Northwest and
Alaska
Fisheries Center

National Marine
Fisheries Service

U.S. DEPARTMENT OF COMMERCE

NWAFC PROCESSED REPORT 83-06

Monthly, Seasonal, and Interannual Variations of the Heat Content in the Surface Layers of the Northern Hemisphere Oceans

June 1983

MONTHLY, SEASONAL, AND INTERANNUAL VARIATIONS OF THE HEAT CONTENT IN THE SURFACE LAYERS OF THE NORTHERN HEMISPHERE OCEANS

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ABSTRACT

Monthly heat content changes in the upper 120 m of northern hemisphere oceans were computed for the years 1967 and 1968, using synoptic sea surface temperature (SST) and mixed layer depth (MLD) analysis, total heat exchange computations (bulk formulas), surface meteorological analysis, and ocean climatic temperatures.

The heat content distribution in the upper 120 m of the ocean is approximately latitudinal in the North Pacific, but in the North Atlantic the heat content of the eastern areas is considerably higher than that of the western areas of the ocean. The heat storage change in the upper 120 m between February and August is highest between 35° and 45°N in the western areas of both oceans (>50 kcal cm^2).

During the winter season, monthly heating and cooling patterns of surface layers are approximately latitudinal. Greatest interannual differences in heating/cooling in winter occur in the tropics, due to cloud cover and trade wind variations. Greatest advective changes of heat in the surface layers occur in the mid-latitudes in winter. In the summer, heat exchange patterns are more complex and greater year-to-year and east to west differences occur than during winter. With the exception of the trade wind regions, advective changes in summer are smaller due to slower surface currents, caused by lighter surface winds.

Monthly changes in SST are relatively small during the winter; however, heat loss at medium and high latitudes and gain at low latitudes continues as a consequence of convection and the deepening of MLD. Greatest changes in SST occur in mid-latitudes during May and November, while year-to-year differences in SST in these months are of the order of 1° to 2.5°C.

Year-to-year differences occur also in the net heat exchange. Most ocean regions north of 15°N lose heat to the atmosphere annually. This heat loss must be compensated by the heat transport with ocean currents. Preliminary calculations show that the heat transport by major ocean currents can fully balance the heat loss at medium and higher latitudes.

1. OBJECTIVES OF THE STUDY

The computations of the heat budget in the northern hemisphere oceans and in the atmosphere above were done in 1969 at the Fleet Numerical Weather Central, Monterey. The main objective of these computations was to study the sources and sinks of sensible and latent heat in the ocean and the effects of energy feedback from the oceans on the atmosphere. The results were published in two technical reports (Laevastu, Clarke, and Wolff, 1970; Laevastu and Wolff, 1970). However, many of the results pertaining to climatic variations remained unpublished.

General interest in ocean climatic changes has intensified in the last decade; some sea surface temperature anomalies in the Pacific Ocean in 1982 and 1983 have received considerable attention. Therefore, I decided to present some of the previously worked-up material on the ocean heat budget in this report with the specific objectives:

1) To show the spatial distribution of the monthly and annual heat content changes in different near-surface layers of the northern hemisphere oceans.

2) To demonstrate the year-to-year variability in monthly sea surface temperature changes.

3) To determine the contributions of local temperature changes caused by net heat exchange, and to evaluate the role of wind driven surface currents in advection of the heat.

2. DATA AND METHODS

Synoptic computations of heat exchange between the atmosphere and the northern hemisphere oceans at twice daily intervals between 1965 and 1972, were made at the Fleet Numerical Weather Central (FNWC) in Monterey. The necessary parameters for these computations were obtained from surface meteorological analyses. The formulas used for the heat exchange computations are given in Table 1. The computation of true surface wind south of 15°N is too inaccurate for heat exchange computations; therefore, the computations for the tropics are somewhat uncertain.

Shellard (1962) published detailed heat exchange computations at Weather Ships I and J in the Atlantic. His monthly values of the sum of sensible and latent heat exchange (Q_{e+h}) and total or net heat exchange (Q_{ℓ}) averaged over eight years, are reproduced in Figures 1 and 2, respectively, together with the corresponding monthly mean values for 1967, computed at FNWC. The differences between Shellard's 8-year mean values and FNWC 1967 values are, in general, within the range of the year-to-year variations indicated by Shellard. It is possible that the total heat gain during the summer, computed at FNWC, is somewhat higher than that by Shellard. This difference might be attributed to differences in the manner in which cloud cover was computed (and/or reported).

It has been shown earlier (Laevastu, 1965) that monthly mean values of heat exchange components must be computed by summing and averaging the synoptic heat exchange computations, and not by averaging the meteorological parameters prior to computations of monthly mean heat exchange. This is primarily due to the nonlinearities in the relations represented by the formulas in connection with the short-term variability of meteorological elements, and secondarily, as a consequence of the fact that most of the empirical formulas used in such computations have been derived and verified on the basis of short-term (synoptic) measurements.

Table 1

Formulas for synoptic computation of heat exchange between the sea and the atmosphere

All units of Q's in g cal cm^{-2} $24h^{-1}$

(1) Insolation, $Q_s = 0.014\, A_n t_d\, (1 - 0.0006\, C^3)$

If cloud cover analysis is made in 3 layers

$$Q_s = Q_{os}\,(1 - 0.0075 C_L^2)$$

$$Q_s = Q_{os}\,(1 - 0.006 C_M^2)$$

$$Q_s = Q_{os}\,(1 - 0.0035 C_H^2)$$

(Minimum Q_s applying)

(2) Albedo, $Q_r = 0.15\, Q_s - (0.01\, Q_s)^2$

(3) Effective back radiation $Q_b = (297 - 1.86\, T_w - 0.95 U_o)(1 - 0.0765C)$

If cloud cover analysis is made in 3 layers

$$Q_b = Q_{ob}\,(1 - 0.085 C_L)$$

$$Q_b = Q_{ob}\,(1 - 0.065 C_M)$$

$$Q_b = Q_{ob}\,(1 - 0.030 C_H)$$

(Minimum Q_b applying)

(4) Latent heat transfer,

$e_w - e_a$ pos.: $Q_e = (0.26 + 0.077\, V)\,(0.98\, e_w - e_a)$

$e_w - e_a$ neg.: $Q_e = 0.077\, V\,(0.98\, e_w - e_a)$

(5) Sensible heat transfer,

$T_w - T_a$ pos.: $Q_h = 39\,(0.26 + 0.077\, V)\,(T_w - T_a)$

$T_w - T_a$ neg.: $Q_h = 3\, V\,(T_w - T_a)$

(6) Total heat exchange, $Q_\ell = Q_s - Q_r - Q_b - Q_e - Q_h$

Symbols used in Table 1

A_n	-	Noon altitude of the sun (degrees)
C	-	Cloud cover (total) (in tenths)
C_H	-	High cloud cover (in tenths)
C_L	-	Low cloud cover (in tenths)
C_M	-	Medium cloud cover (in tenths)
e_a	-	Water vapor pressure of the air (mb)
e_w	-	Saturation vapor pressure of the sea surface (mb)
Q_b	-	Effective back radiation (g cal cm^{-2} $(24h)^{-1}$)
Q_e	-	Latent heat (transfer)
Q_h	-	Sensible heat (transfer)
Q_ℓ	-	Total (net) heat exchange
Q_{ob}	-	Effective back radiation to clear sky
Q_{os}	-	Insolation with clear sky
Q_r	-	Albedo (reflected radiation)
Q_s	-	Insolation
t_d	-	Length of the daylight (min.)
T_a	-	Temperature of the air (°C)
T_w	-	Temperature of the water (°C)
U_o	-	Relative humidity (%)
V	-	Wind speed (m sec^{-1})

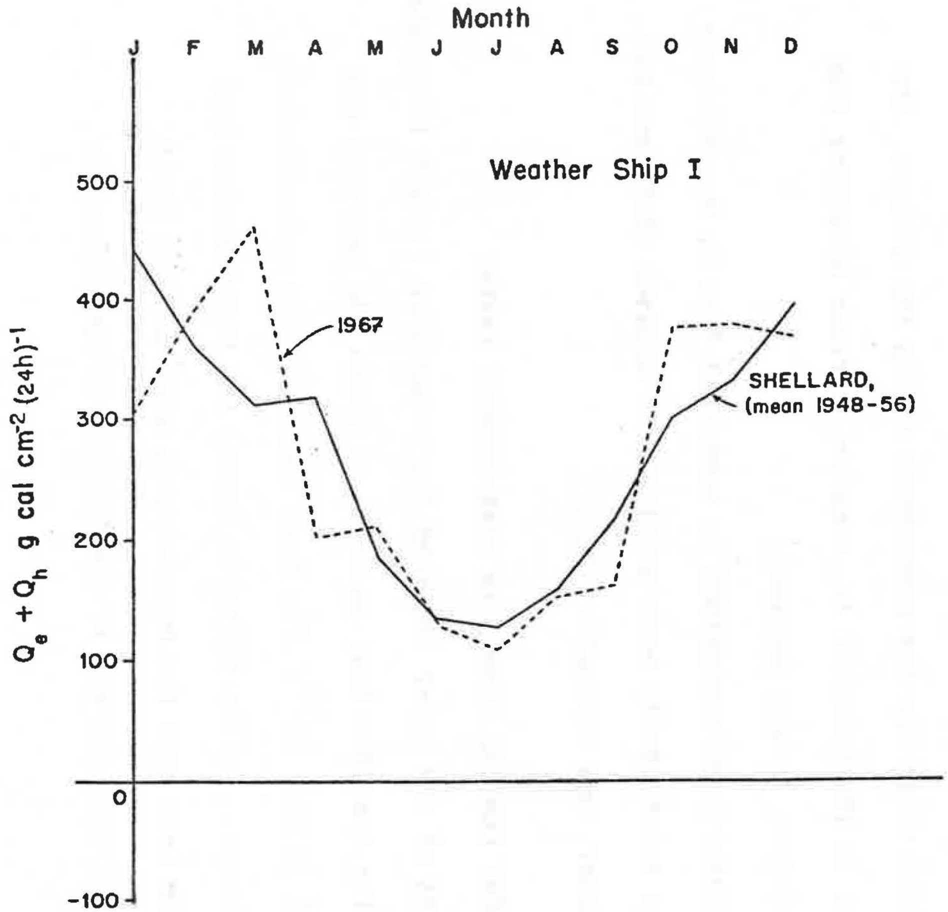

Figure 1.--Monthly mean sensible and latent heat exchange at Weather Ship "I" in the Atlantic in 1967, as compared to 8-year mean computed by Shellard (1962).

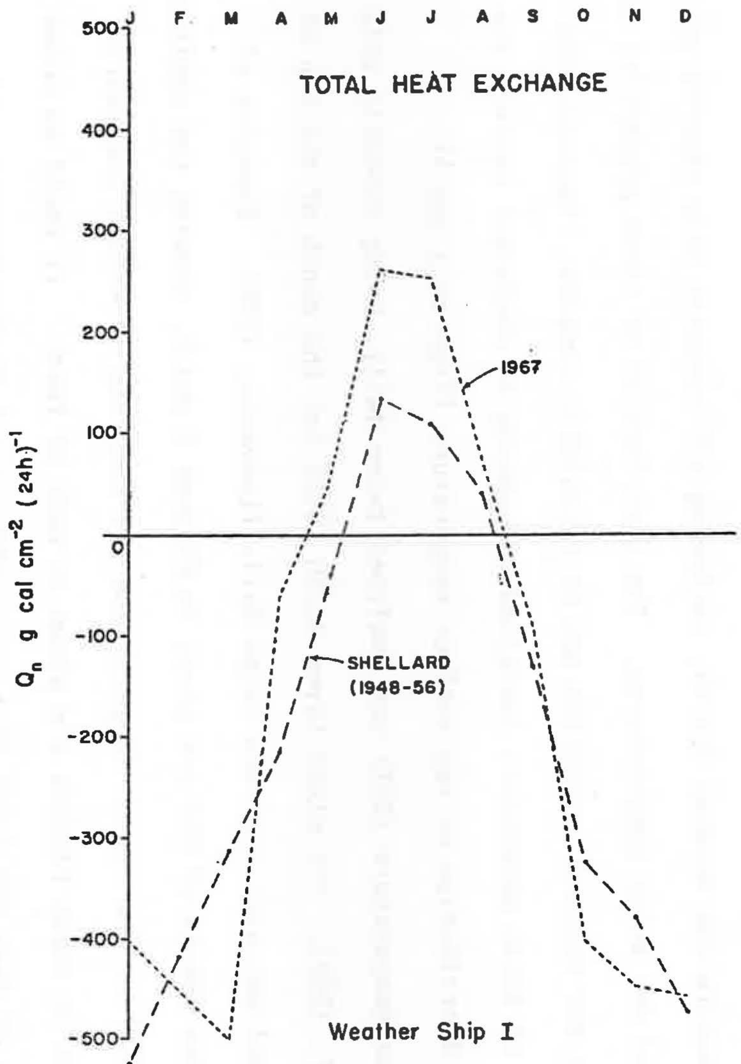

Figure 2.--Monthly mean total (or net) heat exchange at Weather Ship "I" in the Atlantic in 1967, as compared to 8-year mean computed by Shellard (1962).

Surface air temperature and water vapour pressure were computed with the methods of Laevastu and Harding (1974), including all synoptic ship reports of surface air and dew point temperatures. The distribution of these properties of surface air in any synoptic condition can be relatively complex. However, the monthly means of these parameters (obtained by summing 60 analyses) reflect the corresponding distribution of sea surface temperature (Figures 3 and 4).

Sea surface temperature (SST) was analyzed twice daily, using synoptic ship reports (Wolff, 1969). The mixed layer depth (MLD) (or the depth of the top of the thermocline) was also analyzed twice daily (Laevastu, 1976). Examples of two monthly mean charts of MLD are given in Figures 5 and 6, showing the shallow thermocline (MLD) in the summer (August) and the deep MLD in winter (February) (the MLD depths in these figures are given in tens of feet). It could be noted that the areas of deep MLD (>500 feet or ca 150 meters) in the Atlantic and Pacific are the heat source areas for the atmosphere during the winter. The main oceanic storage area in the Atlantic is, however, further upcurrent than in the Pacific (see discussion in next section).

