HEAT BALANCE AT THE SURFACE OF THE ARCTIC OCEAN

By

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ABSTRACT

A resumé of available data on the components of the heat budget of the Arctic Ocean surface shows that radiative interchange with environment is the dominant factor. The presence or absence of an ice cover influences the nature of this interchange and also the relative importance of evaporation to the heat budget. On the basis of these figures a conjecture is made as to the course of events in the event of the artificial removal of the ice cover. It is shown that the ice would re-establish iteself under presently existing conditions.

INTRODUCTION

Starting with the voyage of the Fram in 1893 - 1896 and continuing to the present there have been at least sporadic measurements of those physical variables (meteorological, oceanographic and radiative) which determine the heat balance of the Arctic Ocean. The Russians began their systematic work with floating North Pole stations in 1937 and have continued work at each of their floating stations up to N.P. 9 at the present time. There have been four U. S. floating ice stations starting with "Fletcher Ice Island" which has been occupied several times during its known existence and has been variously called "T-3" and "Bravo". Station Alpha was established in 1957, Charlie in1959, and ARLIS I in 1960. The thick ice of T-3 does not lend itself to heat budget studies but the other American stations have been used for this purpose. In the following sections data from both Russian and American sources have been used.

The measurements do not agree in all details but they are in general agreement and in the following an attempt will be made to resolve what differences do appear.

Most of the Arctic Ocean is ice-covered but there is an appreciable amount of open water and the responses of these two differing surfaces to their environment are appreciably different. Most of the measurements have been made over ice so much of the over-water information must be inferred.

In treating the heat budget of the ice covered ocean surface we will consider the entire thickness of the ice. One of the questions to be answered is whether this will increase or decrease with time. In treating a water surface we will consider the upper layers only and one of the questions is whether or not an ice cover will begin to form.

Components of the Heat Budget

The components to be treated are, in order, (1) visible radiation (2) infra-red radiation, (3) conduction from surface to air, (4) latent heat transferred from surface to air or vice-versa by evaporation or condensation (5) heat conducted from the ocean towards the surface. In the case of the ice surface it will be necessary to consider the energy stored in the melt water and liberated when this water freezes

(1) The visible radiation which originates in the sun may reach the surface of the ocean directly or after single or multiple scattering and reflection from clouds, snow and ice. Having reached the surface it may be absorbed, transmitted, or reflected. At U. S. stations Kipp or Eppley pyranometers have been used to measure both the incoming and outgoing radiation streams. Similar devices have been employed by the Russians.

(2) Infra-red radiation is emitted from the surface, whether it be snow, ice, or water at a rate very close to that of a perfectly black body at the temperature of the surface. Some recent work (W. F. Murcray, unpublished) seems to show that when a very steep temperature gradient exists at the top of a snow layer, that the emission from that layer originates partly at levels slightly below and therefore warmer than the surface. Consequently the total radiative flux is somewhat greater than that of a black body at surface temperature. This effect will be neglected in the discussion below.

A downward flux of infra-red energy is received at the surface from the air and clouds overhead.

Either or both of these fluxes may be measured with an appropriate radiometer (Beckman and Whitley, Agmet, and Schultze radiometers have been used at U. S. Stations) alternatively the fluxes may be estimated from the temperature and emissivity of the surface and the atmosphere. Both of these methods have been used over snow and ice surfaces and give results which compare well with each other. Few actual measurements have been made over Arctic waters so only the computed estimates are available for water surfaces.

The data below come from U. S. and Russian sources and refer to the latitude belt from 82° to 86°. The figures shown in Table 1 for the infra-red balance over the snow surface are the averages for 3 or 4 years taken from instrumented measurements. Not shown are calculated values for comparable months but these agree well with the measurements. The values computed for the water surfaces of open leads were made on the hypothesis that back radiation from the atmosphere would be the same over leads as over floes. This would be badly in error for large water surfaces but not for narrow leads and small open areas.

(3) Turbulent transfer of heat (enthalpy)may be directed either away from the ice flow or downward toward the flow depending on the gradient of temperature. During most of the year an inversion exists over the ice and the heat flow is from atmosphere to ice.

So far as is known, no one has yet measured the fluctuation of temperature and vertical air movement near the ice surface with the speed and precision necessary for a direct determination of the turbulent heat flux. The next best method is to measure the average gradients of wind speed and temperature near the surface and from these to estimate the heat flux. Without going into details this method uses the wind gradient to establish a coefficient of eddy diffusivity analogous to the molecular thermometric conductivity. This and the temperature gradient establish an estimate of the heat flux.

A third method is an approximation to the second. It uses the wind at one level and the temperature at two levels to estimate the gradients and from these the flux is established as in the second method.

