*, *117*, 337–381, doi:10.1007/s10546-004-7954-z.

Untersteiner, N. (1961), On the mass and heat budget of arctic sea ice, *Arch. Meteorol. Geophys. Bioklimatol., Ser. A*, *12*, 151–182, doi:10.1007/BF02247491.

Vowinckel, E., and S. Orvig (1970), The climate of the North Polar Basin, in *Climates of the Polar Regions*, *World Surv. of Climatol.*, vol. 14, edited by S. Orvig, pp. 129–252, Elsevier, New York.

Yang, D. (1999), An improved precipitation climatology for the Arctic Ocean, *Geophys. Res. Lett.*, *26*, 1625–1628, doi:10.1029/1999GL900311.

H. K. Froyland, N. Untersteiner, and S. G. Warren, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195-1640, USA. (sgw@atmos.washington.edu)

M. S. Town, Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, UJF, F-38402 Saint Martin d'Hères CEDEX, France.