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# HEAT BUDGET OF KONGSFJORDEN

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***Abstract:*** A method to assess the heat exchange between sea and atmosphere is presented. The calculation is based on the salt and heat budgets of the water only. The excess heat is considered to be absorbed by the atmosphere. It is applied to a Svalbard fjord, and the heat budget at the fjord surface is computed. The heat is transferred from the fjord water to the above lying atmosphere, annual mean of 23 kJ $cm^{-2}d^{-1}$.

## 1. Introduction

Heat is exchanged between sea water and air at the sea surface. Although the exchange takes place at any part of the sea on the earth, it is believed to be especially important at high latitude, where two major carriers of the global heat circulation load/unload the heat.

It is necessary to measure the heat flow through the air-ocean boundary and related elements *in situ*, in order to assess the exchange mechanisms and to evaluate the exchange amount. The measurement shall be made simultaneously at certain number of points distributed all over the area in question, and continuously over a certain period. This is generally no easy task at the sea surface, where no stable observation platform is available, and requires extensive logistic support, but the difficulties increase drastically especially in the polar region because of its poor accessibility.

While efforts are made to carry out direct measurements, a simple indirect way to estimate the exchanged heat amount with limited mean/data is sought. A method to calculate the heat as a bulk quantity is suggested in this paper. Relatively easily obtainable CTD data of the sea in question and hydrological data on the adjacent land are all this bulk method requires as input. No measurements of atmospheric conditions or phenomena at the sea surface are needed.

Particular topographic conditions, *e.g.* fjords, favor the application of this method, although it can be applied to any form of water in principle. Kongsfjorden was chosen for the pilot study, because data are already available. However, the method was not developed solely for water bodies with such limited extent as fjords. The final aim is application to a larger area such as the Arctic Sea, which presents extra difficulty in the direct measurement of heat balance due to its vast area. The present paper reports, or the extent to which the method is useful.

## 2. Kongsfjorden

Kongsfjorden is one of the large fjords on the western coast of Spitsbergen, Svalbard.

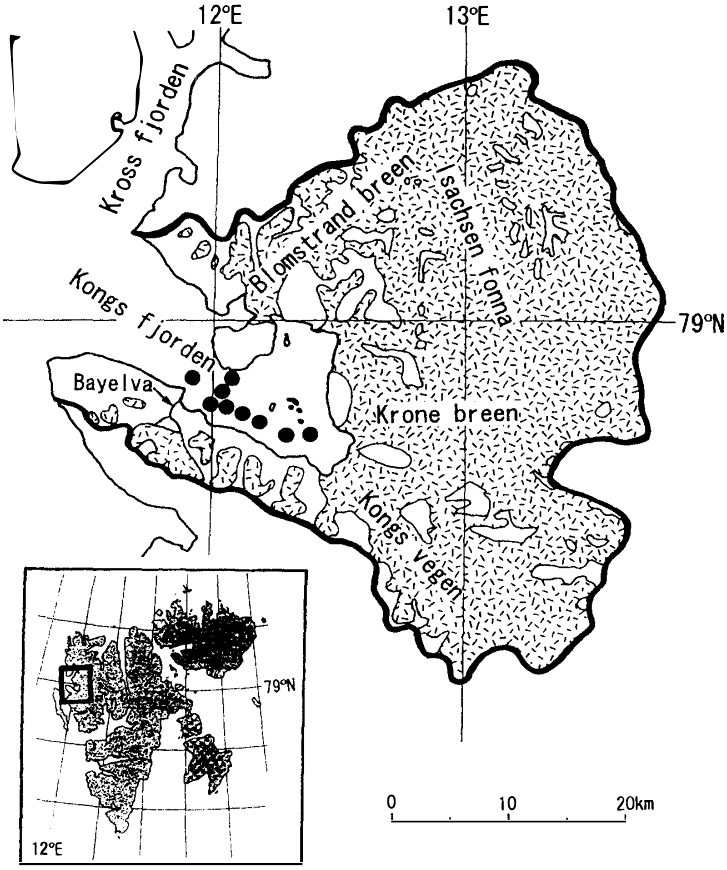

*Fig. 1. Drainage basin of Kongsfjorden. Glaciers are marked. Solid circles show the position of CTD stations in 1993.*