The subsurface temperatures were provided in numerical form by Ms. Robinson and Mr. Bauer, which have subsequently been published in atlases (Robinson and Bauer, 1976; Robinson, Bauer, and Schroeder, 1979).

3. ANNUAL HEAT CONTENT CHANGE IN NEAR-SURFACE LAYERS

The total heat content of the upper 120 m of the ocean (i.e., depth integrated temperature in °C, assuming specific heat to be 1) is given for February and August in Figures 7 and 8 in kcal cm^{-2}. The heat isopleths run approximately parallel to surface isotherms. In the Atlantic Ocean, the northeastern area contains considerably more heat than the northwestern area of this ocean, whereas the distribution of heat storage in the Pacific is approximately latitudinal.

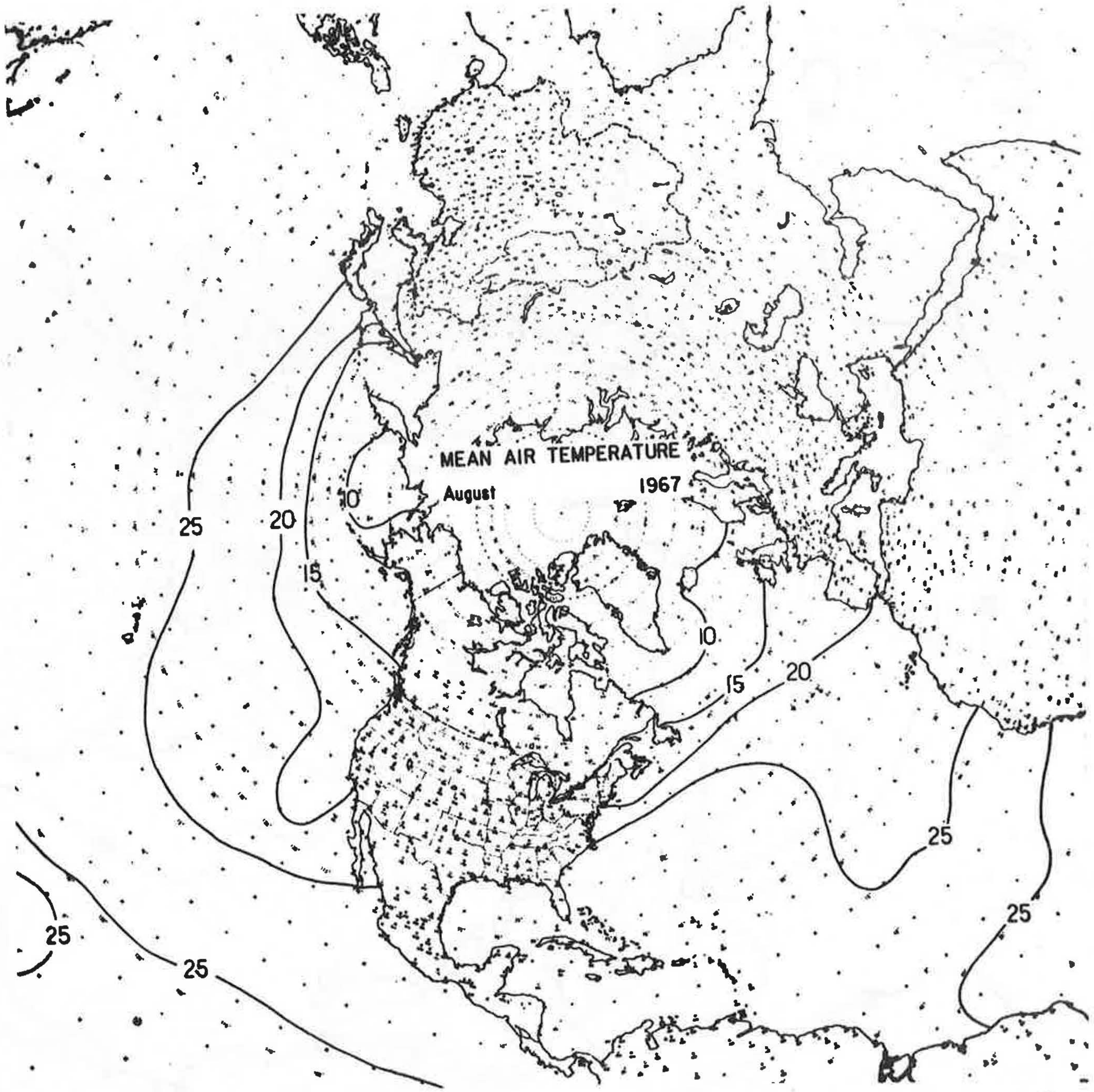

Figure 3.--Mean surface air temperature (°C) over the northern hemisphere oceans in August 1967.

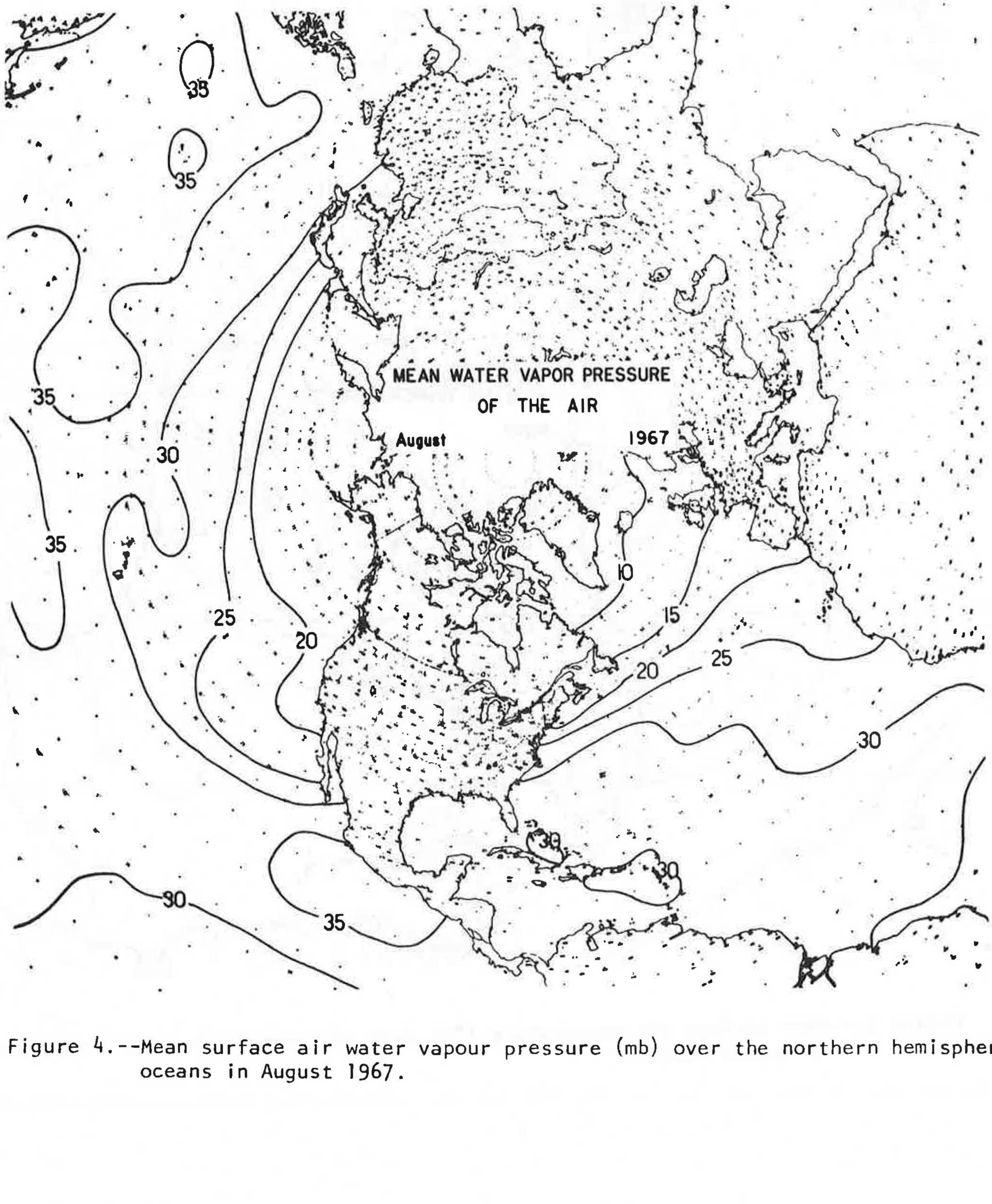

Figure 4.--Mean surface air water vapour pressure (mb) over the northern hemisphere oceans in August 1967.

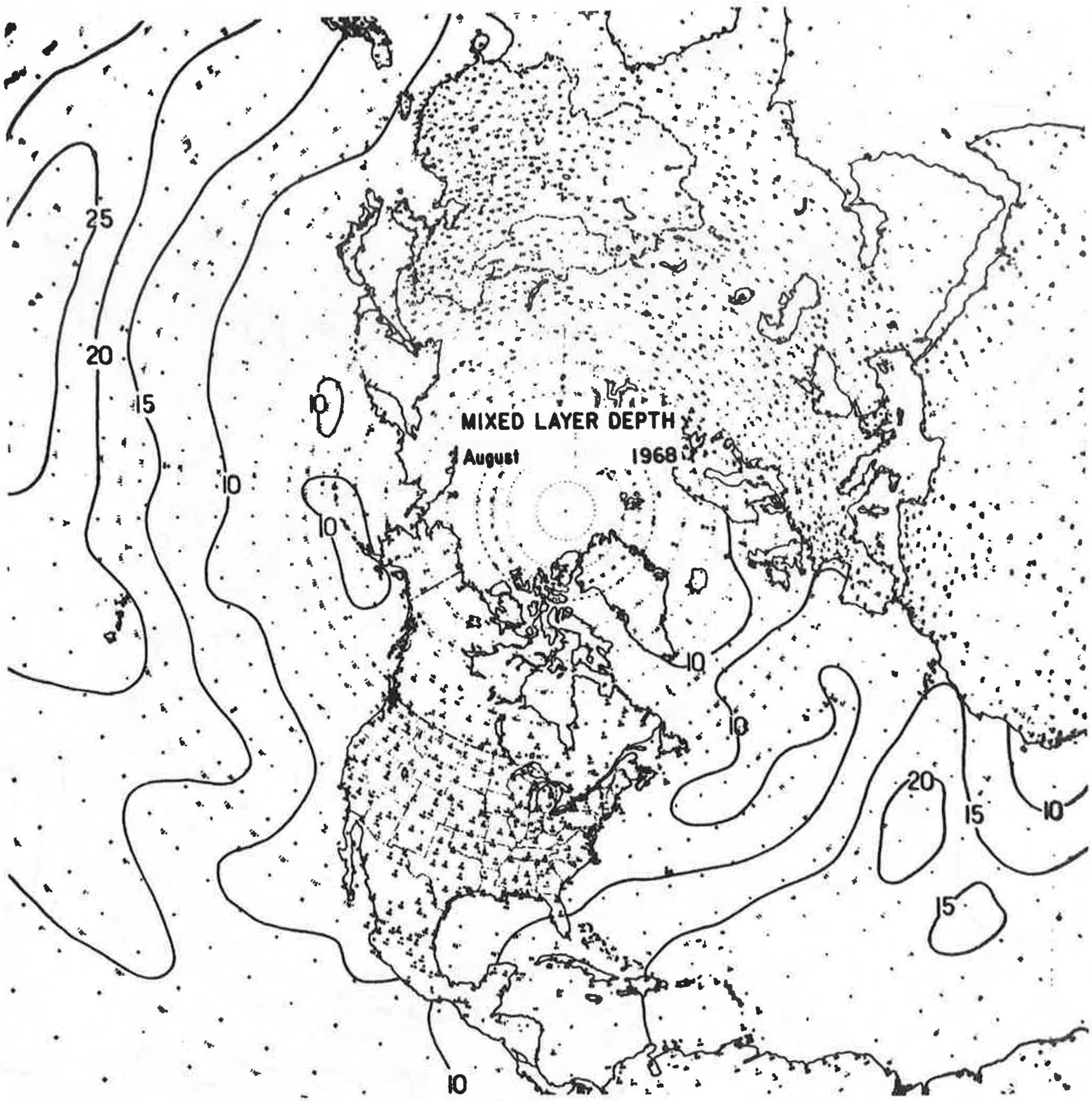

Figure 5.--Monthly mean mixed layer depth (in tens of feet) in the northern hemisphere oceans in August 1968.

