ON THE POSSIBLE THICKNESS OF ARTIFICIAL ICE BUILT UP FOR AIRSTRIP AT SYOWA STATION, ANTARCTICA

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Abstract: The possibility has been examined of constructing an airstrip by the flooding technique near Syowa Station, Antarctica. Analysis of heat exchange at the surface of a flooded layer indicated that the duration between floodings necessary to establish a certain strength of the artificial ice can be calculated with the knowledge of the ambient conditions. From the calculated duration between floodings, the maximum possible thickness of the ice can be determined for a given period. From the meteorological data at Syowa Station, it was found that the built-up ice of about 3 m in thickness is all accumulated from May to August. The possible year-round use of an artificial ice airstrip is briefly discussed.

1. Introduction

Syowa Station is located on East Ongul Island, a small island at 39.59°E; 69.01°S. Its aircraft have been operated using airstrips prepared on an adjacent ice plate of multi-year sea ice, which remained semi-permanently since the establishment of the station in 1957. On March 17 and 18, 1980, the sea ice, on which a Pilatus Porter and a Cessna 185 were tethered, was broken and carried away by strong swells and winds generated by a low pressure system which approached the Sôya Coast. Fortunately the Pilatus Porter was recovered, but the Cessna was lost (KAWAGUCHI, 1981).

It is desirable to keep a year-round airstrip on land at Syowa Station, but it is rather difficult to construct a land airstrip, because no flat area is found on Ongul Islands, and, accordingly, a great deal of construction work would be necessary. It was hence suggested that we examine an alternative method for making a year-round airstrip available.

It was brought to our attention that the flooding technique has been employed in thickening an ice sheet or sea ice in cold regions for various construction purposes. At McMurdo Station, Antarctica, for example, an ice sheet has been thickened by successive floodings of sea water for constructing a wharf. The same method has been used in the Canadian Arctic to make artificial ice platforms to support oil drilling rigs.

Professor Masayoshi MURAYAMA, former Deputy Director of the National Institute of Polar Research, suggested that we examine the possibility of having a sea ice plate thickened so as to make it ground at a vicinity of Syowa Station. This paper puts forward an estimate of the possible thickness of the artificial ice which can be built up near Syowa Station by the flooding technique, and discusses briefly the feasibility of the year-round utilization of the artificial ice airstrip. The thickened ice could also be used as a wharf at Syowa Station.

2. Criteria for Construction

Systematic investigations on the flooding technique started in the early 1950's (*e.g.* KINGERY *et al.*, 1962; DYKINS, 1963). It was found that so called free flooding was one of the most feasible methods for thickening an ice plate artificially. Sea water is discharged onto an existing ice plate without any confinement: no bank is prepared around the area, and the water can flow freely. Distribution of the water can be controlled by periodic adjustment of the discharge direction of the pump nozzle. When the whole area is covered with the flooded water, the discharge is stopped. The water layer is then frozen gradually by natural cooling. After the water layer is solidified, the next flooding is applied. This process can be repeated until the desired thickness is reached.

The period between floodings has to be long enough to let the solidified surface ice become strong enough to satisfy a certain strength criterion. If the period is too short, the resultant ice is of poor quality. Mechanical properties of saline ice are mainly dependent on temperature for a given salinity. Since the salinity is almost constant for the artificial ice built up by successive floodings (NAKAWO and FREDERKING, 1981), the strength criterion can be expressed in terms of ice temperature. The lower the temperature is, the stronger the ice would be.

Temperature of the artificial ice changes periodically near its top surface owing to cyclic floodings of water layers. The average temperature can be represented by the temperature at a depth where the cyclic temperature variation becomes attenuated. This temperature has to be a certain value θ_c, which is called the criterion temperature, to satisfy a certain strength criterion. When sea water of liquidus temperature is frozen to form saline ice at a temperature of θ_c, some amount of heat is produced, which is called the heat of freezing, Q_F. It contains both terms of latent heat and sensible heat, and consequently depends on θ_c, *i.e.*, $Q_F = Q_F(\theta_c)$. The produced heat Q_F has to be removed from the ice to maintain the average ice temperature at θ_c. The criterion for construction, therefore, is that the period between floodings has to be long enough so that the same amount of heat as Q_F would have been removed from each flooded layer.