It is located deep in the Arctic at 79°N and 12°E (Fig. 1). It is 25 km long and 8 km wide with many small islands and runs from ESE to WNW. It joins with Krossfjorden at the mouth and then with the Greenland Sea, Atlantic Ocean. The deepest point is recorded to be 428 m a couple of kilometers to the east of the 280 m deep threshold at the exit. The surface area is 208.8 $km^2$, the volume 29.35 $km^3$ and mean depth 140.5 m. It has a drainage basin of 1016 $km^2$. The fresh water input consists of both river runoff and tidal glacier melting/calving. The tide is diurnal and the range is 2 m. The sea ice grows very little in the fjord, but many small pieces of glacier ice are found at the surface of the fjord most of the year.

## 3. Fjord Hydrology

A fjord is a river in function: all the water precipitated in the basin runs off to the sea sooner or later through the single exit, the mouth of the fjord. The 'river water' can behave quite differently through its course, in terms of interaction with the existing salt water in the fjord (Ito and Furusawa, 1992). Two extreme cases are mentioned.

In some extreme model, a fresh water river has sea water as its bed instead of rock, and has an extremely gentle slope at its lower reach. The fresh water is spread over the sea surface and flows over a sloping interface into the Atlantic. Knudsen proposed a model for this basic scheme (1900). The fjord water is kept unchanged except at the surface.

In the other extreme model, a fjord can be considered a water tank filled with sea water. As fresh water is supplied, the same amount of salt water is exported out of the fjord just as a water tank overflows. A certain amount of salt water is displaced by fresh water every year. The fjord is filled with fresh water after some years. This is the scheme used in the calculation of residence time of in-flowing fresh water.

These models neglect mixture between fresh water and sea water, and describe the fjord hydrology only to a limited extent. A one dimensional model is proposed in this article. Mixture is allowed to any extent and in any form and both extreme cases above are included as limiting cases.

In the present model (Fig. 2), fresh water coming in to the fjord, $Q_f$, is mixed with the existing salt water, $V$. The mixed water runs out of the fjord as a generalized run off, $Q_w$, different from the fresh water supply. Ocean water, $Q_i$, is taken into the fjord in compensation, so that the water level of the fjord does not change with time. The fjord runoff is divided into two parts for the purpose of computation: the same amount as the fresh water income, $Q_{wI}$, and the rest, $Q_{wII}$: $Q_w = Q_{wI} + Q_{wII}$, $|Q_{wI}| = |Q_f|$. The latter has to be supplied to keep the fjord volume constant, and is equivalent to the incoming ocean water in quantity: $|Q_{wII}| = |Q_i|$. In this model (Fig. 2 bottom), fresh water is supplied first. It is mixed with salt water in the fjord before the same amount of water runs off from the fjord. At the same time a certain amount of ocean water makes a return trip to the fjord.