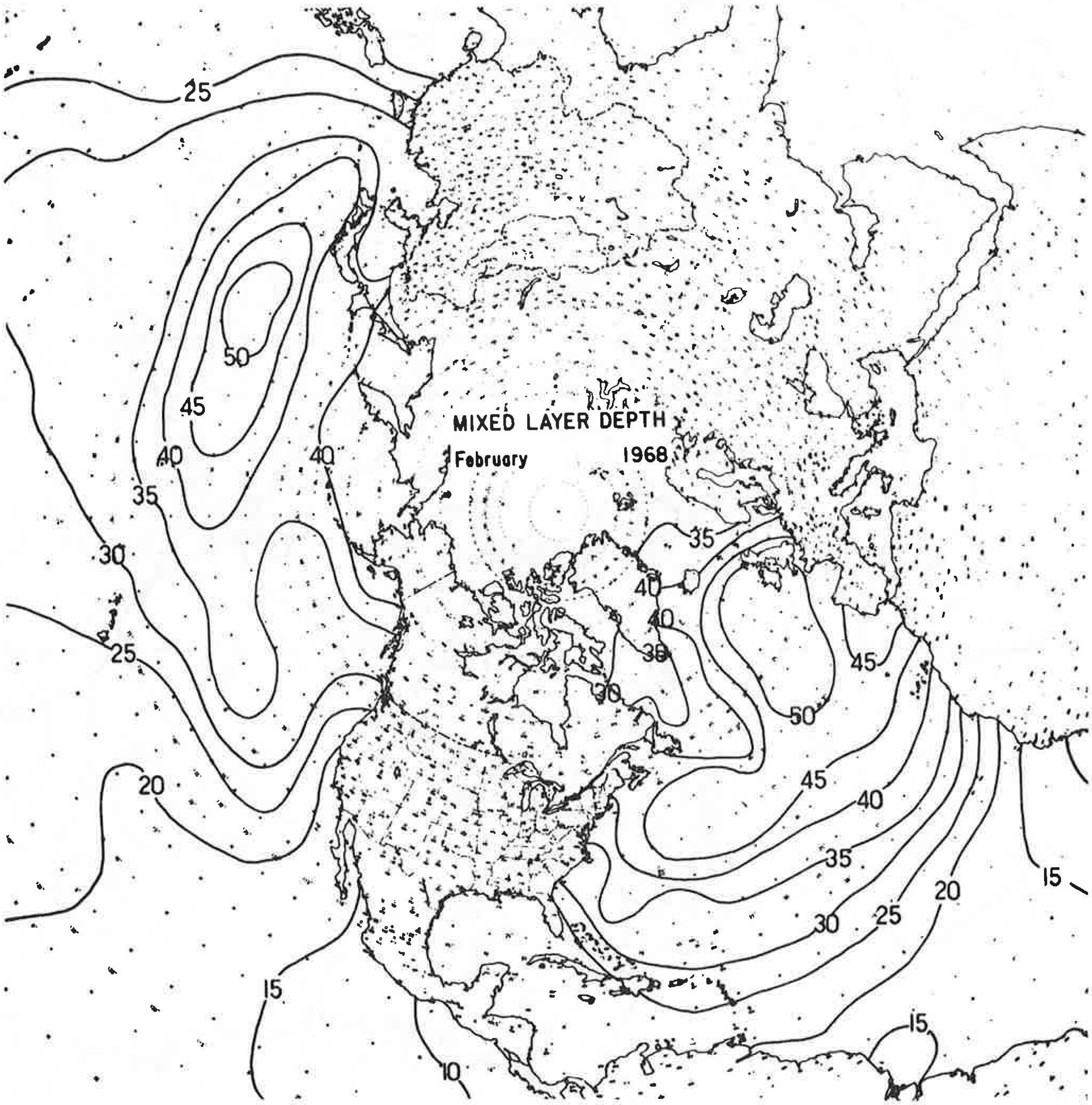

Figure 6.--Monthly mean mixed layer depth (in tens of feet) in the northern hemisphere oceans in February 1968.

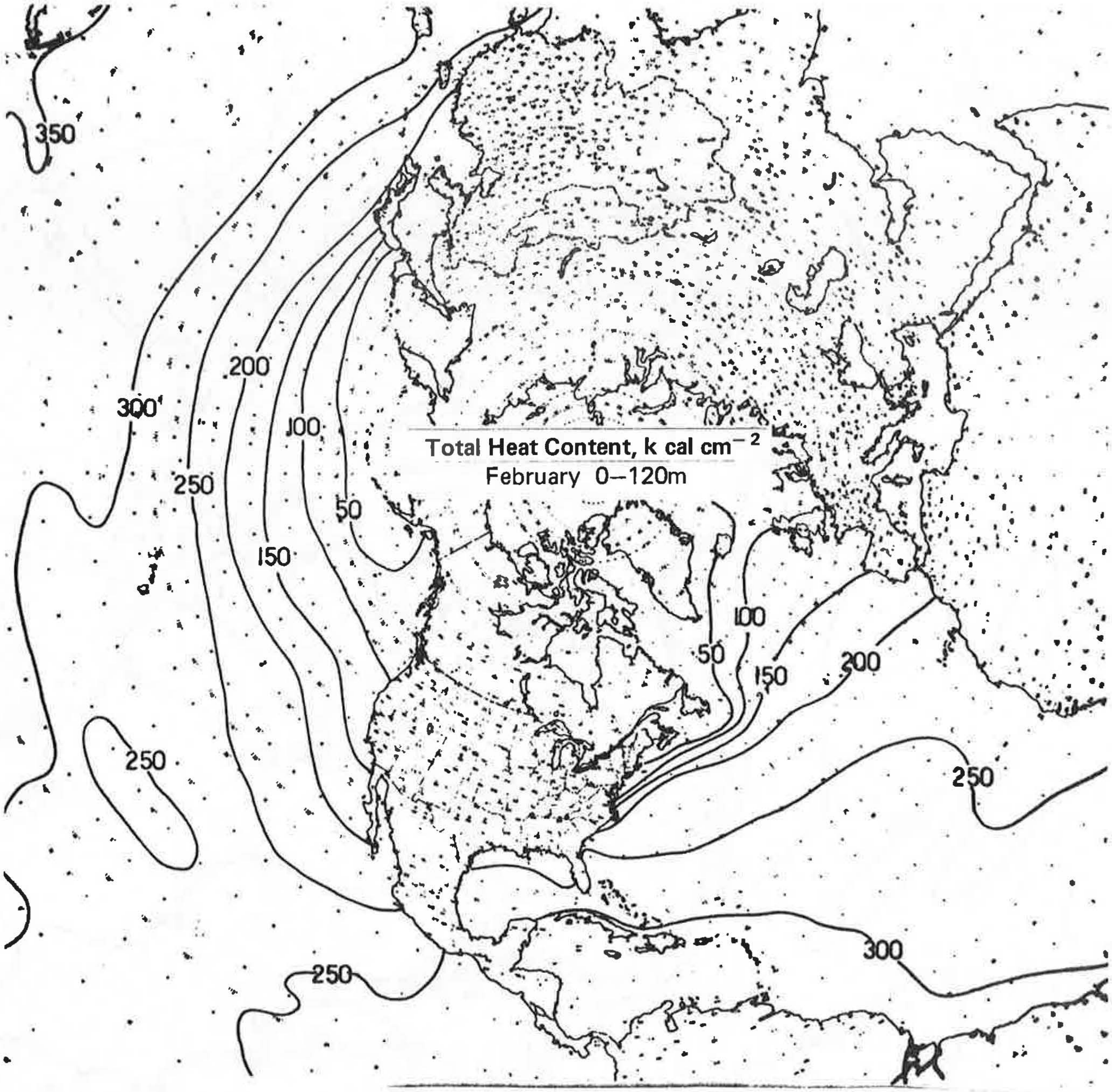

Figure 7.--Mean heat content (k cal cm^{-2}) in the upper 120 m in the northern hemisphere oceans in February.

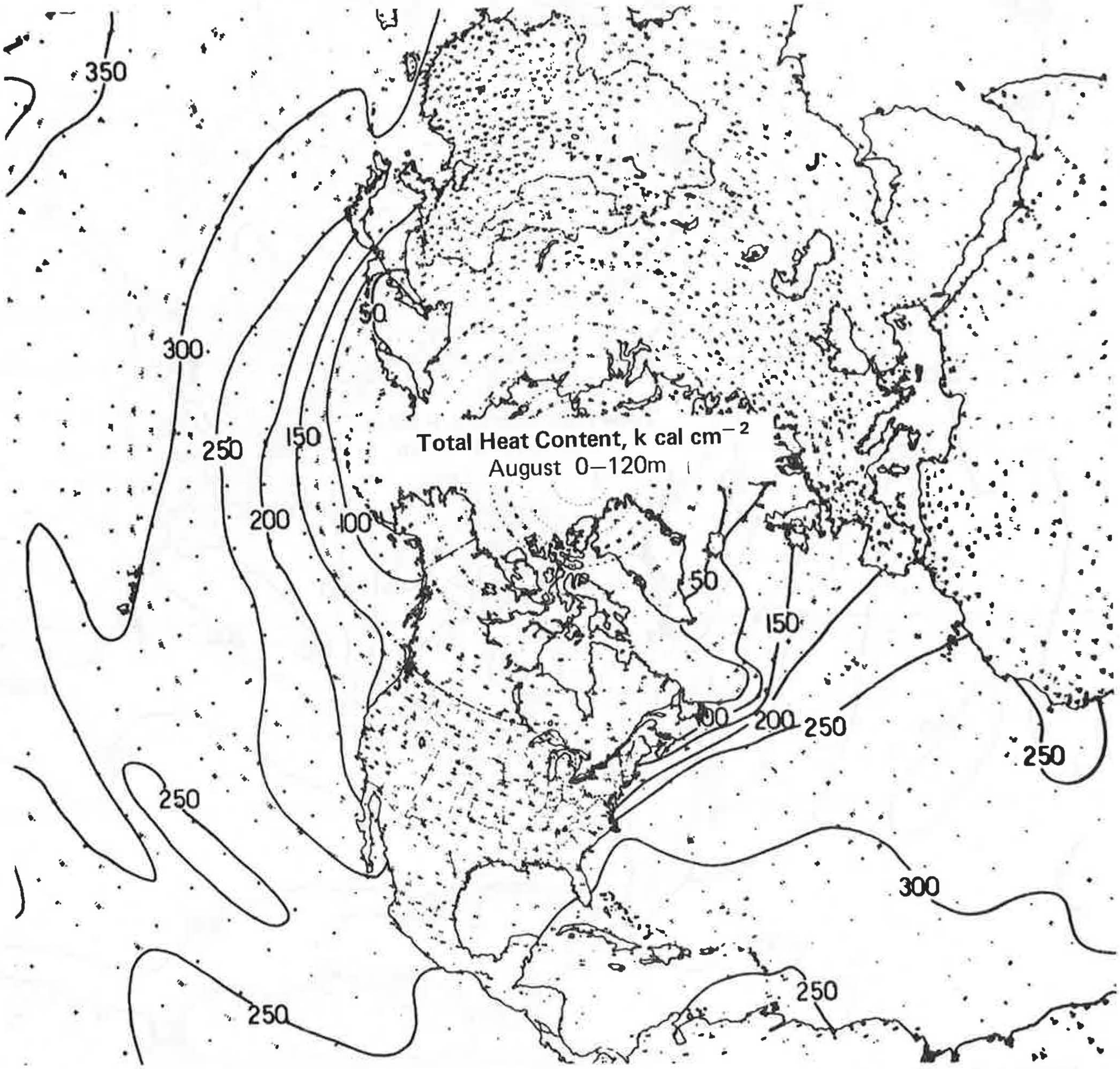

Figure 8.--Mean heat content (k cal cm^{-2}) in the upper 120 m in the northern hemisphere oceans in August.

When we subtract the February heat content from the heat content of August for the same 120 meters surface layer, the difference presents the annual heat content change (or annual heat storage change) (Figure 9). This storage change is largest (>60 kcal cm^2) in the central and western Pacific between about 30° and 40°N (approximately along, or slightly south of the axis of Kuroshio). In the Atlantic, the maximum heat storage change is at about 40°N in the western Atlantic, south of the Gulf Stream axis. These areas of maximum annual heat storage change indicate that seasonal changes in heat advection by currents might play an important role in maintaining the heat balance (see Section 5). Rodewald (1966) has shown that the major long-term changes and anomalies of sea surface temperature occur in the same areas as the abovedetermined maximum heat storage change.

The annual heat content change of 30 meter layers are shown in Figures 10 to 13. The greatest amount of annual change occurs in the first 30 meter layer (Figure 10). The next two 30 meter layers (30 to 60 and 60 to 90 meters) (Figures 11 and 12) show decreased annual change, and in 60 to 90 meter layer the change approaches zero in some areas. The abovedetermined high heat content change areas are still recognizable in the 60 to 90 meter layer. The annual heat content change in the 90 to 120 meter layer is close to zero in most areas and has even reversed in other areas.

4. MONTHLY SEA SURFACE TEMPERATURE CHANGES AND INTERANNUAL VARIABILITY IN THESE CHANGES

As the greatest annual heat storage change occurs in the sea surface layer above about 30 meters (Figures 10 and 11), the sea surface temperature (SST) should be a good indicator of this change. SST is also one of the few oceanographic properties which can be analyzed using the synoptic ship reports.

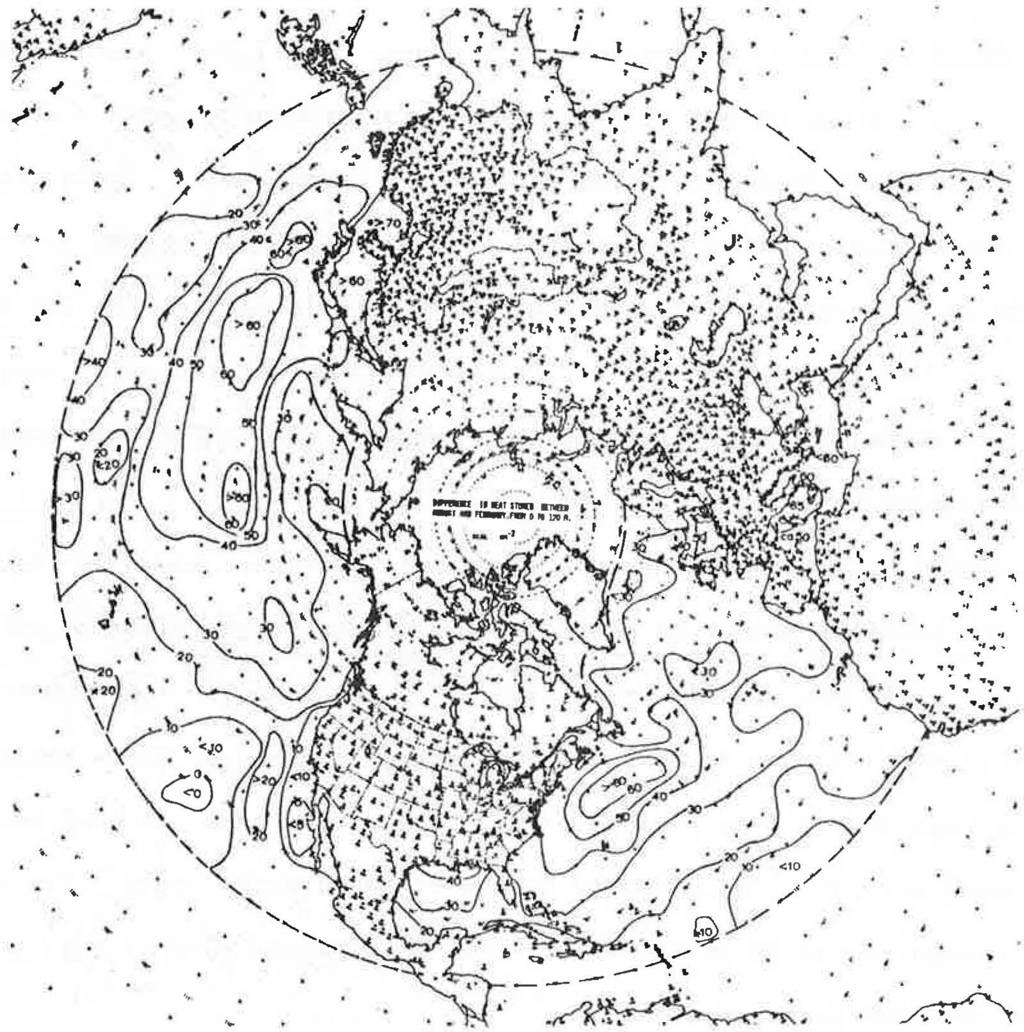

Figure 9.--Difference of mean heat content (k cal cm^{-2}) between August and February of the northern hemisphere oceans (north of 15°N).

