

Surface heat budget of a polynya in the coastal waters off Queen Maud Land, Antarctica, during austral summer

M. R. RAMESH KUMAR* and Y. SADHURAM*

(Received 20 October 1988; in revised form 20 March 1989; accepted 10 August 1989)

Abstract—The daily surface heat budget of a polynya in the coastal waters off Queen Maud Land, Antarctica is studied for the period from 23 December 1986 to February 1987 using the surface meteorological data collected on board the Swedish vessel M.S. *Thuleland*.

The incoming solar radiation was found to be the most important component in the surface heat budget; its mean value for the study period was found to be about 209 W m^{-2} . The latent and sensible heat fluxes were found in opposition and nearly balancing each other out. The average net heat gain over the polynya, for the study period, was 141 W m^{-2} . From the mean heat storage values obtained from the temperature profiles, the heat gain at the surface is seen to be almost lost through advection and other interior physical processes in the top 50 m layer of the water column. This is reflected in sea surface temperature which was almost steady during the study period.

INTRODUCTION

ENERGY exchange over a polynya in the coastal waters off Queen Maud Land, Antarctica was studied from 23 December 1986 to February 1987. These surface fluxes form a very important component of the regional heat budget studies and control the atmospheric circulation over the study area. Since this kind of particular regional information is not available elsewhere, the authors have made an attempt to study the heat budget of the polynya. The study area together with the bathymetry in meters is given in Fig. 1.

The observational studies of the Indian summer monsoon clearly show a significant influence of the intensity and location of Mascarene High on the performance of the monsoon. The interannual variations in the heat budget, ice cover and atmospheric circulation of the study area and surrounding oceanic regions could thus influence the Mascarene High.

DAS and DATTA (1985) have shown a possible relationship between the seasonal variation of surface temperature over Antarctica (which is related to ice cover) and the performance of the monsoon. They have examined the temperature variation over SANE ($2^{\circ}21'W$, $70^{\circ}19'S$) in Antarctica. The above station is quite close to the permanently manned Indian station, Dakshin Gangotri ($12^{\circ}00'E$, $70^{\circ}06'S$). Their study revealed the performance of the Indian summer monsoon to be good following a cold epoch over Antarctica and the reverse for the warm epoch period.

* National Institute of Oceanography, Dona Paula, Goa 403004, India.

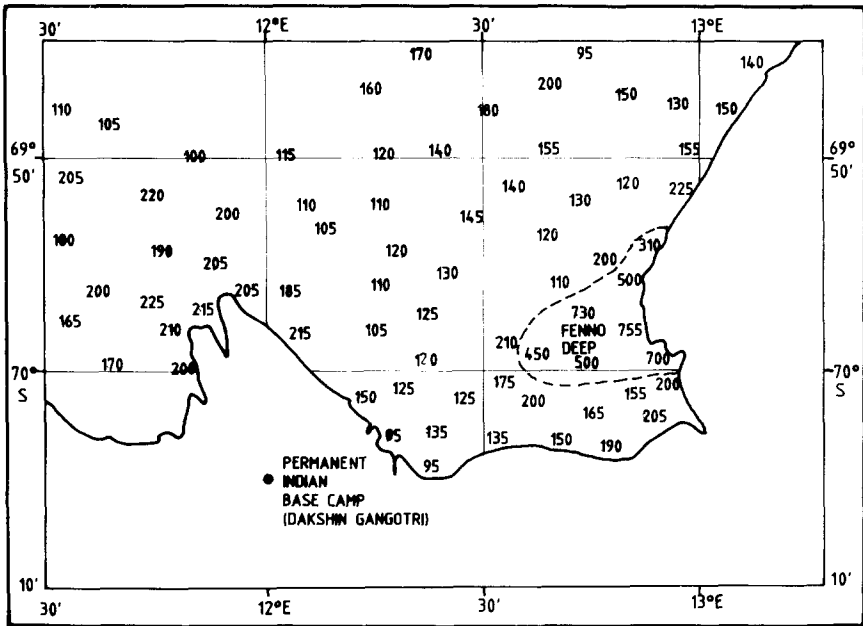


Fig. 1. Location of the study area together with the bathymetry in meters.