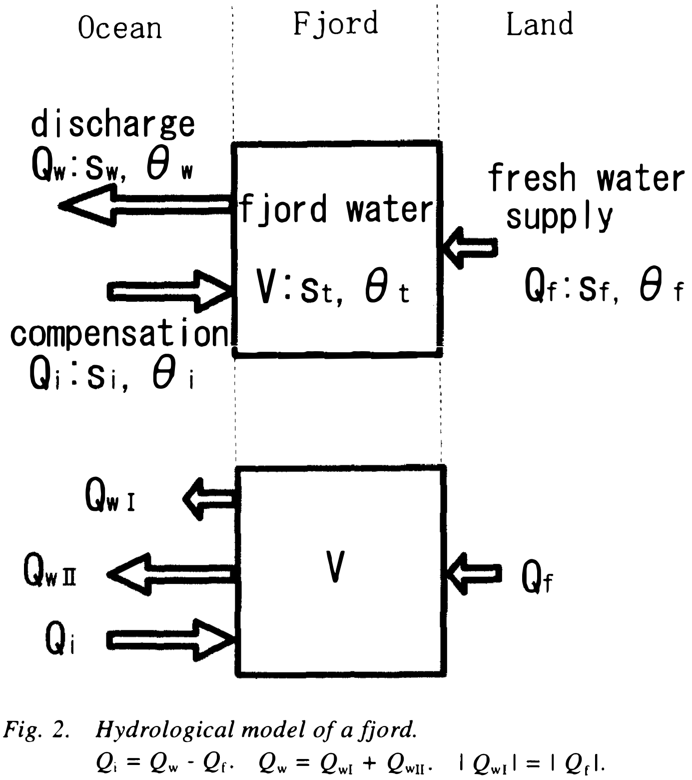

Fig. 2. *Hydrological model of a fjord.*
$Q_i = Q_w - Q_f$. $Q_w = Q_{wI} + Q_{wII}$. $|Q_{wI}| = |Q_f|$.
$|Q_{wII}| = |Q_i|$. *s : salinity. θ : temperature. Subscript, f: of fresh water, t: of fjord water, w: of discharge, i: of compensation.*

This water can also be changed in quality during the stay in the fjord. The compositions of the two out-going waters are thus kept unknown in this general model.

This model is applied more appropriately to fjords than to other water bodies for the reasons listed below. A fjord has a definite drainage basin and the fresh water income can be determined. It has a single and rather narrow exit, where the water budget can be controlled in principle. The fjord volume is great relative to the fresh water supply, so that the system is, though essentially driven by the latter, not so sensitive to its short term fluctuation. The depth is great enough, so that the deep water of the sea outside can contact the fjord water independently of what is happening near the surface.

A further assumption is made in this paper on the general model above to proceed with calculation: the water in the fjord is mixed instantaneously and completely at all the time, so that any out-going water is characterized by the mean fjord water, which is unique at a given time.

## 4. Calculation

State of water is described by temperature and salinity. Heat and salt budgets are treated separately.

Fresh water from land, $Q_f$, is assumed to contain no salt, $s_f = 0‰$. The exchange of salt between water and air at the sea surface and that between water and water through the vertical boundary at the fjord exit are assumed to be zero as well. The incoming salt water, $Q_i$, is assumed to originate from the Atlantic Deep Water, with constant salinity of 34.95‰.

The salt budget is expressed by the equation:

$$s_f Q_f dt + s_0 Q_i dt = s_t Q_w dt, \tag{1}$$

$Q_f$ fresh water supply from land,
$Q_i$ ocean water coming into the fjord,
$Q_w$ water going out of the fjord,
$s_f$ salinity of fresh water,
$s_0$ salinity of Atlantic Deep Water,
$s_t$ salinity of fjord water at time t,
$dt$ short time interval.

The total salt amount contained in the fjord at a given time can be computed from the fjord geometry and salinity profile. Mean salinity, $s_t$, is then obtained by dividing the total salt by total water. This is the salinity of the fjord discharge, $Q_w$, according to the assumption. Thus both out-going water blocks, $Q_{wI}$ and $Q_{wII}$, have common salinity value of $s_t$. Net out-going water, $Q_{wI}$, is equivalent to the freshwater income from land, $Q_f$, in amount: $|Q_{wI}|=|Q_f|$, and this value can be known from hydrological study of the basin. The salinity of the two in-coming water blocks $Q_f$ and $Q_i$ are known from the assumptions give above: 0 and 34.95‰ respectively.
Substituting these values, eq. (1) is rewritten:

$$0\,Q_f\,dt + s_0 Q_i\,dt = s_t\,(Q_f + Q_i)\,dt,$$

$$s_0 Q_i\,dt = s_t (Q_f + Q_i)\,dt. \tag{2}$$

There is only one variable, $Q_i$, left unknown and one equation. The water quantity exchanged with the outside ocean, $Q_i$, is thus obtained.