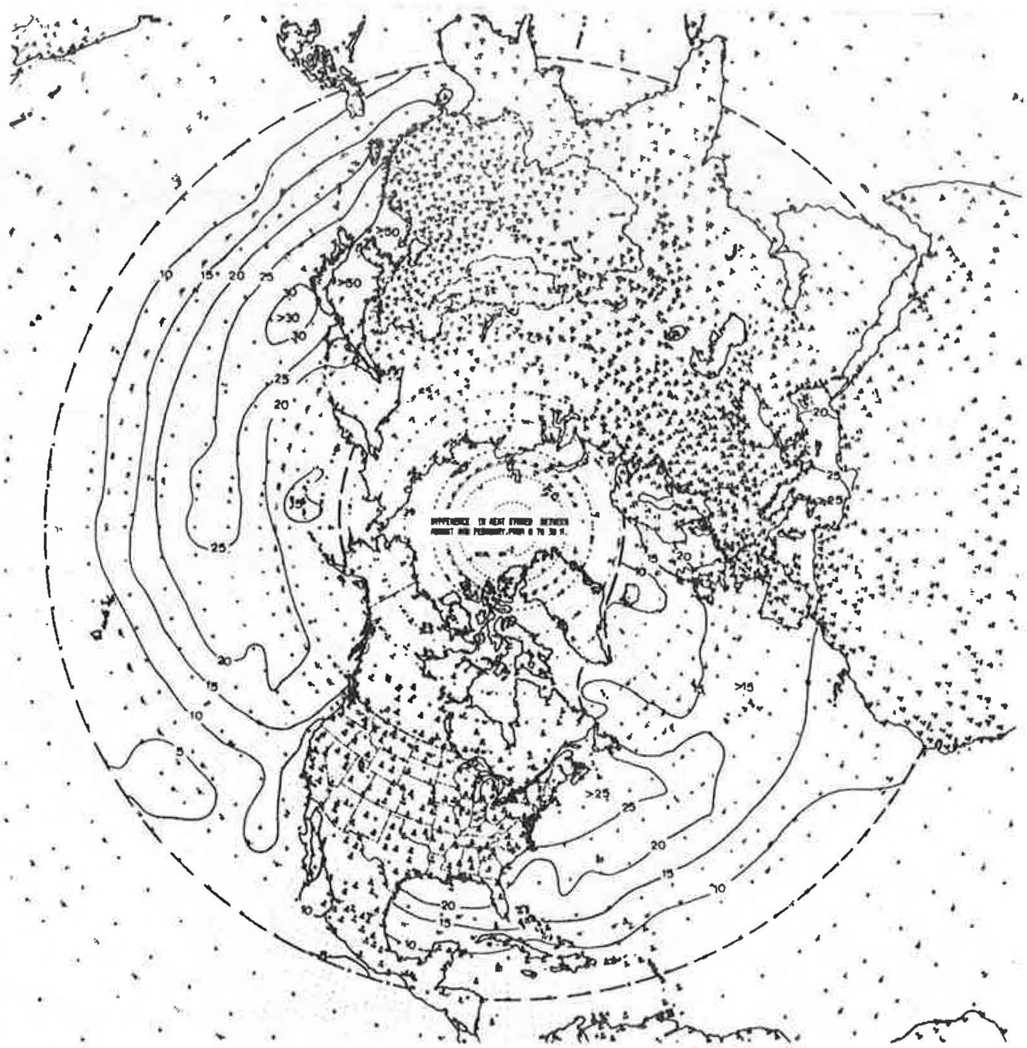

Figure 10.--Difference of mean heat content (k cal cm^{-2}) between August and February in upper 30 m of the northern hemisphere oceans (north of 15°N).

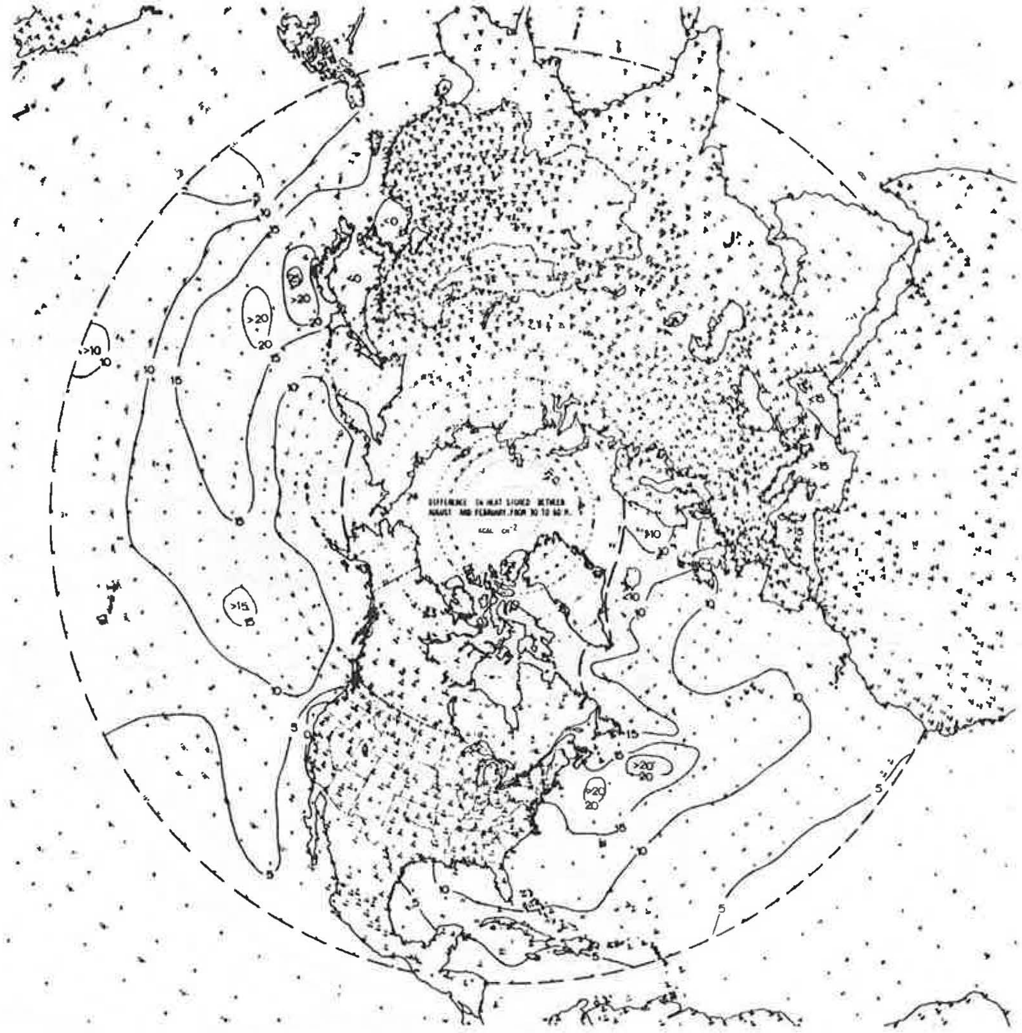

Figure 11.--Difference of mean heat content (k cal cm^{-2}) between August and February in 30 to 60 m layer of the northern hemisphere oceans (north of 15°N).

Figure 12.--Difference of mean heat content (k cal cm^{-2}) between August and February in 60 to 90 m layer of the northern hemisphere oceans (north of 15°N).

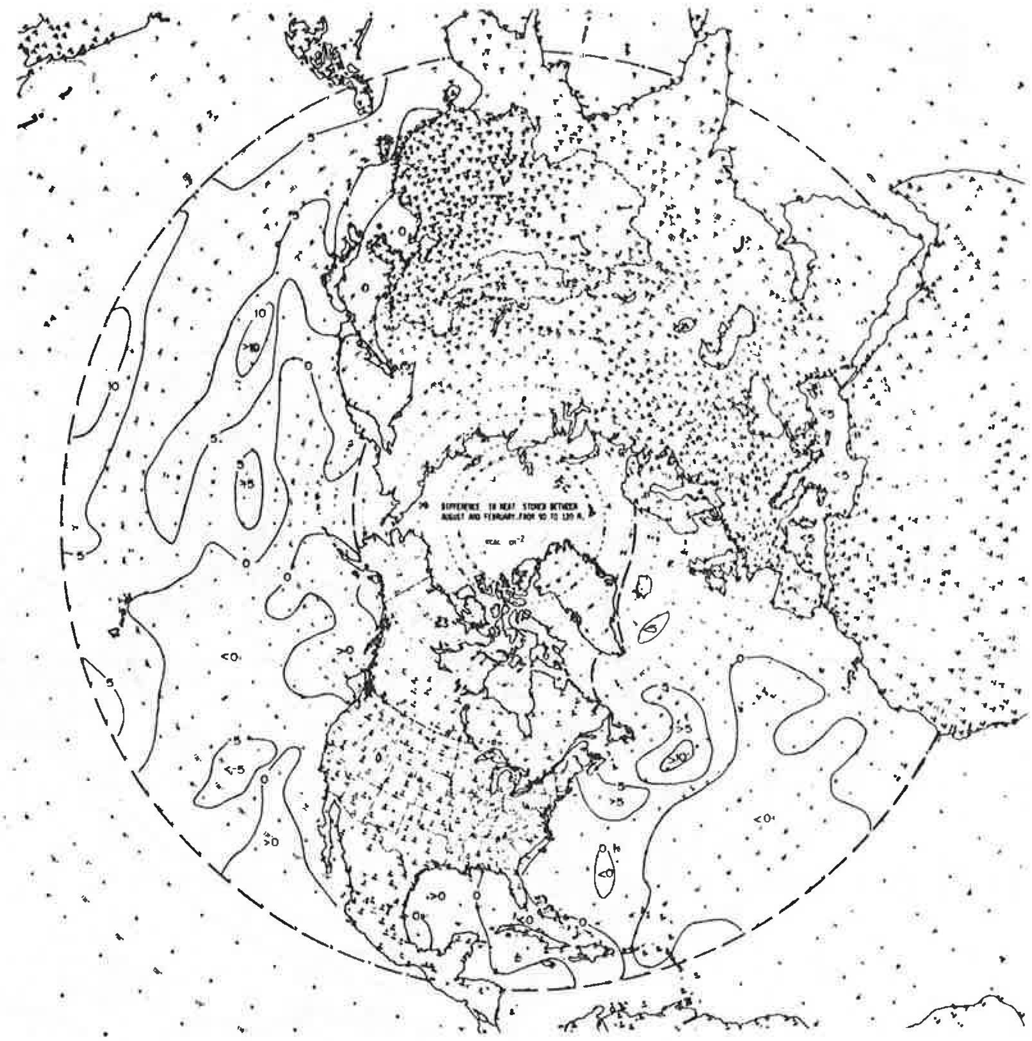

Figure 13.--Difference of mean heat content (k cal cm^{-2}) between August and February in 90 to 120 m layer of the northern hemisphere oceans (north of 15°N).

Twice daily SST analyses were at hand from which momthly means were computed. The latter were used to compute the changes during a month.

Of the voluminous material on monthly sea surface temperature changes, only eight monthly examples are given here (Figures 14 to 21) to demonstrate the seasonal patterns of SST change and the annual variability in this change.

Figures 14 and 15 show SST changes in February in two different years. Cursory examination of these figures indicates that the SST change in February is the smallest of all seasons (compare Figures 14 and 15 with Figures 16 to 21). This does not mean, however, that heat loss is lowest during the winter, because the thermocline is deep, in fact still deepening, in February in most areas) and thus convective turnover brings heat to the surface. Second conclusion is that there are considerable year-to-year differences in heat loss from the sea; the February 1968 SST patterns (Figure 15) being more complex than in February 1967 (Figure 14).

In May (Figures 16 and 17), the ocean gains heat everywhere north of equator. (The heat gain can be higher in April in lower latitudes.) The heat gain patterns in May are considerably different in the Pacific than in the Atlantic. In the Pacific, the area of greatest gain is between 30° and 40°N where the annual heat content change is also largest. In the Atlantic, the highest heat gain is in the northwest Atlantic, along northeast coast of U.S.A. and east coast of Canada, and is considerably further north than the area of maximum heat content change. The interannual differences, although present, are smaller in May than in February.