Heat removal from a particular flooded layer takes place at both of its surfaces toward the atmosphere and toward the underlying ice. It was shown that the latter conductive heat loss from the layer is significant and cannot be disregarded. When the next flood is applied on top of the layer, however, some amount of heat is transported by conduction from the newly flooded layer to the previous layer now under consideration (heat gain). This process is repeated by subsequent floodings, and the contribution of the conductive heat fluxes can be neglected as a whole. In addition to this heat conduction, there can be a general heat flow upward from the bottom of the ice plate, where the temperature is at the freezing point, but this general heat flow was also assumed to be negligible. The validity of this assumption will be discussed in Section 5. For examining the heat removal from a particular layer, therefore, it is sufficient to take into account the heat exchange between the atmosphere and the layer only during the period when the layer is at the top of the ice sheet, *i.e.*, after the layer is flooded and before the next lift. This period is called a (single) freezing period. Four heat flux terms are involved in the heat removal from the layer toward the atmosphere: short wave radiation flux S, long wave radiation flux L, sensible heat flux H, and latent heat flux E. All the terms are taken positive upward.

Because of the flooding technique, it is difficult to control the thickness or depth of an individual flooded layer. Observations showed that the thickness of a single layer ranged from 10 to 20 mm with an average of about 15 mm (NAKAWO, 1980). Assuming the thickness to be this average, the total heat to be removed from the layer, Q_F for meeting the requirement by the above-mentioned criterion, becomes constant for a given criterion temperature θ_c.

Suppose a water layer is flooded at the time $t=0$. The net heat flux at t toward the atmosphere, $Z(t)$ is

$$Z(t)=S(t)+L(t)+H(t)+E(t)\ . \tag{1}$$

If $Z(t)$ is positive, the total heat removed from the layer by the time t, $Q_Z(t)$ increases uniformly with time, since

$$Q_Z(t)=\int_0^t Z(t)\mathrm{d}t\ . \tag{2}$$

The next flooding can be applied when $Q_Z(t)$ becomes equal to $Q_F(\theta_c)$, which is the criterion for construction as mentioned above. In other words, the duration of a single freezing period, T, can be determined so as to satisfy the following equations.

$$Q_F(\theta_c)=Q_Z(t) \tag{3}$$

or

$$Q_F(\theta_c)=\int_0^t [S(t)+L(t)+H(t)+E(t)]\mathrm{d}t\ . \tag{4}$$

Each term of the right side of eq. (4) is a function of ambient conditions, and hence T is also a function of them since Q_F is constant for a given θ_c.

3. Estimate of the Duration of a Freezing Period

As was mentioned in the previous section, the thickness of each layer, h, is about 15 mm and cannot be controlled (this value will be used in the calculation below). The rate of construction r is, therefore, solely dependent on the duration of a freezing period, T alone, since

$$r=\frac{h}{T}\ . \tag{5}$$

With very cold weather conditions, T can be small, and consequently a large r is established. When the ambient conditions are mild, on the other hand, r would be very small or could be zero corresponding to a large T value.

The value of T can be determined by eq.(4) if S, L, H, and E are provided as functions of t for given ambient conditions. For L, H, and E, NAKAWO (1980) presented the following empirical/semi-empirical equations.