For the heat budget, similar considerations lead to the equation :

$$h_f Q_f dt + h_0 Q_i\,dt = h_t Q_w\,dt + h_a V dt, \tag{3}$$

| | |
|---|---|
| $h_f$ | heat contained in a unit volume of fresh water, |
| $h_0$ | heat contained in a unit volume of Atlantic Deep Water, |
| $h_t$ | heat contained in a unit volume of fjord water at time t, |
| $h_a$ | heat lost from a unit volume of fjord water, |
| $V$ | volume of fjord water. |

The heat contained in liquid water at 0°C is taken to be 0 for the sake of simple calculation. The mean heat contained in the fresh water supply is then estimated on this heat scale. Consideration was given to the facts, that the river discharge may be a couple of degrees above the fresh water freezing point and that calved ice pieces floating in the fjord have negative latent heat. However, the mean heat contained in the fresh water is considered to be zero because most of the fresh water supply comes directly from glacier ice melting. The Atlantic Deep Water is assumed to be at the constant temperature of 2.25°C. The heat exchange through the vertical wall at the fjord exit is also neglected here. However, the heat exchange between the air and water at the sea surface cannot be ignored, and this is unknown. Everything above the water surface including the sun is regarded as the atmosphere, so that the radiation balance is also included in the heat balance. These values are substituted in eq. (3).

$$h_0 Q_i\,dt = h_t\,(Q_f + Q_i)\,dt + h_a V dt. \tag{4}$$

Again there is one equation for one unknown, and the exchanged heat, $h_a$, radiation inclusive, can now be calculated. (All $h$'s have the same dimension formally, so that $h_a$ is not heat loss per unit area but per unit volume.)

The calculation is done with the integrated equations.

$$s_2 V = s_1 V + s_0 Q_i - s_m\,(Q_i + Q_f), \tag{5}$$

| | |
|---|---|
| $s_1$, $s_2$ | salinity of fjord water at times $t_1$ and $t_2$, |
| $s_m$ | mean salinity of fjord water (see text). |

The equation is simplified by replacing $Q_i$ by $Q_I = \int Q_i\,dt$ and then $Q_I$ is rewritten as $Q_i$. $s_m$ is introduced: $s_m \int Qdt = \int s_t Qdt$. $s_m$ is an unknown variable of time, but its value is expected to be between $s_1$ and $s_2$.

The heat equation is also integrated, where comment on the symbols given above is applicable, also to $h_a$.

$$h_2 V = h_1 V + h_0 Q_i - h_m (Q_i + Q_f) - h_a V, \tag{6}$$

$h_1$, $h_2$ heat in a unit volume of fjord water at time $t_1$ and $t_2$,
$h_m$ mean heat in a unit volume of fjord water.

## 5. Observations

Intensive hydrological observations has been made since 1991 in Bayelva basin, a major river discharging in Kongsfjorden (Kodama *et al.*, 1995). The discharge period and annual discharge are used for the current study. The discharge was detected to start in the middle of June in years 1989 through 1993, and ceased at the beginning of October. The discharge height was between 927 mm and 1266 mm with a mean of 1136 mm. The results are applied to the entire basin of 1016 km$^2$: there is fresh water income to the fjord of $1.15 \times 10^{12}$ kg in a year, which is discharged in three summer months. (Bayelva basin has only 54% of glacier cover and no tidal glacier. To which degree the basin represents the entire drainage basin of Kongsfjorden is left for future study. There is no better way of estimating basin discharge available at the moment.) Thus the estimated annual discharge is 2.9% of the fjord water, $Q_f$(year) = 0.029 $V$. The observed discharge fluctuated daily and extended over four months, with gradual increase at the beginning and decrease at the end. In the model, a constant daily discharge is assumed in the three months from the end of June to the middle of September and none in the rest of the year, for the sake of simple calculation.

The oceanographic stations were established in Kongsfjorden repeatedly in the years 1991 through 1994. The stations occupied in 1993 are plotted in Fig. 1. The stations of other years are not exactly on the same spots but cover the same area. The water temperature and salinity were measured to the bottom at intervals of 50 cm at the stations (Ushio *et al.*, 1995). The observation dates are summarized in Table 1.