The gain of heat by the sea has slowed in August south of about 40°N, but north of 40°N the heating of the sea surface is more pronounced in August than in May (Figures 18 and 19). Considerable year-to-year differences in the features of SST between consecutive years occur in August. For example, the

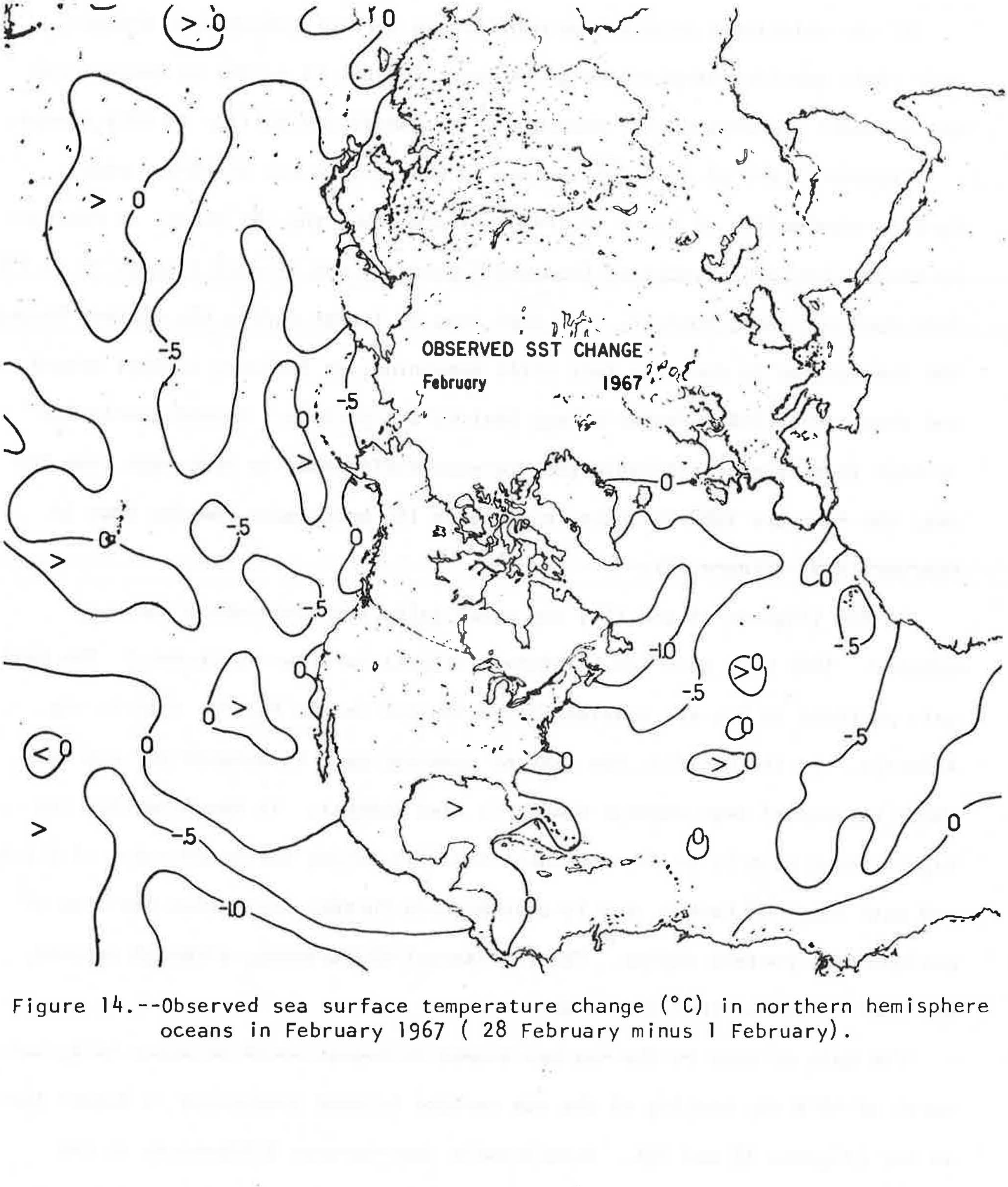

Figure 14.--Observed sea surface temperature change (°C) in northern hemisphere oceans in February 1967 (28 February minus 1 February).

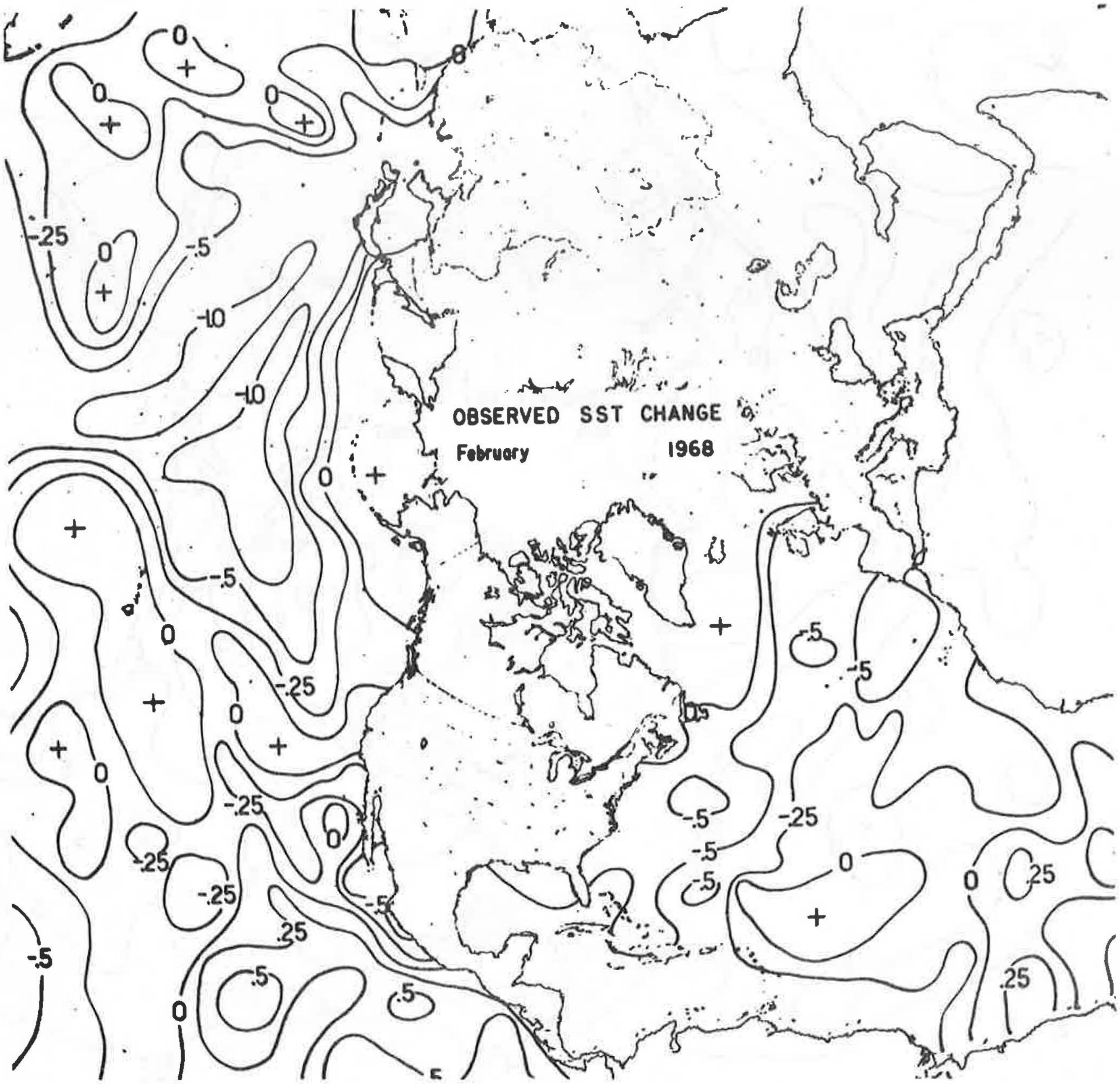

Figure 15.--Observed sea surface temperature change (°C) in northern hemisphere oceans in February 1968 (28 February minus 1 February).

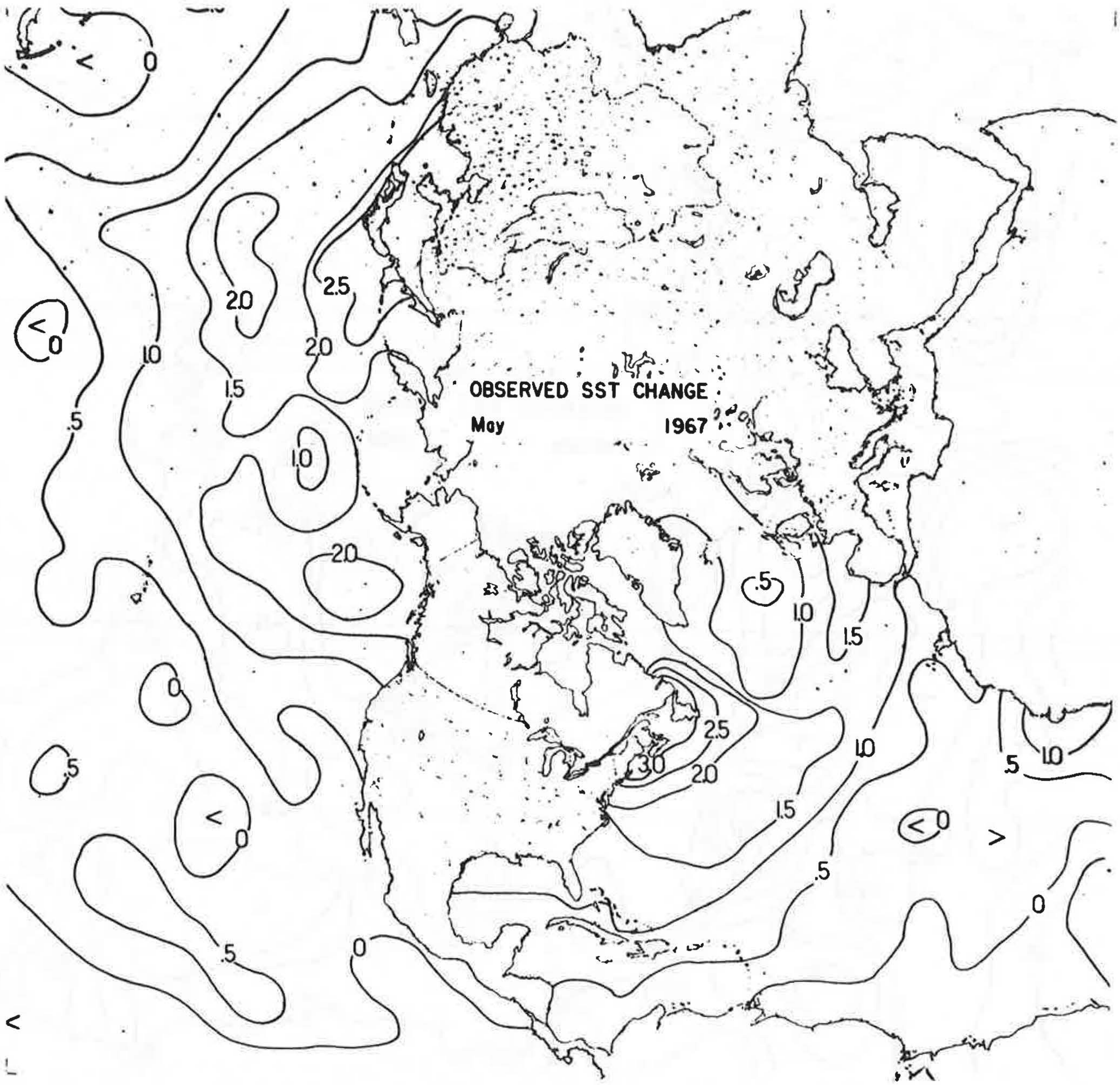

Figure 16.--Observed sea surface temperature change (°C) in northern hemisphere oceans in May 1967 (31 May minus 1 May).

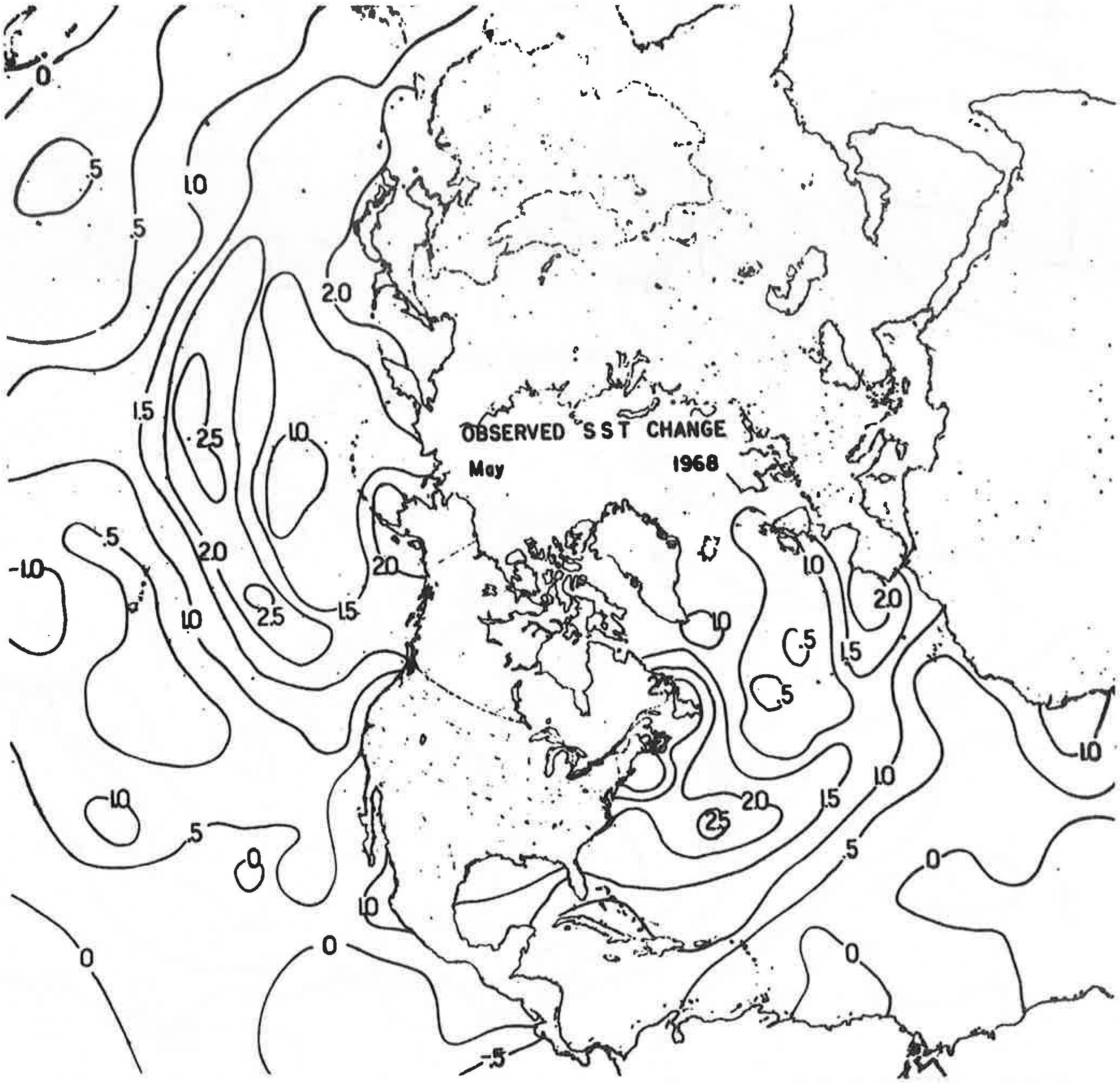

Figure 17.--Observed sea surface temperature change (°C) in northern hemisphere oceans in May 1968 (31 May minus 1 May).