$$L=[0.15+0.21 \exp(-0.614\, t)](1-0.060 a_c^{1.2}), \tag{6}$$

in which a_c is cloud amount in tenths, and L and t are taken in MJ $m^{-2}h^{-1}$ and in h respectively. Also,

$$H=-\beta\rho_a c_p u_a(\theta_a-\theta_s), \tag{7}$$

$$E=-\beta L_e \rho_a u_a \frac{0.623}{p}(e_a-e_s), \tag{8}$$

where β is a dimensionless coefficient of heat and mass transfer, ρ_a is density of air, c_p is specific heat of air at constant pressure, u_a is wind speed, θ_a is air temperature, θ_s is surface temperature, L_e is latent heat of evaporation, p is atmospheric pressure, e_a is vapor pressure in air, and e_s is vapor pressure at the surface. The time dependence of θ_s in eq.(7) is given by

$$\frac{\theta_a-\theta_s}{\theta_a-\theta_m}=\exp(-\alpha u_a t), \tag{9}$$

in which θ_m is liquidus temperature, and α is a constant. Assuming e_s to be the saturation vapour pressure at the surface, the time dependence of e_s can also be obtained from eq.(9). Adopting the values of 4.5×10^{-3} for β, and 3.5×10^{-5} m^{-1} for α (NAKAWO, 1980), L, H, and E can be given by these equations with the data on a_c, u_a, θ_a, p, and e_a, which are available at Syowa Station.

The short wave radiation flux S is considered not to be dependent on t and would be given by

$$S=(1-\gamma)G, \tag{10}$$

where γ is the albedo, and G is the global radiation taken positive upward, *i.e.*, a negative value is placed on G. Data on G are also available at Syowa Station. The value for γ is highly dependent on surface conditions. An applied water layer is frozen at its surface very quickly, and the surface can be regarded as an ice surface rather than a water surface for most of each freezing period. The value of 0.5, an average value of γ for saline ice (ISHIKAWA *et al.*, 1982), is used in the calculation shown in the following section. This assumption would not be reasonable when snow is deposited at the surface, because the albedo of snow is much higher than of ice. Snow deposition usually takes place at Syowa Station by snow storms, during which construction work would not be possible in any event. Therefore, the effect of the snow layer was disregarded in the present calculation.

4. Possible Ice Thickness at Syowa Station

The maximum possible thickness of artificial ice M is estimated by

$$M=rP=\frac{Ph}{T}, \tag{11}$$

where r is the rate of construction, P is the period available for construction, h is

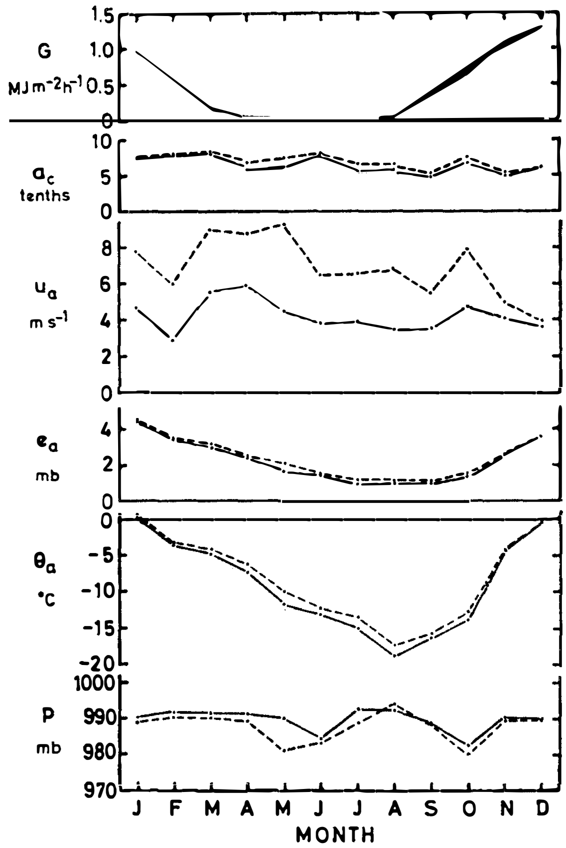

Fig. 1. Monthly mean values of meteorological data in 1980 at Syowa Station. G, Global radiation; a_c, cloud amount; u_a, wind speed; e_a, vapour pressure; θ_a, air temperature; p, atmospheric pressure. Broken lines correspond to the average for full days of each month, and solid line only for available days for construction.

the thickness of an individual layer (15 mm), and T is the duration of a single freezing period. Therefore, M can be estimated by giving a value for T. As shown in the previous section, T can be obtained from data on G, a_c, u_a, e_a, θ_a, and p.