The geometry of the fjord and hence the volume was measured by planimetering along the depth contours on a chart (Norwegian Polar Research Institute, 1974). The fjord was divided into five horizontal layers. Mean salinity and temperature were computed for each layer for each set of CTD measurements. They are multiplied by the

*Table 1. CTD observation and state of water.*

| Year | Nominal date | Observation date | Number of stations | Salt content (× $10^{15}$ g) | Heat content (× $10^{17}$J) |
|---|---|---|---|---|---|
| 1991a | 12 September | 10, 12, 13 September | 12 | 1.020 | 4.780 |
| 1991b | 22 September | 22 September | 7 | 1.016 | 5.216 |
| 1992 | 23 June | 23, 24 June | 10 | 1.006 | 0.342 |
| 1993a | 30 May | 29, 31 May | 8 | 1.010 | −0.543 |
| 1993b | 7 June | 7 June | 8 | 1.010 | −0.244 |
| 1993c | 14 June | 14 June | 8 | 1.011 | −0.176 |
| 1993d | 18 June | 18 June | 4 | 1.010 | 0.369 |
| 1994 | 18 June | 17, 18, 20 June | 9 | 1.008 | 1.419 |

volume of the corresponding layer and added up from the bottom to the surface to yield the total salt and heat of the fjord at the time of the CTD measurements.

*Table 2. Annual heat balance.*

| $t_1$ | $t_2$ | Period (days) | $Q_i$ (km$^3$d$^{-1}$) | Heat loss (kJ cm$^{-2}$d$^{-1}$) |
|---|---|---|---|---|
| 12/9/91 | | 365 | 15.30 | -51.019 |
| 22/9/91 | | 365 | 10.01 | -40.712 |
| 23/6/92 | | 365 | 4.73 | 18.635 |
| 30/5/93 | | 365 | 6.12 | 33.102 |
| 07/6/93 | | 365 | 6.01 | 29.535 |
| 14/6/93 | | 365 | 6.37 | 30.555 |
| 18/6/93 | | 365 | 6.12 | 23.881 |
| 18/6/94 | | 365 | 5.39 | 11.663 |
| 23/6/92 | 18/6/93 | 365 | 5.36 | 21.004 |
| 18/6/93 | 18/6/94 | 365 | 5.72 | 17.219 |

*Table 3. Seasonal heat balance.*

| $t_1$ | $t_2$ | Period (days) | $Q_i$ (km$^3$d$^{-1}$) | Heat loss (kJ cm$^{-2}$d$^{-1}$) |
|---|---|---|---|---|
| Summer | | | | |
| 26/6/92 | 12/9/91 | 90 | 119.01 | 5.915 |
| 30/5/93 | 12/9/91 | 90 | 143.24 | 33.566 |
| 07/6/93 | 12/9/91 | 90 | 141.32 | 24.627 |
| 14/6/93 | 12/9/91 | 90 | 147.24 | 23.632 |
| 18/6/93 | 12/9/91 | 90 | 143.24 | 7.206 |
| 18/6/94 | 12/9/91 | 90 | 130.80 | -21.389 |
| 23/6/92 | 22/9/91 | 90 | 105.33 | -48.163 |
| 30/5/93 | 22/9/91 | 90 | 123.94 | 17.256 |
| 07/6/93 | 22/9/91 | 90 | 122.50 | 9.701 |
| 14/6/93 | 22/9/91 | 90 | 123.94 | 8.321 |
| 18/6/93 | 22/9/91 | 90 | 123.94 | -5.525 |
| 18/6/94 | 22/9/91 | 90 | 114.50 | -29.585 |
| Winter | | | | |
| 12/9/91 | 23/6/92 | 275 | –0.45 | –0.929 |
| 12/9/91 | 30/5/93 | 275 | –0.36 | –0.834 |
| 12/9/91 | 07/6/93 | 275 | –0.37 | –0.865 |
| 12/9/91 | 14/6/93 | 275 | –0.35 | –0.868 |
| 12/9/91 | 18/6/93 | 275 | –0.36 | –0.925 |
| 12/9/91 | 18/6/94 | 275 | –0.41 | –1.024 |
| 22/9/91 | 23/6/92 | 275 | –0.30 | –0.966 |
| 22/9/91 | 30/5/93 | 275 | –0.20 | –0.849 |
| 22/9/91 | 07/6/93 | 275 | –0.21 | –0.889 |
| 22/9/91 | 14/6/93 | 275 | –0.19 | –0.896 |
| 22/9/91 | 18/6/93 | 275 | –0.20 | –0.969 |
| 22/9/91 | 18/6/94 | 275 | –0.25 | –1.097 |