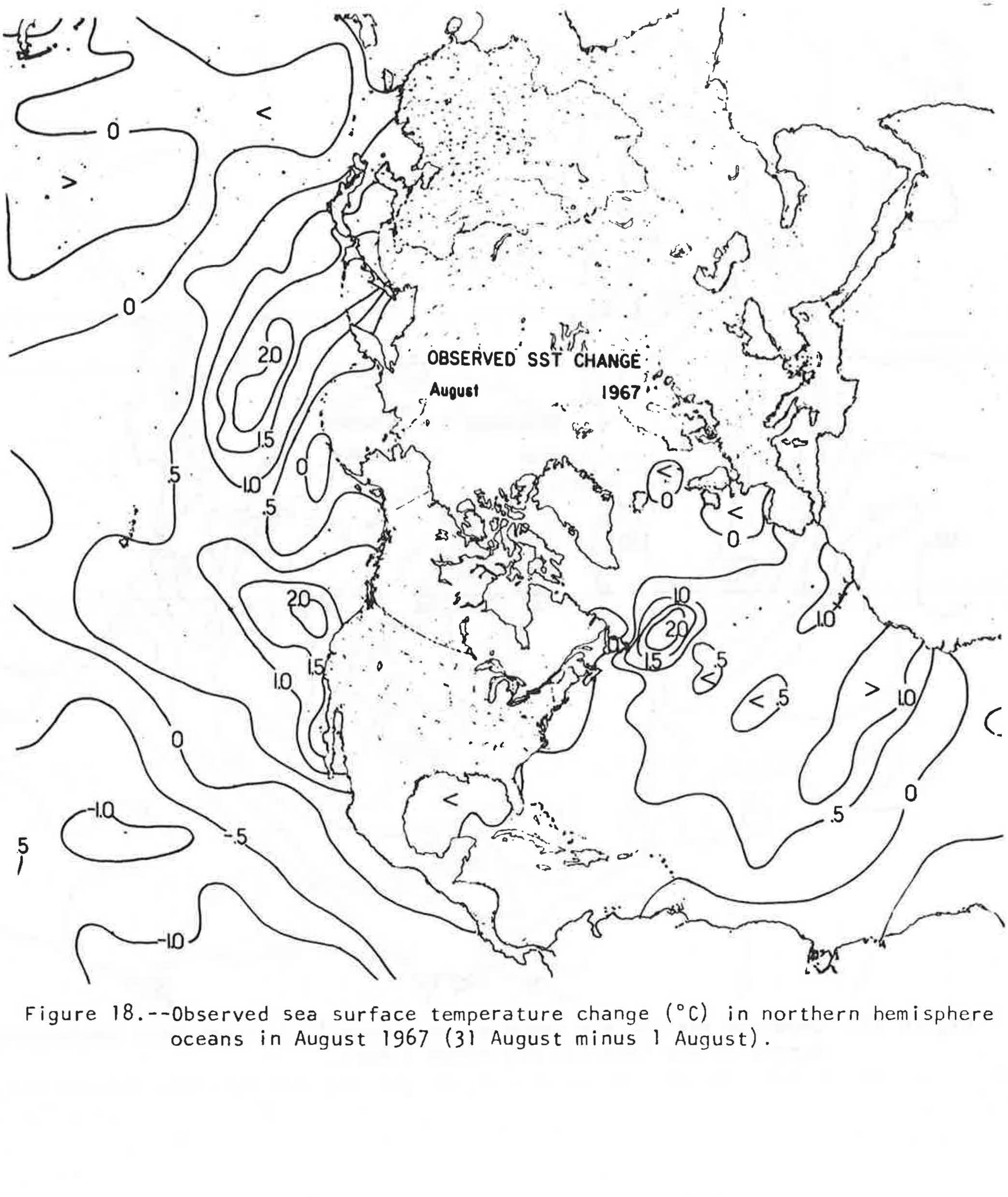

Figure 18.--Observed sea surface temperature change (°C) in northern hemisphere oceans in August 1967 (31 August minus 1 August).

Figure 19.--Observed sea surface temperature change (°C) in northern hemisphere oceans in August 1968 (31 August minus 1 August).

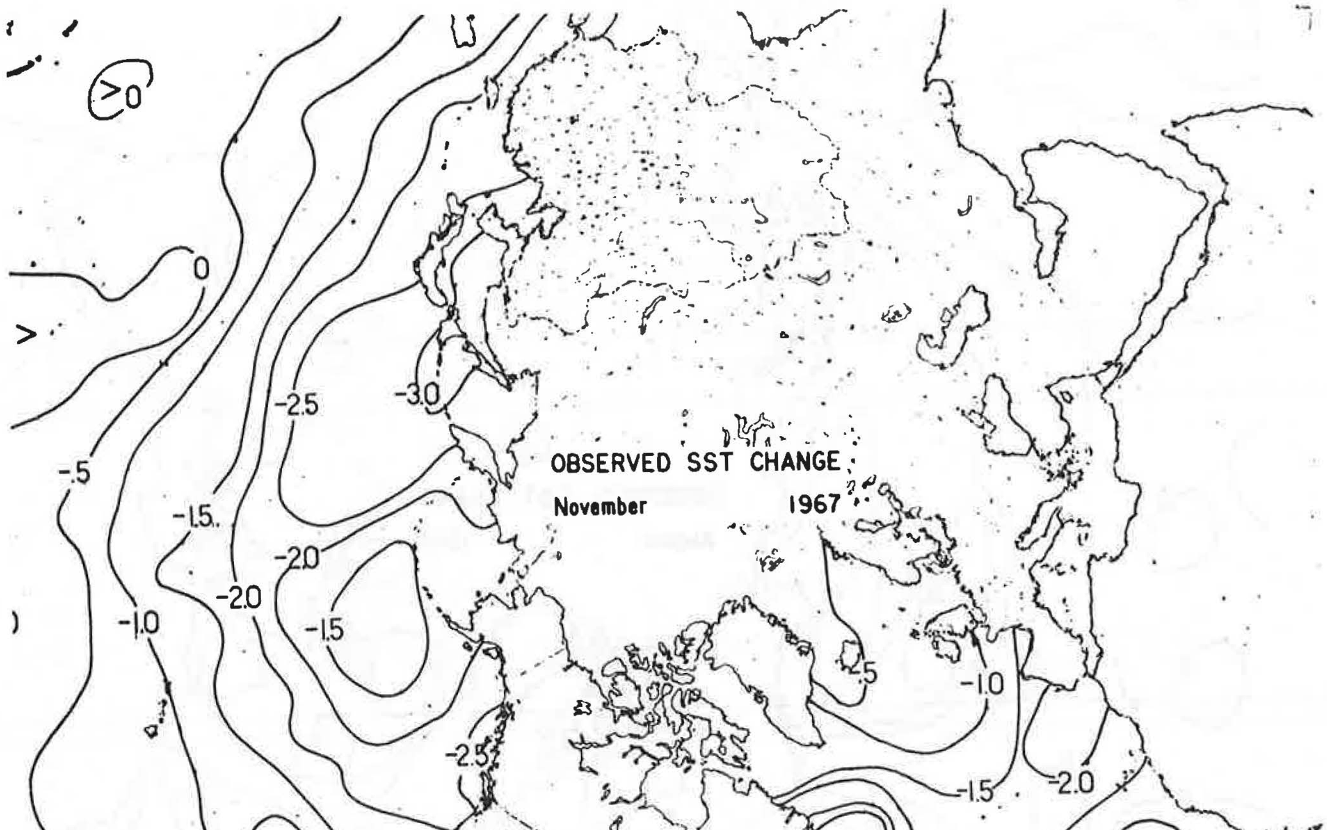

Figure 20.--Observed sea surface temperature change (°C) in northern hemisphere oceans in November 1967 (30 November minus 1 November).

Figure 21.--Observed sea surface temperature change (°C) in northern hemisphere oceans in November 1968 (30 November minus 1 November).

area of higher heating in the Pacific at about 40°N was further east in 1968 (Figure 19) than in 1967 (Figure 18). In August 1967, there was a center of higher heating east of Newfoundland (Figure 18). These differences are caused by differences in surface weather patterns, especially by surface winds, and result in summer-time sea surface temperature anomalies.

In November (Figures 20 and 21), the cooling of the sea surface is intensive. The cooling patterns start at northern latitudes and along the eastern seaboards of the continents, and move further south as time progresses. The heat loss from the oceans is highest in October and November. During this season, the sea surface temperature anomalies which were created and persisted in the summer months, will disappear. Although year-to-year differences in surface cooling (and heating) patterns in individual months do occur, these differences are usually in timing rather than total heat change, and the total annual differences are small. The subsurface oceanographic data are too sparse to analyze the year-to-year differences in total heat contents.

5. THE ROLES OF HEAT EXCHANGE AND ADVECTION IN NEAR-SURFACE HEAT CONTENT CHANGES

Monthly mean net heat exchange (in $kcal/cm^2/month$) was computed for years 1967 and 1968 by summing twice daily heat exchange computations. Four examples of the results of these computations are shown in Figures 22 to 25. Net heat exchange for February 1967 and 1968 is shown in Figures 22 and 23. There are noticeable differences between these two Februaries in NE Pacific, along U.S. east coast and in the equatorial regions. The latter regions gain heat year-round. Heat must be transported northwards from these regions by currents, as will be briefly discussed later.

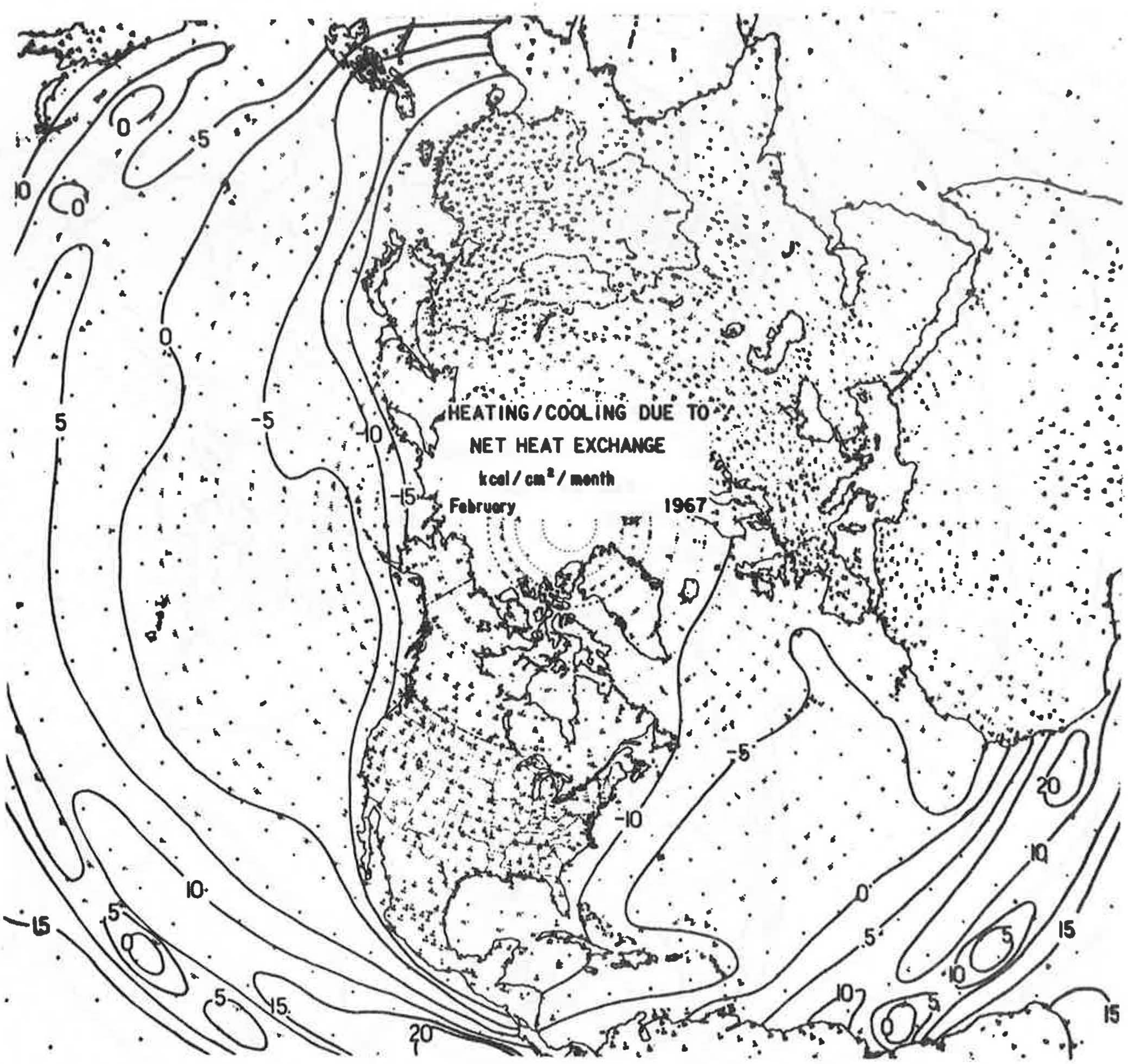

Figure 22.--Heating/cooling of the northern hemisphere oceans due to net heat exchange (k cal cm^{-2})month) in February 1967.