The monthly mean values of these variables in 1980 at Syowa Station are shown by dots with broken lines in Fig. 1. Estimates of T were made for each month, using those data. Sample calculations for July are shown in Fig. 2: the time dependence of L, H, E, and Z ($G=0$ in July, and consequently $S=0$) in a and of Q_Z in b. Each flux term decreases with time as the freezing of a water layer proceeds. The integration of the net heat flux is the total heat removed from the layer by the time t, which increases with time. The construction criterion given by eq.(3) or (4) requires that the next flooding be applied when $Q_Z(t)$ reaches $Q_F(\theta_c)$. The duration of a freezing period T can thus be obtained as indicated by arrows in Fig. 2b, where θ_c is taken to be $-15°C$, $-10°C$, or $-5°C$.

Another example is given in Fig. 3 for October 1980. With the presence of negative S, Z decreases to zero at $t=2.9$ h and exhibits negative value thereafter, although its general decreasing trend is similar to that of July (Fig. 2a). After the initial increase of Q_Z, therefore, Q_Z decreases with time, having its maximum at $t=2.9$ h. The value of Q_Z never reaches either $Q_F(-15°C)$, $Q_F(-10°C)$, or $Q_F(-5°C)$. This implies that no ice can be built up in the ambient conditions in October for $\theta_c=-15°C$, $-10°C$ or $-5°C$.

It is found from similar calculations that the weather conditions from October to February are too mild to have an ice sheet thickened by the flooding technique.

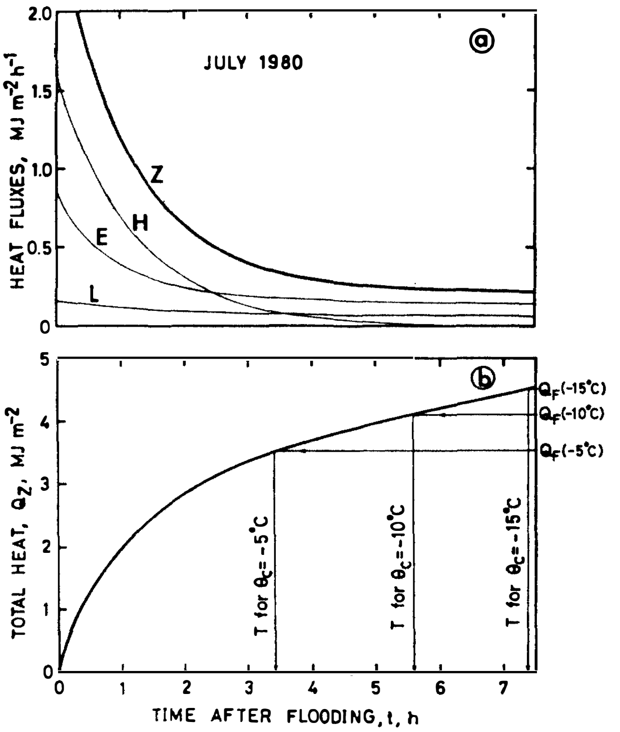

Fig. 2. Heat exchange at a flooded surface in July 1980. Z, net heat flux; H, sensible heat flux; E, latent heat flux; L, long wave radiation flux; Q_z is the integration of Z. The duration of a single freezing period T can be determined as indicated by arrows in b.