The calculated total salt and total heat are also given in Table 1.

## 6. Results

Various types of calculations were done, all using eqs. (5) and (6).

If the state of the fjord is, though it fluctuates seasonally, kept constant over the long term, the state observed on a given date is identical on the same date in the next year. The steady state solution is obtained using only a single set of data. The results are given in Table 2, first half.

Unless the steady state assumption above is applied, the equations require a pair of fjord states measured at two different time points, $t_1$ and $t_2$. Furthermore, the value of $s_m$ has to be given. A different combination of two data sets requires a different type of calculation, as shown below. In all the calculations, $s_m$ is taken to be arithmetic mean of $s_1$ and $s_2$ for simplicity.

In the years 1992, 1993 and 1994 the observation dates are close to each other. Data sets of two succeeding years are used to calculate the annual heat loss. The results are also given in Table 2, second half.

Summer and winter conditions can be calculated separately, when spring data and previous/next fall data are available. The fall data are available in one year only. The fall state is assumed to be identical each year, *i.e.* 1991 September data are used as those of September 1992, 1993 and 1994. Under this assumption, the summer and winter heat budgets are calculated separately. Summer is assumed to have a constant daily discharge, and winter no discharge at all. The results are shown in Table 3.

The measurements were made repeatedly with a short interval in 1991 and 1993. The "short time calculation" was made for these years. It was not known with certainty whether the periods belong to the winter or to the summer defined above. Three cases,

*Table 4. Short term heat balance.*

| $t_1$ | $t_2$ | Period (days) | $Q_i$ ($km^3d^{-1}$) | Heat loss ($kJ\ cm^{-2}d^{-1}$) |
|---|---|---|---|---|
| With full discharge | | | | |
| 12/9/91 | 22/9/91 | 10 | 1747.06 | –179.30 |
| 30/5/93 | 07/6/93 | 8 | 1118.71 | 124.82 |
| 07/6/93 | 14/6/93 | 7 | 1320.16 | 122.47 |
| 14/6/93 | 18/6/93 | 4 | 2284.53 | 102.39 |
| With partial discharge | | | | |
| 12/9/91 | 22/9/91 | 10 | 397.29 | –42.42 |
| 30/5/93 | 07/6/93 | 8 | 273.44 | 29.18 |
| 07/6/93 | 14/6/93 | 7 | 335.12 | 30.71 |
| 14/6/93 | 18/6/93 | 4 | 543.53 | 19.43 |
| With no discharge | | | | |
| 12/9/91 | 22/9/91 | 10 | –28.34 | 0.74 |
| 30/5/93 | 07/6/93 | 8 | 273.44 | 0.98 |
| 07/6/93 | 14/6/93 | 7 | 24.50 | 1.78 |
| 14/6/93 | 18/6/93 | 4 | –5.46 | 6.73 |

with full discharge, partial discharge and no discharge, are calculated for each pair and shown in Table 4.

## 7. Discussions

### *7.1. Exchanged water mass*

Through the computation, $Q_i$ is obtained in addition to $h_a$. It may indicate to what extent the model and assumptions are appropriate.