METHODOLOGY

The meteorological equipment used in the present study was mainly provided by the I.M.D. (India Meteorological Department) and consisted of (a) Assmann psychrometer and whirling sling psychrometer for dry and wet bulb temperatures; (b) conventional seawater bucket and mercury-in-glass thermometers, for sea surface temperature; (c) DR wind vane and anemometer, with indicator panel, for wind direction and speed; (d) conventional mercury barometer, barograph and aneroid barograph, to measure the atmospheric pressure; and (e) cloudiness and cloud type were estimated by visual observations. In addition to this, the meteorological instruments fitted on board M.S. *Thuleland* for recording surface observations were used.

To compute the energy fluxes, data on sea surface temperature (T_s), dry bulb temperature (T_a), wet bulb temperature (T_w), mean sea level pressure (SLP), wind speed (W) and direction, cloudiness (C) were collected at standard (synoptic) hours (i.e. at three hourly intervals) from 23 December 1986 to 2 February 1987 on board M.S. *Thuleland* during the sixth Indian scientific expedition to Antarctica.

The net heat gain, Q , can be obtained as

$$Q = SW - LW - Q_e - Q_s \quad (1)$$

where Q is net heat gain ($W m^{-2}$), SW is incoming solar radiation ($W m^{-2}$), LW is outgoing longwave radiation ($W m^{-2}$), Q_e is latent heat flux ($W m^{-2}$) and Q_s is sensible heat flux ($W m^{-2}$).

The formulae used for computing the various fluxes are

$$Q_e = \rho_a C_e L (q_s - q_a) W \quad (2)$$

$$Q_s = \rho_a C_h C_p (T_s - T_a) W \quad (3)$$

$$SW = Q_o (1 - aC - bC^2) (1 - \alpha) \quad (4)$$

$$LW = \varepsilon \sigma T_s^4 (0.39 - 0.056 \sqrt{Q_a}) (1 - 0.53 C^2) + 4\varepsilon \sigma T_s^3 (T_s - T_a), \quad (5)$$

where ρ_a is density of air = 1.175 kg m^{-3} , C_h and C_e are exchange coefficients for sensible and latent heat fluxes, C_p is specific heat of air at constant pressure = $1.012 \text{ kJ kg}^{-1} \text{ C}^{-1}$, T_s is sea surface temperature (in °K), T_a is air temperature in (°K), W is scalar mean wind speed (m s^{-1}), L is latent heat of vaporization = $2484 - 2.39 \times T_s$ (kJ kg^{-1}), q_s is saturation specific humidity at T_s (g kg^{-1}), q_a is specific humidity at T_a (g kg^{-1}), ε is emissivity (assumed to be 1), σ is Stefan-Boltzmann's constant = $567 \times 10^{-10} \text{ W m}^{-2} \text{ K}^4$, C is fraction of cloud cover, Q_o is short wave radiation incident on the Earth's surface on a cloudless day (from a table given in KONDRAATYEV, 1969), $a = b$ is constant = 0.38 (following BUNKER, 1976) and α is albedo = 0.06 (from PAYNE, 1972).

In the present study we have used bulk aerodynamic formulae that are commonly used by most researchers. A critical problem in their usage is the selection of exchange coefficients. BUDYKO (1958), in his estimate of the annual mean energy transfer over the world ocean, has used constant transfer coefficients. BUNKER (1976) estimated the energy balance over the North Atlantic Ocean using coefficients that are functions of atmospheric stability and wind speed, ignoring the difference between latent and sensible heat exchange coefficients. HASTENRATH and LAMB (1978, 1979) have used constant exchange coefficients for the tropical Atlantic, eastern Pacific and tropical Indian Ocean. These investigators also ignored the difference between the latent and sensible heat exchange coefficients. SMITH (1981) has computed the transfer coefficients and validated them (SMITH *et al.*, 1983) for a polynya in the Canadian archipelago. In the present study we have used a constant exchange coefficient of 1.4×10^{-3} for both the latent and sensible heat fluxes, and these values were found to be reasonable when compared with SMITH'S (1981) values.