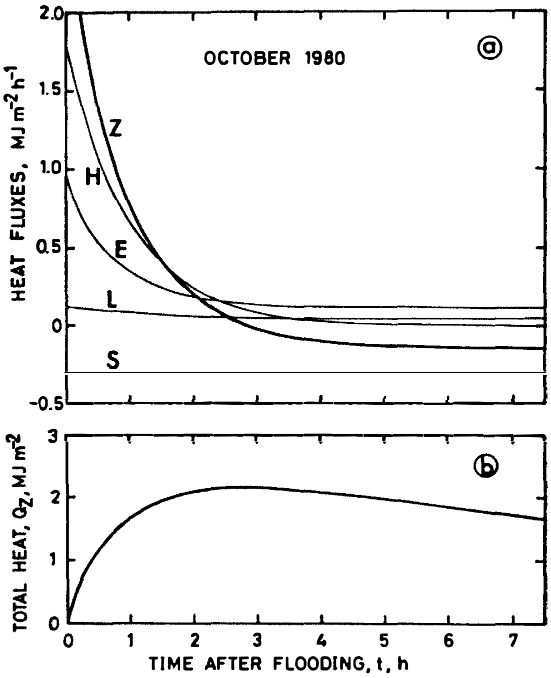

Fig. 3. Heat exchange at a flooded surface for October 1980. Z, net heat flux. H, sensible heat flux; E, latent heat flux; L, long wave radiation flux; S, short wave radiation flux; Q_z is the integration of Z.

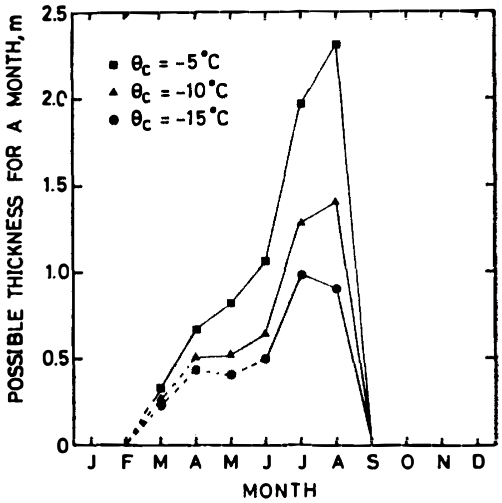

Fig. 4. Possible thickness of built-up ice calculated for each month. Calculations were done using meteorological data at Syowa Station in 1980. Data points with broken lines were discarded (see the text).

In the period from March to September, on the other hand, construction of artificial ice is possible. From the values for T obtained by the calculations for each month of the period, M was estimated from eq.(11), in which h is taken to be 15 mm and it is assumed that all of each month is employed in the construction. Taking

$\theta_c = -10$°C, for example, it is found that M ranged from 1 to 2 m for a month. The maximum possible thickness of built-up ice for a year (construction from March to September) became 6.5, 8.5, and 15.1 m for $\theta_c = -15$, -10, and -5°C respectively.

In stormy conditions, however, it is difficult to keep constructing the artificial ice. It is assumed, hence, that no construction work can be done when the daily mean wind speed exceeds 10 ms^{-1}. Excluding those days with this condition, the mean values of the meteorological variables were calculated for each month of 1980, which are presented in Fig. 1 by dots with solid lines. The number of days available for the construction (*i.e.* $u_a \leq 10$ ms^{-1}) ranged from 16 to 30 for a month.

Using those data, the possible thickness of artificial ice was estimated for each month with the procedure employed previously. The results are shown in Fig. 4. Note that no ice can be built up in September in this calculation, although the previous estimation gave a different result. By summing up the thickness in every month, the maximum possible thickness of artificial ice was obtained for a year: 3.5 m for $\theta_c = -15$°C, 4.6 m for $\theta_c = -10$°C, and 7.2 m for $\theta_c = -5$°C.

5. Discussion

As mentioned in Section 2, the general heat flow upward from the bottom of the ice sheet was neglected, although this is considered valid only for a large r. When r is small, the heat flux $Q_Z(t)$ involves the heat flow from the bottom as well as the heat of freezing of flooded water layers. This would result in underestimation of T, and consequently overestimation of M. Those are indicated by the peculiar fact that $\theta_c \leq \theta_a$, for the early months of the year, yet the calculation resulted in some ice being built up (*e.g.* 0.3 m of ice can be built up in March for $\theta_c = -15$°C, despite $\theta_a = -4.8$°C). The thicknesses estimated for those months (which are indicated by broken lines in Fig. 4) are therefore, considered incorrect, and hence have to be discarded. The maximum possible thickness, then, becomes 2.0 m for $\theta_c = -15$°C, 3.8 m for $\theta_c = -10$°C, and 6.8 m for $\theta_c = -5$°C.