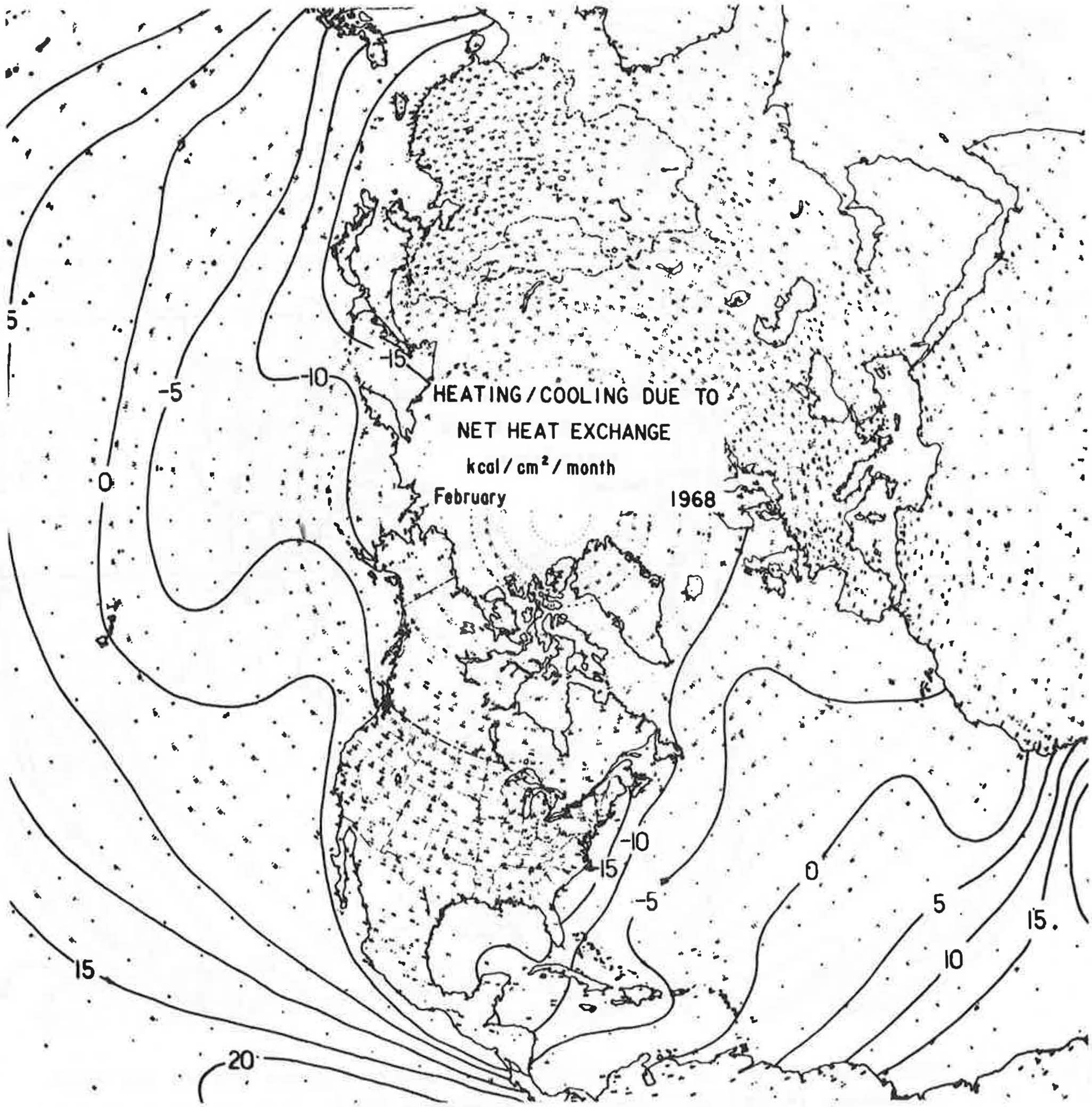

Figure 23.--Heating/cooling of the northern hemisphere oceans due to net heat exchange (k cal cm^{-2} month) in February 1968.

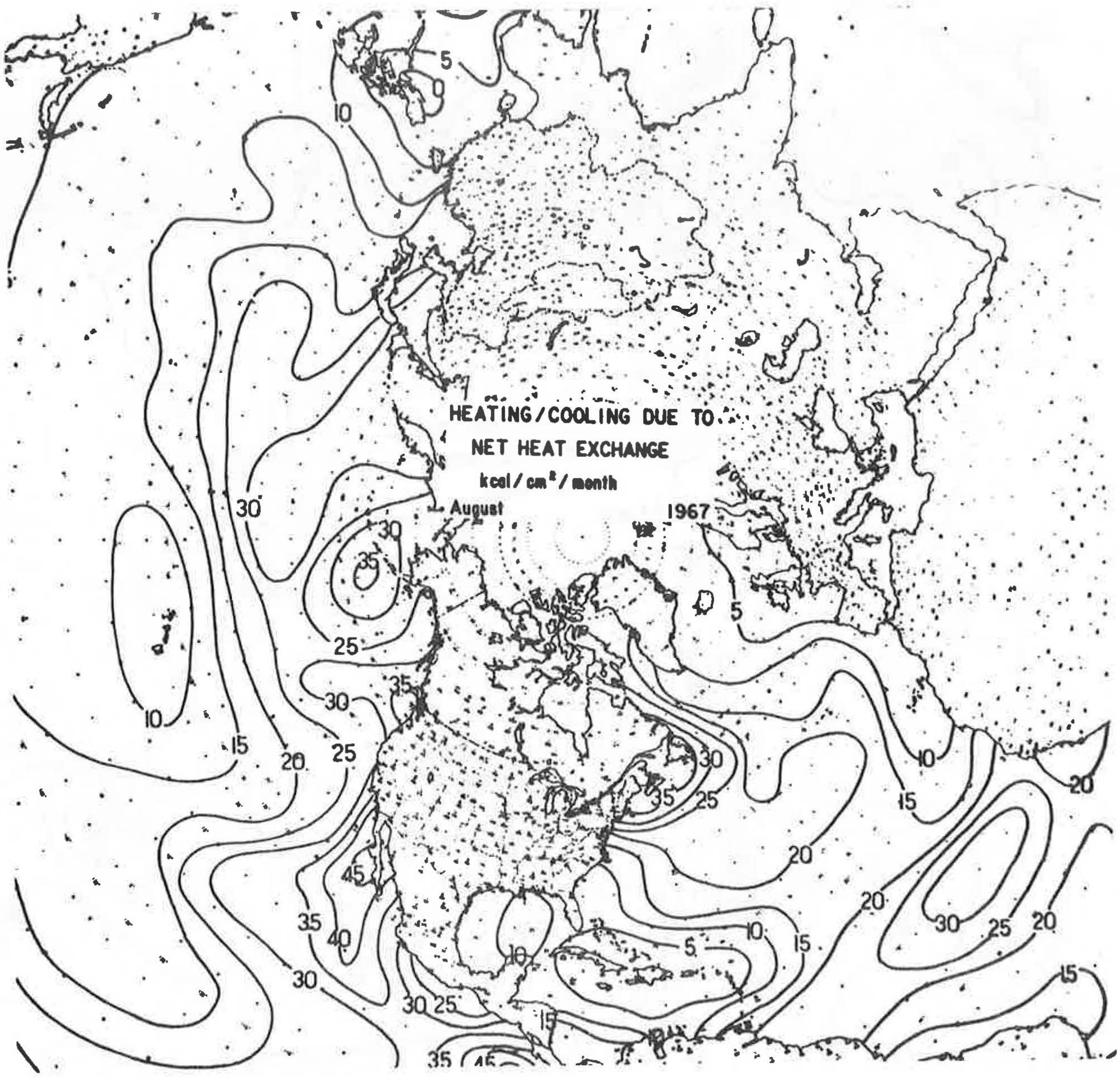

Figure 24.--Heating/cooling of the northern hemisphere oceans due to net heat exchange (k cal cm^{-2} month) in August 1967.

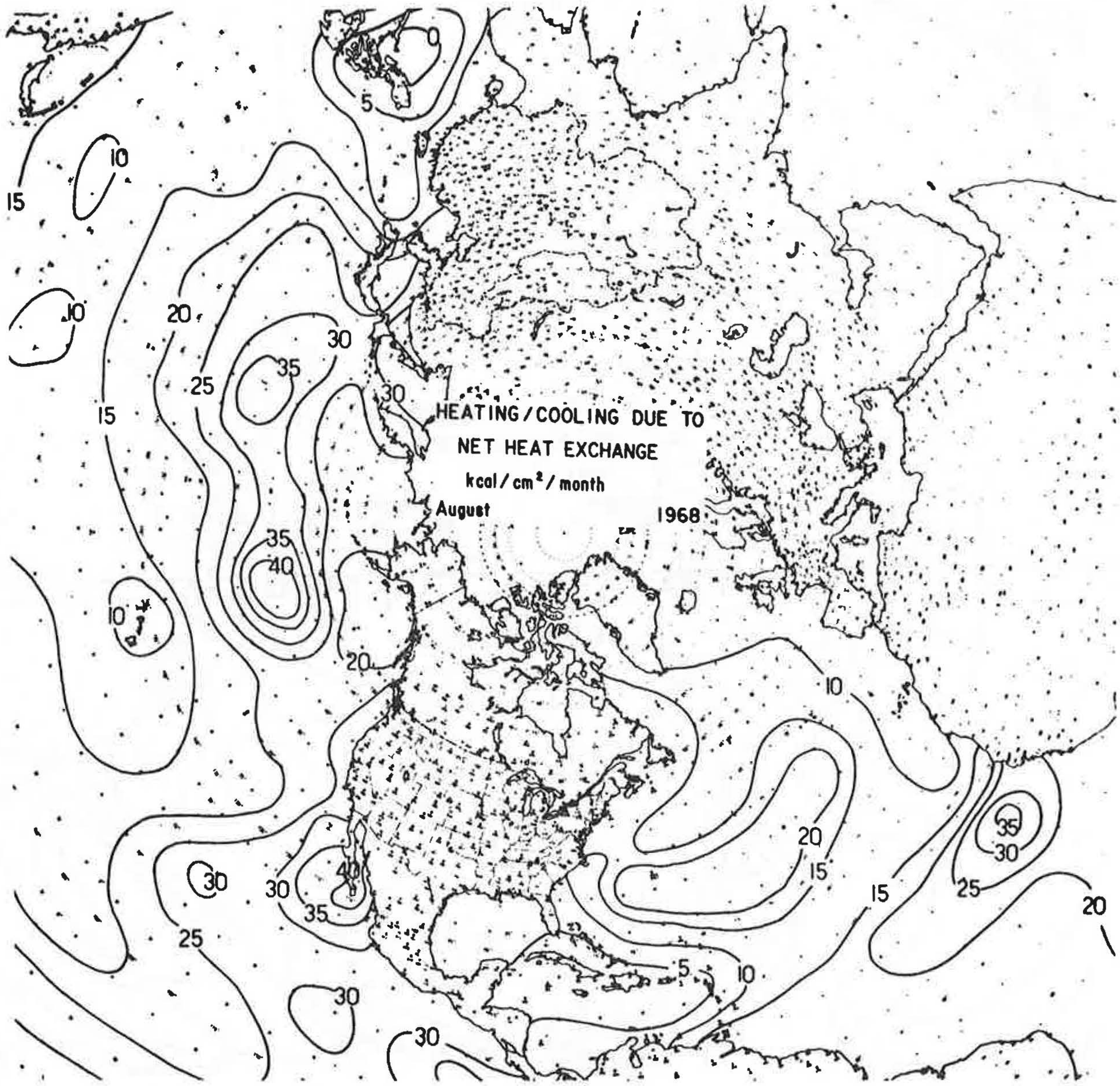

Figure 25.--Heating/cooling of the northern hemisphere oceans due to net heat exchange (k cal cm^{-2} month) in August 1968.

Net heat exchange for August 1967 and 1968 is shown in Figures 24 and 25. The heating patterns are considerably more complex than in February, and considerable year-to-year differences are noticeable, especially along both coasts of the North American continent.

Heat content change in surface layers can also be computed from the twice daily analyses of sea surface temperature and mixed layer depth. This computation includes the effects of transport by currents. An example of heat content change in November 1968 is shown in Figure 26. This figure reflects largely sea surface temperature change (see Figure 21), and also the annual heat content difference patterns (see Figure 9).

Shellard (1962) pointed out in quantitative terms the importance of heat transport by ocean currents. He found that about 85% of the heat has to be transported to Weather Ship I's location (the corresponding value for Weather Ship J was 75%). Both Weather Ships were located off major ocean currents, however.

A general heat budget summary for North Polar Seas, including a consideration of heat advection, has been published by Mosby (1963). A simplified model for the computation of heat transport by the air and oceans has been proposed by Shuleykin (1968). Dickson and Lee (1969) discuss the importance of heat transport with the following words: "It is clear, therefore, that changes in the atmospheric circulation over the North Atlantic have a dramatic response in the sea itself and that there are possibly feedback effects since the ocean is seen to be actively transporting heat from one place to another and not acting merely as a reservoir."