RESULTS AND DISCUSSION

A schematic, vertical cross-section of various processes operating between the water body of the polynya and the atmosphere is given in Fig. 2 (adapted from DEN HARTOG *et al.*, 1983).

The diurnal cycle of the various surface meteorological parameters is given in Fig. 3, for 25 December 1986. The sea surface temperature does not show marked diurnal variation over the polynya. The maximum range in the variation of T_s was about 1°C for the whole study period and in the present case (25 December 1986) it was only 0.2°C . The air temperature undergoes large variations (being maximum at 1200 h), as do the other surface variables — wind speed, atmospheric pressure and cloudiness. The atmospheric pressure at mean sea level varied from 975 to 983 mb (i.e. an increase of about 8 mb in a day). The cloudiness as well as the wind speed also showed large diurnal variations. The former increased from 1 Octa in the morning to about 7 Octas in the evening, while the latter increased from 6 kn (3.1 m s^{-1}) to about 24 kn (12.3 m s^{-1}). These variations are expected as the weather over the study area undergoes sudden variations within a day. Table 1 gives the range of various surface meteorological parameters observed during the present study.

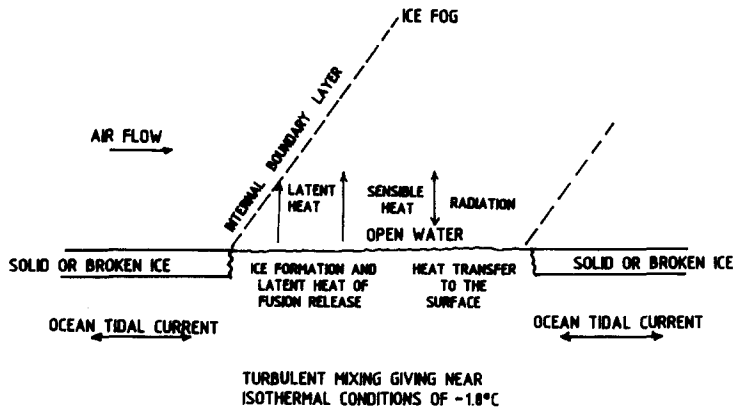


Fig. 2. Schematic diagram of the various processes in the polynya (adapted from DEN HARTOG *et al.*, 1983).

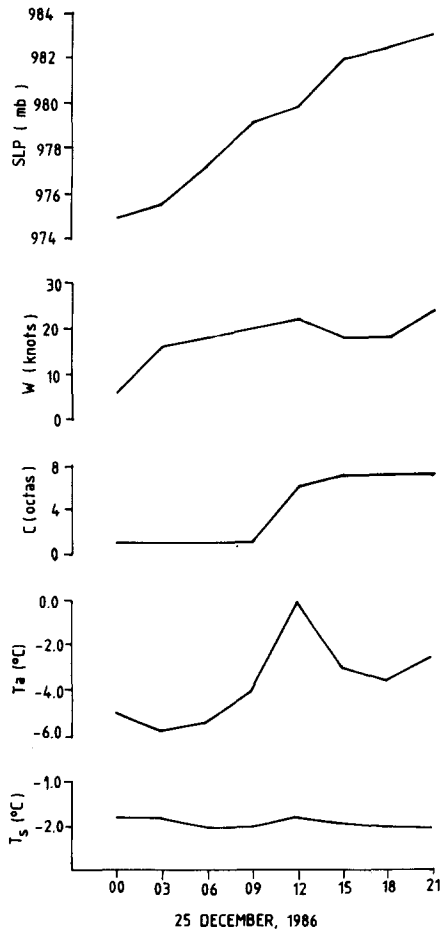


Fig. 3. Diurnal cycle of various surface meteorological parameters on 25 December 1986. SLP, mean sea level pressure (mb), W, scalar mean wind speed (kn), C, cloudiness (Octas), T_a, air temperature (°C) and T_s, sea surface temperature (°C).