The range of $Q_i$, the equivalent or apparent exchanged water mass, is considered. This is related to the 'real' exchanged water mass, $Q_r$, by eq. (7), where the values $s_x$ and $s_y$ are unknown for the moment.

$$(s_o - s_m)\,Q_i \;-\; s_m Q_f = (s_o - s_x)\,Q_r \;-\; s_y Q_f\,. \tag{7}$$

$Q_r$ cannot be negative, as there is no possibility to pump out Atlantic Deep Water from the fjord. The exchange can be totally stopped, hence the minimum value of $Q_r$ is zero. Maximum $Q_r$ cannot be easily evaluated, but is set to $10^1$ km$^3$d$^{-1}$ for discussion.

The minimum apparent exchange, $Q_i$, is realized when the real exchange is totally suppressed and salty fjord bottom water is drained . The minimum $Q_i$ is calculated to be close to zero. The maximum $Q_i$ is obtained when $Q_r$ is large and fresh water is returned to the ocean in exchange for Atlantic Deep Water. The maximum $Q_i$ is tens of times $Q_r$ in this case. The apparent water exchange has a rather wide range, from nil to $10^2$ km$^3$d$^{-1}$, the larger value indicating that real exchange is indeed active and the outgoing water contains little amount of salt.

### *7.2. Annual heat exchange*

The steady state assumption seems to be violated, as the 1991 data presented completely different results from other years' data (Table 2). An interpretation is that the salt balance and heat balance do not proceed simultaneously but with a delay. This disappears within a year, so that the state is maintained for a long time. However, at a certain moment of the year the time lag between the two balances can be quite large. Most probable moment for the maximum time lag to occur is at the end of summer, immediately after the active period. The September data cannot be used under the assumption of steady state. Excluding the data of 1991, the steady state calculation and annual calculations give the heat loss through 1 cm$^2$ surface in a day as 12 kJ to 31 kJ with a mean of 23 kJ. Heat loss of this amount can cool one hundred forty meters (mean depth of the fjord) of water column 0.4°C every day. Fjord water is not cooled down through this mechanism, but is only prevented from being heated. The fjord gains heat from the outside ocean. The excess heat is discharged to the air, and the water temperature is kept constant.

### *7.3. Seasonal heat balance*

The process need not be identical all through the year. Different processes can occur in winter and in summer.

In summer, calculated heat loss is scattered over a wide and unrealistic range (Table 3). This indicates that the fall state measured in 1991 may not represent the fall state in other years. (It is not certain that the September data even represents the fall of 1991. Observations in October and November are recommended for future study.) Nevertheless, some qualitative discussion is possible. The value $Q_i$ is quite large; water exchange is intensive in summer, and the water drained by the exchange is taken from the surface of the fjord rather than from the bottom. Assuming that the annual heat loss calculated above is concentrated in summer, the daily heat loss in summer is calculated to be 100 kJ cm$^{-2}$. This would imply that the heat loss is zero in winter.

In winter, the system seems indeed to be inactive. Virtually no water exchange takes place at all, and no heat is lost at the surface. A little heat gain is suggested, perhaps by freezing of the surface water, and/or by year-round fresh water supply.

### 7.4. *Short-term heat balance*

Detailed measurements can often be carried out in situ only for a short period for technical reasons. If the present method gives information for a short period, comparison with detailed study of various related elements possibly done in the future, can reveal the mechanism of heat exchange in more detail. An attempt to calculate short-term heat balance was not successful. Values of $Q_i$ are scattered over a wide range. The present bulk calculation cannot be applied to a short period heat balance, unfortunately. In a fjord, a large water body, different phenomena take place simultaneously at different points individually for a given moment. Before they interact with each other and a sort of averaged-phenomenon is build up, which requires certain length of time, a bulk treatment seems to be inadequate.

## 8. Conclusions

The method proposed in this article seems to be promising in some cases. Further pilot studies are desirable to determine under what conditions it produces useful results. Direct in situ measurements are, nevertheless, encouraged even more, as the current method works very badly under some other conditions. Kongsfjorden transfers 23 kJ cm$^{-2}$d$^{-1}$ (annual average) of heat to the air according to the calculation. The heat transfer is inactive in winter, it is concentrated in summer, when the fjord has fresh water income, with estimated value of 100 kJ cm$^{-2}$d$^{-1}$.

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