Both the Russians and ourselves have used the second and third methods. They make no statement about how precise they believe their estimates to be but they are probably no better than ours which we think are within ± 35% of the true values. The various Russian investigators do not agree between themselves. Laikhtman's estimates run several times greater than do Jakovlev's. Ours are in closer agreement with the latter's but even smaller on the average. Our disagreement with Jakovlev's figures is minor and probably due to the high average roughness length (0.5 cm) that he assumes for the flow compared to our 0.02 cm. Our disagreement with Laikhtman is a major one, however; I see no way of reconciling the two estimates and believe his to be wrong.

The estimates in Table 1 are therefore based on Jakovlev's figures for NP2 and ours for Station Alpha.

The eddy flux of heat is many times smaller than either the upward or downward stream of radiation (by a factor of 30 or more) and is even small compared to the difference between these streams, that is to the net radiative flux. It is in this latter comparison that we and Jakovlev differ from Laikhtman. He finds the eddy flux to be of the same magnitude as the net radiative flux, even exceeding it in some months. I see no way in which our results could be interpreted to coincide with this.

(4) The estimation of the energy flux associated with evaporation and condensation at the floe surface can be made in a manner quite analogous to estimations of eddy heat flux and subject to even greater uncertainties because of the difficulties of measuring the vertical gradient of water vapor. An entirely different approach is to measure the amount of evaporation or condensation occurring from a representative area of the floe. This means measuring the change of weight of a pan of known area and containing a sample taken from the surface being tested. This method is subject to quite different but just as serious uncertainties as the other,including weight changes due to precipitation, blowing snow, water leakage, and others. We do feel that our estimates are accurate to within a factor of two, that is that the real value probably lies within the range from 1/2 to 2 times the computed value for evaporation-condensation. The figures in the Table 1, should be considered as the roughest of estimates meant to show the order of magnitude.

Again we find ourselves in substantial agreement with Jakovlev whose results, however, only extend from June through October. We find Laikhtman's results for the winter period quite reasonable but for the summer period from five to ten times the magnitude of our results, although usually having the same sign.

(5) The final term to be estimated, the flow of heat from the ocean to the surface, is a small one but interesting because it maintains the same sign and presumably the same magnitude year around. At some hundreds of meters below the ocean surface the water is characteristically at a temperature of about +1°C. The top surface is at -1.7°C. Due to the ice cover there should be only minor variations in the turbulence from winter to summer.

Two methods suggest themselves for estimating this flux. In late summer the lower layers of ice become almost iso-thermal, there should be little heat conduction through it and little radiation reaching the bottom of the floe. Any wastage of the bottom then should be due to heat from the ocean.

TABLE 1

HEAT BUDGET OF ICE AND SNOW SURFACES 82°-86°N.

(+) indicates energy added to floe (-) indicates energy leaving floe

average flux in cal/cm^2 min

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
(1) Net Visible Radiation (incident minus reflected)	0	0	.014	.046	.077	.107	.087	.052	.009	0	0	0	.033
(2) Net Long Wave Radiation (incident minus emitted)	-.030	-.035	-.042	-.051	-.034	-.035	-.035	-.007	-.025	-.025	-.045	-.042	-.034
(1)+(2) Net Radiation (visible plus long wave	-.030	-.035	-.028	-.005	+.043	+ .072	+.052	+.045	-.016	-.025	-.045	-.042	-.001
(3) Turbulent Heat Flux	+.016	+.013	+.014	+.000	-.013	-.014	-.000	-.004	-.007	+.002	+.006	+.009	+.002
(4) Latent Heat Flux	0	0	0	0	-.010	-.013	-.010	-.001	+.005	+.006	+.004	+.001	-.0015
(5) Heat Flux from ocean	+.003	+.003	+.003	+.003	+.033	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003
Total	-.011	-.019	-.011	-.002	+.023	+.048	+.043	+.043	-.015	-.014	-.032	-.029	+.002

TABLE 2

HEAT BUDGET OF AN ICE FREE SURFACE (ESTIMATED 82°-86°N)

(+) indicates energy flux toward surface (-) energy flux from surface average flux in cal/cm^2min

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Net Visible Radiation (1) (incident minus reflected)	0	0	.050	.207	.382	.368	.280	.162	.054	.002	0	0	.125
Net Long Wave Flux (2) (incident minus emitted)	-.164	-153	-.222	-.160	-.086	-.035	-.023	-.029	-.134	-.159	-.216	-.291	-.139
Net Radiation (1)+ (2) (visible plus long wave)	-.164	-.153	-.172	+.047	+.296	+.333	+.257	+.133	-.080	-.157	-.216	-.291	-.014
(3) Turbulent Heat Flux	-.450	-.400	-.310	-.200	-.100	-.014	.000	-.004	-.100	-.200	-.300	-.400	-.206
(4) Latent Heat Flux	-.150	-.160	-.150	-.100	-.050	-.007	0	-.002	-.050	-.100	-.120	-.160	-.089
(5) Heat Flux from ocean	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003	+.003
Total	-.761	-.710	-.629	-.250	+.149	+.315	+.260	+.130	-.227	-.454	-.633	-.848	-.306

This wastage has been measured on U. S. Ice Station Charlie and found to be on the order of 2 cm per month in September. This is equivalent to a heat flow of .003 cal/cm^2 min.