The importance of heat transportation by ocean currents can be visualized by summing the net heat exchange by ocean region. (The basic computations were

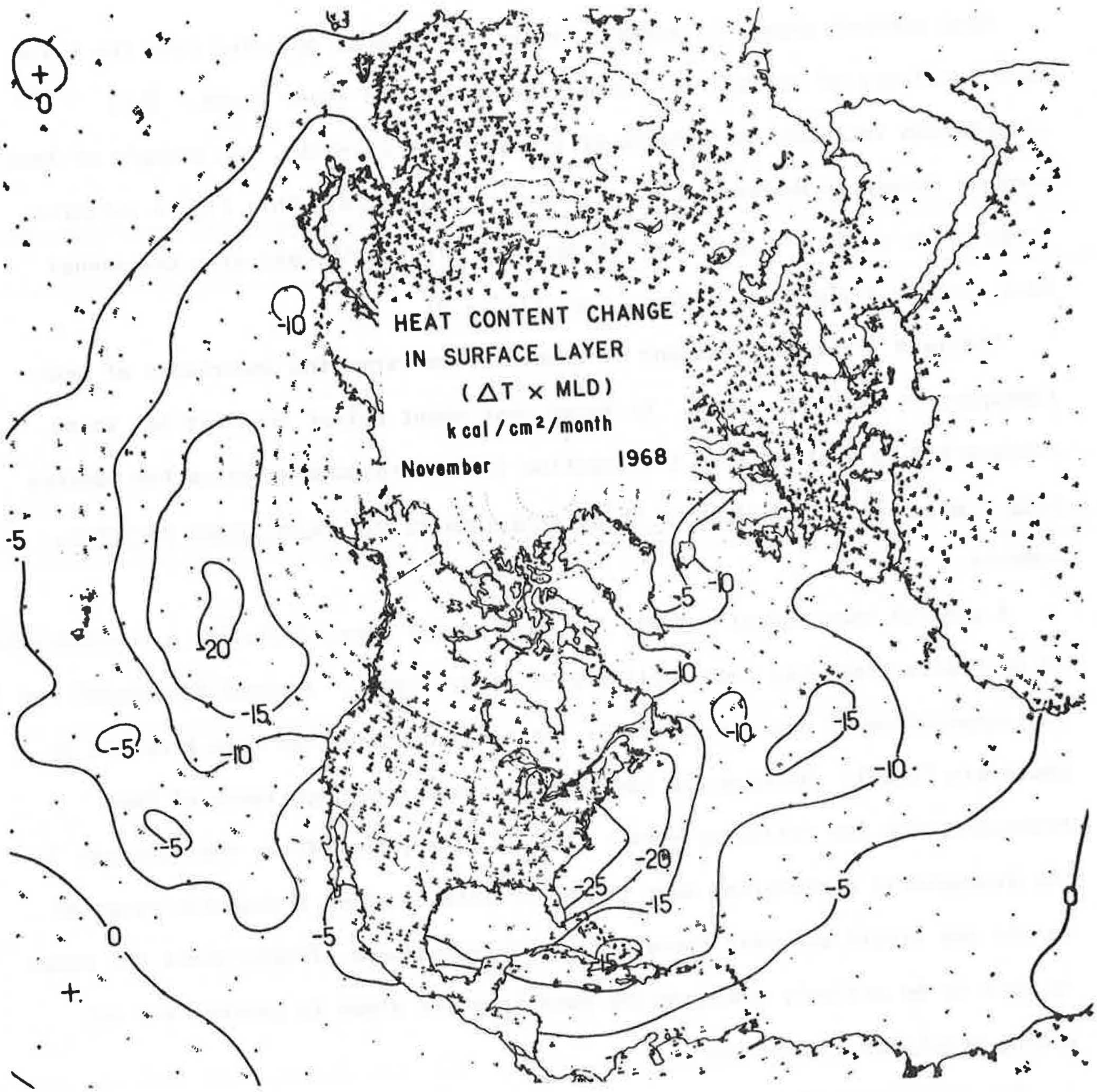

Figure 26.--Heat content change in surface layers above thermocline in November 1968 (k cal cm^{-2} month) (computed from SST change and monthly mean MLD).

done in a 63x63 hemispheric grid for twice daily observations. The total heat surplus and/or deficit of different ocean regions for 1967 is given in Figure 27. A brief, quantitative examination of the heat transport for a few regions follows, testing whether the computed heat deficits can be compensated through heat transport by currents:

1) It is of interest to ascertain whether the Gulf Stream is capable of transporting the heat deficit in Atlantic regions A1, A2 and partly A4 (Figure 27). The respective heat deficits in 1967 in these regions were 169 x 10^{-19}, 228 x 10^{-19}, 228 x 10^{-19}, and 104 x 10^{-19} calories. Assuming the transport of the Gulf Stream to be 100 x $10^6 m^3 sec^{-1}$ (Warren and Volkmann, 1968) (= 3.5 x $10^{21} cm^3 year^{-1}$) and a temperature difference of 5°C between the source and destination regions, a transport of 15.8 x 10^{21}cal per year is possible. The total heat deficit of the three regions listed above is only 5 x 10^{21}cal. However, Wunsch, Hansen, and Zetler (1969) show that according to Wertheim the mean transport of Florida Current fluctuates between 17 and 39 x $10^6 m^3 sec^{-1}$ with mean value about 28 x $10^6 m^3 sec^{-1}$. This value would give a heat transport of only 4.4 x 10^{21}cal with the previous assumptions, thus very close to the heat deficit of 5 x 10^{21}cal. Knauss (1969) summarized other estimates of volume transport of Gulf Stream, which, excluding two high estimates, vary between 33 and 76 x $10^6 m^3 sec^{-1}$. Thus the values above indicate that the variations in volume transport of Gulf Stream may affect the heat supply to downstream regions.

2) Assuming a transport of 10 x $10^6 m^3 sec^{-1}$ for the Alaskan Gyral and a temperature difference of 2°C for source and destination regions, this gyral can transport about 6 x 10^{20}cal. The heat deficit of the corresponding region is 0.9 x 10^{20}cal in 1967.

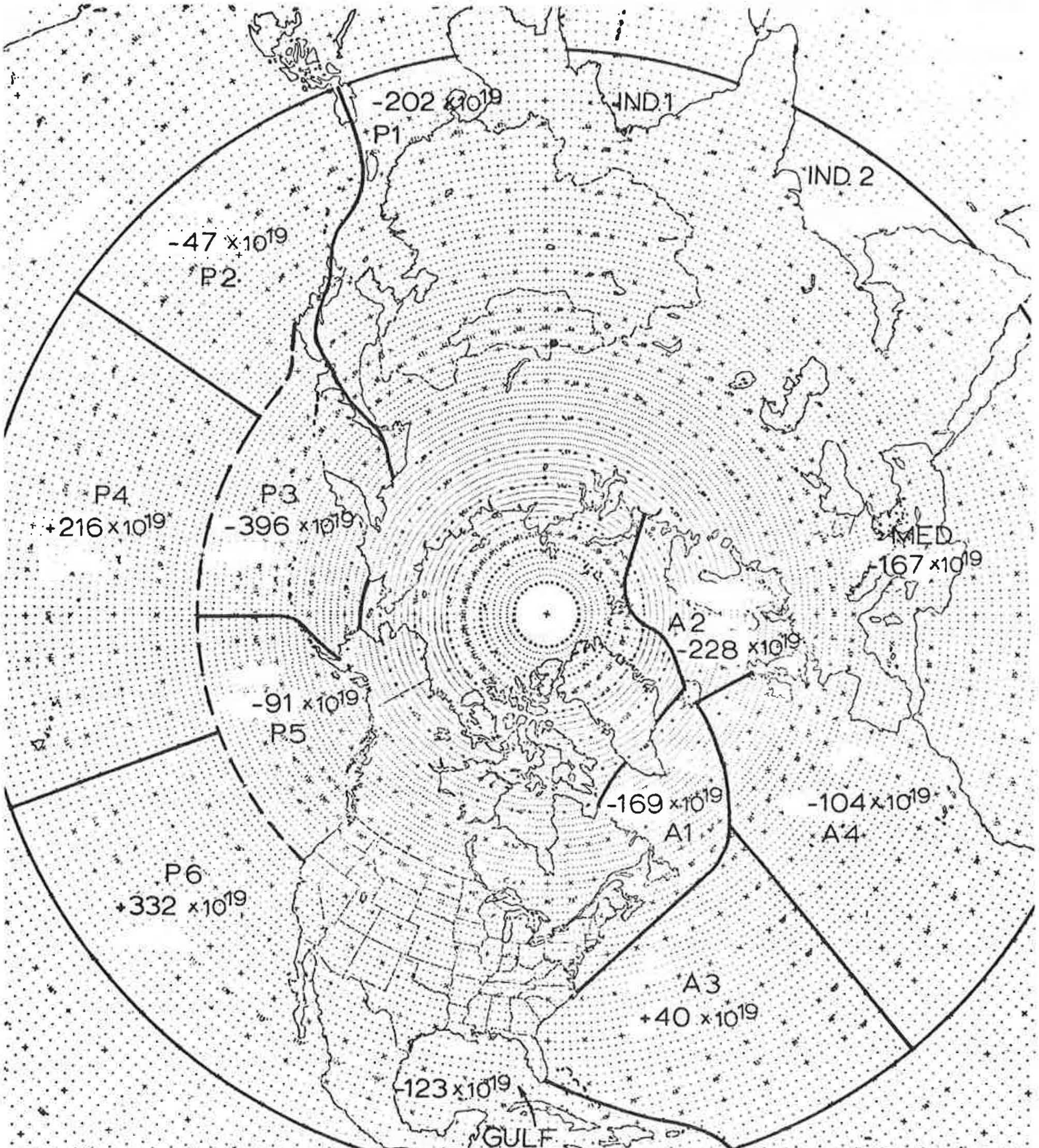

Figure 27.--Total heat gain or loss of the oceanic regions north of 15°N in 1967 (cal year^{-1}).

3) Assuming a plausible value of $10 \times 10^6 m^3 sec^{-1}$ as the transport through the Faeroer - Shetland Channel (which is somewhat above the average (see Dickson and Lee, 1969)) and a temperature difference of 5°C between the source and destination regions, the heat transport would amount to 1.6×10^{31} calories. The corresponding heat deficit of the Norwegian Sea in 1967 was about 2.3×10^{21} calories. Obviously some heat is also transported to the Norwegian Sea between Faeroers and Iceland.

The above sample calculations show that (a) major currents are capable of transporting the required heat in high latitudes, (b) the year-to-year fluctuations in transport through some areas such as Faeroer-Shetland Channel and Faeroer-Iceland area can influence considerably the heat storage of the "downstream" areas, such as Norwegian Sea, and (c) that these fluctuations would have pronounced effects on the weather during the cooling season. Even the fluctuations of Gulf Stream transport may affect year-to-year variations of heat storage in North Atlantic.

It should be noted that the heat loss from the Norwegian Sea might have been above normal in 1967 (average 73.5 k cal cm^{-2}year). For comparison the corresponding value for region A1 was 44.6 k cal $cm^2$2year, and Hankimo (1964) found a mean value of 41 k cal cm^{-2}year for the Baltic.

The above examples indicate the need for exact analyses of current transport and ocean thermal structure and its anomalies in connection with heat exchange computations in order to understand the distribution of heat, its seasonal and year-to-year variations and consequent effects on the weather.

6. SUMMARY

Synoptic sea surface temperature, mixed layer depth, and heat exchange analyses, and climatological ocean temperature data were used to study monthly, seasonal, and interannual variations in heat content of the surface layers of the northern hemisphere oceans.

The annual heat storage changes are largest (>60 k cal cm^{-2}) between 30° and 40°N in the north Pacific, and at about 40°N in the western north Atlantic, south of the Gulf Stream axis. Most of this annual heat storage change occurs in the upper 50 m of the ocean.

The monthly sea surface temperature changes are smallest in the winter (February); however, the thermocline is deep and consequently considerable heat loss at medium and higher latitudes occurs in this season. The highest heat loss from the mid- and high latitude oceans occurs in October and November. Year-to-year differences for individual months in the heating/cooling patterns (and magnitudes) occur. The heating/cooling patterns deduced from sea surface temperature changes are different from those deduced from net heat exchange. These differences are caused by heat transport by surface currents.

Tropical oceans south of about 20°N gain heat year-round. There are considerable heat deficits in net heat exchange in mid- and high latitude regions of the oceans. These heat deficits must be compensated with heat transport by ocean surface currents. Preliminary calculations show that these major currents are capable of this compensation; however, year-to-year differences in current transport is likely to occur, which would affect the availability of heat at mid- and high latitudes. The annual variations in the transport of heat by ocean currents is, however, ill known at present.

7. REFERENCES

Dickson, R. and A. Lee.

1969. Atmospheric and marine climate fluctuations in the North Atlantic Region. Pergamon Press, Progr. in Oceanogr., 5:55-65.

Hankimo, J.

1964. Some computations of the energy exchange between the sea and the atmosphere in the Baltic Sea. Finnish Met. Office Contr. 57:26 pp.

Knauss, J.

1969. A note on the transport of the Gulf Stream. Deep-Sea Res. 16:117-123.

Laevastu, T.

1965. Daily heat exchange in the North Pacific, its relation to weather and its oceanographic consequences. Soc. Scient. Fennica, 31(2):55 pp.

Laevastu, T.

1976. Classification and forecasting near-surface ocean thermal structure. In: Topics in ocean engineering (C. L. Bretschneider, Ed.) Gulf. Publ. 70-85.

Laevastu, T., L. Clarke, and P.M. Wolff.

1970. Annual cycles of heat in the northern hemisphere oceans and heat distribution by ocean currents. Fleet Num. Weather Central, Monterey, Techn. Note 53:19 pp + 52 figures.

Laevastu, T., and J.M. Harding.

1974. Numerical analysis and forecasting of surface-air temperature and water vapor pressure. J. Geophys. Res. 79(30):4478-80.

Laevastu, T., and P.M. Wolff.

1970. Feedback of energy from the sea to the atmosphere. Fleet Num. Weather Central, Monterey, Techn. Note 54: 21 pp + 32 figures.

Mosby, H.

1963. Water, salt and heat balance in the North Polar Sea. Proc. Arctic Basin Symp. 69-89.

Robinson, M.K. and R.A. Bauer.

1976. Atlas of North Pacific Ocean, monthly mean temperatures and mean salinities of the surface layer. Naval Oceanogr. Office, Wash., D.C.

Robinson, M.K., R.A. Bauer, and E.H. Schroeder.

1979. Atlas of North Atlantic-Indian Ocean monthly mean temperatures and mean salinities of the surface layer. Naval Oceanogr. Office, Bay St. Louis, Miss.

Shellard, H.C.

1962. Some calculations of terms in the energy balance for monthly periods at the ocean weather stations I and J in the North Atlantic. Meteorological Office, London, Scient. Paper 11:13 pp.

Shuleykin, V.A.

1968. The climate of Europe as related to heat transfer in the Atlantic. Izv. Akad. Nauk, Atmosph. and Oc. Phys. 4(3):139-148.

Warren, B.A. and G.H. Volkmann.

1968. Measurement of volume transport of the Gulf Stream south of New England. J. Mar. Res. 26(2):110-126.

Wolff, P.M.

1969. Numerical synoptic analysis of sea surface temperature. Int. J. Oceanol. & Limnol. 1(4):277-90.

Wunsch, C., D.V. Hansen, and B.D. Zetler.

1969. Fluctuations of the Florida Current inferred from sea level records. Deep-Sea Res. 16:447-470.