The maximum possible thickness of the built-up ice was thus obtained, but it depends significantly on θ_c. The value of θ_c has to be used to find whether the appropriate strength criterion for the built-up ice can be met. The dependence of the ice strength on θ_c, however, is not yet known quantitatively. The value of -15°C was considered compatible with the value observed in the actual construction of an ice platform for oil exploration in the Arctic. This value, however, may be too conservative with regard to the strength of the ice, since the value is justified only by the fact that no accidents have occurred in the past. Furthermore, the ice platform was floating on the sea, while the airstrip now under consideration is designed to be grounded on the sea bed. The strength criterion for it, therefore, could be less than that for a floating ice platform. At a temperature higher than -5°C, the saline ice is very porous and fragile, which is mainly due to the increasing fraction of brine with temperature. It is considered reasonable, therefore, to take the value of -10°C for θ_c. Hence, it would be possible, in one winter season, to build up an artificial ice about 3.8 m thick on top of the natural sea ice.

After a snow storm, however, the deposited snow on the flooded surface, if any, has to be removed before the next flooding to avoid the formation of a weak layer. The period available for construction, therefore, could be shorter than the value (24 hours a day) employed in the calculation of the ice thickness. Consequently, the possible thickness of the artificial ice could be slightly smaller than the above estimation. It would probably be about 3 m.

Taking into account this value of the ice thickness, a potential site has to be found near Syowa Station suitable for constructing an airstrip of the artificial ice plate to be grounded on the sea bottom. If the water depth is greater, at the potential site, than the total ice thickness below the water level (total thickness minus freeboard), the ice plate cannot be grounded there within a year. One might have to construct the artificial ice, then, spending more than one winter season. For doing this, and certainly to operate the aircraft on the ice plate throughout the year, one has to examine how the ice would be during the summer.

Strong solar radiation in summer could cause the formation of puddles at the surface of the sea ice plate (*e.g.* TAKAHASHI, 1960; ENDO, 1970), which would not allow aircraft operation. By preparing the high albedo layer of chipped ice and powdered ice at the surface, however, sub-surface melting was prevented successfully (PAIGE, 1968). The compacted snow layer, which would be rather easy to be distributed over the surface, could also prevent the puddle formation. It is considered, hence, that the surface of the artificial airstrip would be well maintained rather easily even in summer.

Because of the increasing air temperature toward summer, in addition to the strong solar radiation, however, the temperature of the saline ice increases to about the liquidus temperature (*e.g.* ISHIKAWA *et al.*, 1982), which results in significant increase in brine volume of the ice. The degree of this deterioration is proportional to the salinity of the ice. Since the salinity of the built-up ice ($\sim$2%) is much higher than that of natural sea ice ($\sim$0.6%), the artificial airstrip could be suffered more than natural sea ice. At a temperature of $-2°$C, for example, built-up ice of 2% in salinity contains as much as 50% of brine by volume (ANDERSON, 1960). As the temperature increases toward summer, however, natural desalination takes place at the same time and the salinity of the sea ice decreases (*e.g.* WEEKS and LEE, 1962). When the ice temperature reaches $-2°$C, say, the salinity of the built-up ice may have already decreased substantially, and the artificial ice plate could be strong enough to be used for an airstrip. Because of the layered structure of the built-up ice, however, the desalination may not be that significant, and the ice sheet could be sponge like. It is considered essential, therefore, to investigate the desalination process caused by warming of the ice for assessing quantitatively the ice strength during summer, and hence the feasibility of utilizing the ice plate as a year-round airstrip.

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