Another approach is to look for a time when there is no wastage or freezing at the bottom surface and a linear temperature gradient in the ice near the bottom. These conditions are met in December. Estimating the conductivity of ice at $5.5 + 10^{-3}$ cal/cm sec. deg. and the temperature gradient as $2 + 10^{-2}$ deg/cm, the heat flow would be $11.0 + 10^{-5}$ cal/cm^2 sec or 6.6×10^{-3} or .006 cal/cm^{2}m.

If expressed on a hearly basis the above estimates give 1600 to 3100 calories per sq. cm per year. This is in the range suggested by Laikhtman who arrives at estimates of between 850 and 5000 cal/cm^2 year by two different methods.

Many of the figures in Table 2 are estimates and should not be taken too seriously. In any case they refer to conditions over narrow leads or small ponds in an otherwise frozen surface. Even though the estimates are crude they show that the heat loss from an open surface over the period of a year far exceeds that which occurs from a frozen surface. During all months except May, June, July, and August all cracks and ponds would tend to freeze. This jibes with the observed facts.

It has been occasionally proposed that if the present ice sheet were destroyed, that it would not spontaneously reappear and that the Arctic Ocean would remain open. This is based on the assumption that the low albedo of the open water would allow enough energy to be absorbed during the summer so that ice would not re-establish itself with sufficient thickness to be self-sustaining during the coming year or years.

The figures of Table 2 immediately raise doubts that this would be true but they cannot be said to disprove the possibility. If the ocean, or large parts of it, were free of ice many of the assumptions on which the table is based would be invalid. For example, the cloudiness and humidity would be increased, thereby changing the radiative fluxes. Changes in humidity and temperature profiles would change the turbulent fluxes of heat and momentum and the consequent changes in the temperature regime could in turn affect the larger scale circulation.

One way to reach a reasonable estimate of the over-all effect is to postulate for the winter months a purely radiative exchange between the ocean surface at about 0°C and an opaque atmospheric layer (idealized cloud layer) at some lower temperature which is to be computed. This cloud layer is to remain in quasi-equilibrium between the energy it gains and losss by radiation and that which it gains by advection from outside the arctic. This advective term remains the same as it is at present, about 10^{22} calories per year. When this computation is carried out it shows a net loss of .155 cal/cm^{2}min or 6.7×10^3 cal/cm^{2}mo. This flux is enough to remove all the excess energy supplied by the sum over a period of about 10 months. In the succeeding two months an ice cover could re-establish itself. Just how thick this might become before the next melt season is problematical but thicknesses of a meter or more could be expected. With an ordinary snow cover this thickness of ice could easily maintain itself for future seasons.

It has also been suggested that an increased flow of Atlantic water into the Arctic Ocean would dissipate the ice cover. This increased flow could conceivably occur naturally or be produced by pumping water across an artificial barrier at Bering Straits.

Although the quantitative arguments will not be presented here it may be somewhat obvious that the ice floes will approach some limiting thickness which depends on the net heat flow out the top and in at the bottom. When these two are balanced over a long period of time the ice will be in a quasi steady state. If the influx of heat at the bottom were increased, the floe would thin until a new equilibrium was reached. In order for the ice to disappear in the summer it should not be much more than 1/2 meter thick, one sixth of its present thickness. Assuming that the snow cover, which represents about 1/3 of the resistance to heat flow, would remain unchanged, this means that the total resistance to heat flow would be reduced to 4/9 of its present value. This would mean that the heat flow from the ocean should be increased by 9/4 or 2.25 times its present value, an increase of approximately .004 cal/cm^{2}min. Assuming Atlantic water were drawn in at +1°C and discharged at -1.7°C this would call for an increased flow of $2.4 + 10^8$ m^3/min; equivalent to a river a mile wide and 200 feet deep flowing at about 1 1/2 miles per minute.

The conclusion is that no artificial means is feasible to produce the desired effect. It is conceivable that some natural cause could increase the present flow by a factor of two or three and thereby cause the dissipation of the ice but this remains in the realm of conjecture.