Table 1. Range of meteorological parameters used in the present study

Variable	Unit	Range
T_a	°C	-6.5 to 6.7
T_s	°C	-2.0 to -1.0
T_a	°C	-4.9 to 2.0
T_d	°C	-16.4 to 0.1
$Q_s - Q_a$	g kg^{-1}	-0.1 to 1.8
W	m s^{-1}	0 to 17
C	Octas	0 to 8
SLP	mb	967.4 to 1009.6

The daily means of various surface fluxes (SW , LW , Q_e , Q_s and Q) computed are presented in Fig. 4. Among the above-mentioned parameters, the maximum variation occurs in the incoming solar radiation over the study period. Such variations can be attributed to the variations in cloud cover, which varied from 0 to 8 Octas.

The outgoing longwave radiation does not undergo similar variations, as expected, since it is mainly dependent on the sea surface temperature. The range of T_s for the study

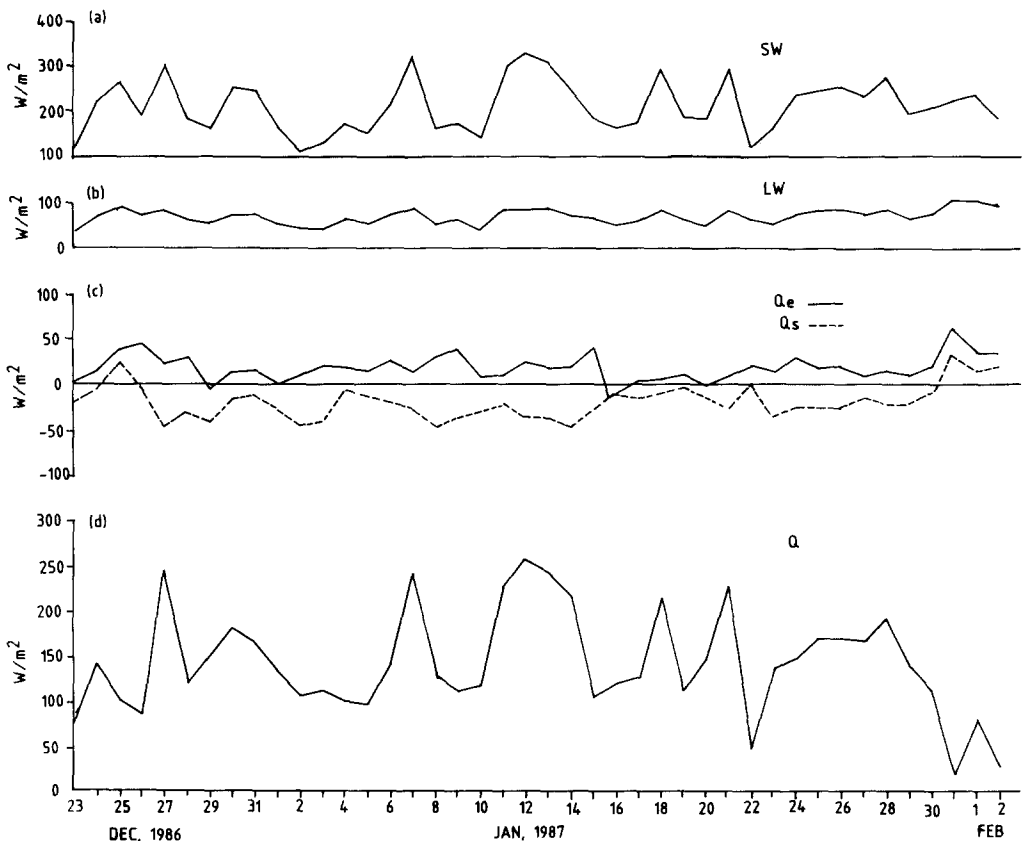


Fig. 4. Daily progression of the surface fluxes from 23 December 1986 to 2 February 1987. (a) SW , incoming solar radiation (W m^{-2}); (b) LW , outgoing longwave radiation (W m^{-2}); (c) Q_e , latent heat flux (W m^{-2}); Q_s , sensible heat flux (W m^{-2}) and (d) Q , net heat gain (W m^{-2}).

period is only 1°C. The latent and sensible heat fluxes do not exhibit large variations. In general these fluxes are of opposite sign (the polynya loses heat through evaporation and gains heat through conduction).

The fluxes (Q_e and Q_s) for the study period as a whole seemed to nearly balance each other out, with values of 20 and -23 W m^{-2} , respectively. In an earlier study, DEN HARTOG *et al.* (1983) have shown that the sensible heat flux forms a dominant component of the surface heat loss. This may be mainly attributed to the larger temperature gradients in the polynya of the Arctic region as compared to the relatively low temperature gradients over the polynya in the present case (Antarctic region). Secondly, the observations were taken over the Arctic region (DEN HARTOG *et al.*, 1983) during northern winter when the gradients of various surface meteorological parameters were large as compared to the present observations which were taken during the austral summer period.

The net heat gain over the polynya seems to be mainly dependent upon the incoming solar radiation. The mean net heat gain (Q) during the observational period is 141 W m^{-2} . If the advection and other processes are not dominant, one can expect a net heat storage of the same magnitude in the top layer. To verify this, the mean heat storage in the layers (0–25, 0–50 and 0–100 m) was computed, making use of the temperature profiles shown in Fig. 5.

One can clearly see from Fig. 5 that the fluctuations are very rapid and higher in the top 50 m layer compared with the bottom layer (50–100 m). The mean heat storage is found to be -111 , -164 and -250 W m^{-2} in the 0–25, 0–50 and 0–100 m layers, respectively. From this it can be mentioned that the heat gain at the surface is lost through advection and other interior physical processes in the top 50 m layer: this has resulted in the constant sea surface temperature observed during the study period. Unfortunately, no other information is available in this region to compare our results.

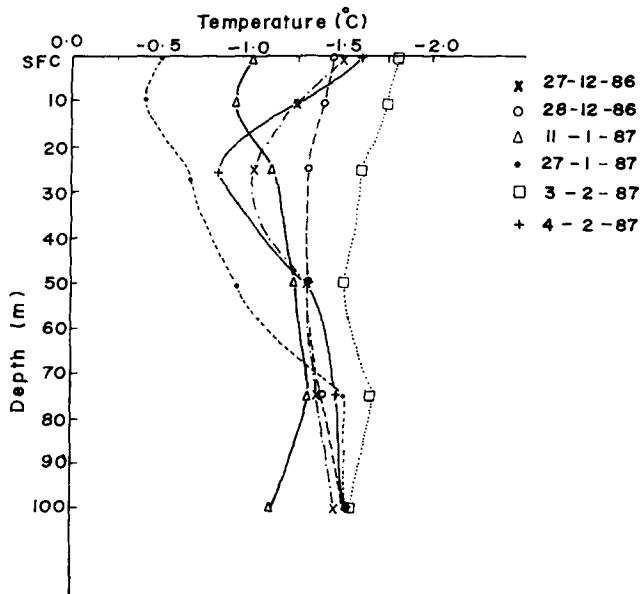


Fig. 5. Thermal structure of the polynya for the study period.

Table 2. Mean values of surface fluxes along with the standard error of the mean (S.E.M.) and number of observations (N)

Flux	N	Mean (W m^{-2})	S.E.M. (W m^{-2})
SW	42	208.60	9.0
LW	42	66.88	2.4
Q_e	42	20.16	2.1
Q_s	42	-23.08	2.1

Table 2 gives the mean values of SW, LW, Q_e and Q_s , along with the standard error of the means (S.E.M.) for the study period. The S.E.M. was computed using the following formula:

$$\text{S.E.M.} = \sqrt{\frac{\sigma^2}{N}}$$

The S.E.M.'s provide the measure of uncertainties in the variable. Here σ^2 is the variance of the variable and N the number of observations. The mean values of SW, LW, Q_e and Q_s for the study period are 209, 67, 20 and -23 W m^{-2} , respectively. The S.E.M.'s are well within the error limits and the largest S.E.M. is for SW, which is about 9 W m^{-2} .

CONCLUSIONS

The heat exchange over a polynya in the coastal waters off Queen Maud Land, Antarctica was studied for the period 23 December 1986 to 2 February 1987. The diurnal cycle of the different surface meteorological variables, as well as the daily march of the surface fluxes, are presented. The incoming solar radiation was found to be the single most important component in the surface heat budget, the mean value being 309 W m^{-2} . The latent and sensible heat fluxes were found to be opposite in sign and nearly in balance. The mean heat gain over the polynya for the study period is 141 W m^{-2} . This heat gain at the surface is lost through advection and other interior physical processes and resulted in stable sea surface temperature during the study period.

It is thought that the heat budget of this area plays a vital role in influencing the surface air temperature at Dakshin Gangotri, the permanently manned station at Antarctica. The air temperature of this station was found to have a strong relationship with the monsoon activity over India (DAS and DATTA, 1985). The surface fluxes and the heat content of this area can influence the intensification/weakening of Mascarene High which is considered to be an important component of the Indian summer monsoon.

Hence only a systematic and detailed data collection programme over the study area and the surrounding oceanic regions can throw better light on the relationship between the surface fluxes, Mascarene High intensification/weakening and the Indian summer monsoon.

Acknowledgements—The authors would like to thank Dr S. Z. Qasim (Secretary, Department of Ocean Development, Government of India) for encouragement and (the late) Dr H. N. Siddique and Dr B. N. Desai (Director, National Institute of Oceanography) for permission to one of the authors (M.R.R.) to participate in the sixth Indian scientific expedition to Antarctica. The authors are thankful to Dr J. S. Sastry (Deputy Director and Head, Physical Oceanography, N.I.O.) for his keen interest and encouragement. They are grateful to the reviewers for their useful suggestions in improving the manuscript.

REFERENCES

- BUDYKO M. I. (1958) The heat balance of the earth's surface. Translated (from the Russian) by Nina A. Stepanova. U.S. Department of Commerce, Washington D.C., 258 pp.
- BUNKER A. F. (1976) Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. *Monthly Weather Review*, **104**, 1122-1140.
- DAS S. K. and R. K. DATTA (1985) Antarctica and Indian monsoon. *Mausam*, **36**, 525-526.
- DEN HARTOG G., S. D. SMITH, R. J. ANDERSON, D. R. TOPHAM and R. G. PERKIN (1983) An investigation of a polynya in the Canadian Archipelago, 3. Surface heat flux. *Journal of Geophysical Research*, **88**, 2911-2916.
- HASTENRATH S. and P. J. LAMB (1978) *Heat budget atlas of the tropical Atlantic and eastern Pacific Oceans*. University of Wisconsin Press, Madison, Wisconsin, 104 pp.
- HASTENRATH S. and P. J. LAMB (1979) *Climate atlas of the Indian Ocean — Part II. The oceanic heat budget*. University of Wisconsin Press, Madison, Wisconsin, 110 pp.
- KONDRAATYEV K. Ya. (1969) *Radiation in the atmosphere*. Academic Press, New York, pp. 471.
- PAYNE R. E. (1972) Albedo of the sea surface. *Journal of the Atmospheric Sciences*, **29**, 959-969.
- SMITH S. D. (1981) Coefficients of sea surface wind stress and heat exchange. Rept. BI-r-81-19, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada.
- SMITH S. D., R. J. ANDERSON, G. DEN HARTOG, D. R. TOPHAM and R. G. PERKIN (1983) An investigation of a polynya in the Canadian Archipelago, 2. Structure of turbulence and sensible heat flux. *Journal of Geophysical Research*, **88**, 2900-2910.