Arch. Met. Geoph. Biokl., Ser. B, 17, 147—174 (1969)

553.583 : 551.515.11 (98)

Department of Meteorology, McGill University, Montreal

Climate Change over the Polar Ocean

III. The Energy Budget of an Atlantic Cyclone[1]

E. Vowinckel and Svenn Orvig

With 14 Figures

Received April 2, 1969

Summary

The heat budget of a deep stationary January Low in the North Atlantic is studied, together with those of a series of peripheral Lows moving around it. The atmospheric and surface budgets are calculated from synoptic data. The system accomplished heat accumulation in its northern part and a decrease in heat storage in the Southwest sector. This was made possible by the effect of the turbulent terms in transporting heat from the ocean.

Zusammenfassung

Klimaänderung über dem Polarmeer

III. Das Energiebudget einer atlantischen Zyklone

Die Wärmebilanz eines tiefen stationären Januartiefs im Nordatlantik wird zusammen mit derjenigen einer Serie darum kreisender Randtiefs untersucht. Die Bilanzen der Atmosphäre und der Erdoberfläche werden auf Grund synoptischer Daten berechnet. Das ganze System führte zu einer Wärmeanreicherung im nördlichen Teil und zu einer Wärmeabnahme im Südwestsektor. Dieses Ergebnis wurde durch die Turbulenzglieder beim Wärmetransport vom Ozean her erzeugt.

1. Introduction

Short period energy budgets should give information on the magnitude of the heat storage changes associated with a particular circulation type (Großwetterlage), and on the role played by advec-

[1] The research reported in this paper was sponsored in part by the National Science Foundation under NSF Grant GA-765.

tion. Such information illustrates the reaction of the earth-atmosphere system to the synoptic conditions. Once a certain number of circulation types have been investigated, over different geographical regions, it will become possible to make statements and predictions about the influence of particular synoptic sequences on the climate and the general circulation.

PETTERSSEN et al. [5] examined the turbulent terms of a model North Atlantic moving cyclone. For climatological purposes the energy exchanges should, however, be studied over particular points. As the cyclone passes over a certain location, the energy budget terms may go through positive and negative phases. The important fact is the aggregate influence of the cyclone. This does not mean that it is unimportant to know the energy budget of different parts of a moving system — clearly this is necessary in order to understand the structure and behaviour of the system. Climatologically, however, it is of importance to know the influence a particular cyclone family, or a particular stationary High, will exercise on the local energy budget.

MANABE [3] investigated the energy budget over the Japan Sea and gave, in fact, the characteristic parameters of a circulation type. The present investigation is somewhat similar, although a larger area will be considered, and additional energy budget components will be included. The discussion will deal with conditions over the North Atlantic between 22 and 28 January, 1967. The synoptic situation was very stable and characterized by a deep central Low, south of Iceland, around which moved a number of peripheral disturbances. These originated in North America and were usually rather weak until coming under the influence of the central Low. They then intensified rapidly over the Mid-Atlantic and moved towards Iceland and Greenland, discernible in the cloud patterns of satellite pictures. The circulation type was persistent, and similar synoptic sequences repeated themselves so that the period was particularly suitable for a study of a typical oceanic energy budget.

The components of the budget were determined following the method previously described by VOWINCKEL and ORVIG [10]. The following elements were calculated for 00 and 12 GMT:

SGA	short wave radiation absorbed at the surface under actual cloud conditions
SGC	short wave radiation absorbed at the surface under conditions of clear sky

SAA	short wave radiation actually absorbed in the atmosphere
SAC	short wave radiation absorbed in the atmosphere with clear sky
$L\uparrow$	long wave (terrestrial) radiation
$L\downarrow$	actual long wave radiation from atmosphere to ground (back radiation)
$L\downarrow C$	long wave radiation from atmosphere to ground (back radiation) for clear sky
$L\,300\uparrow$	actual long wave radiation up across the 300mb level
$L\,300\uparrow C$	long wave radiation up across the 300mb level for clear sky
$L\,300\downarrow$	long wave radiation down across the 300mb level
AS	sensible heat advection (geostrophic)
AW	latent heat advection (geostrophic)
QE	turbulent transport of latent heat
QS	turbulent transport of sensible heat
$DSTG$	change in ground heat storage

The 24-hour average value of each element (X) was obtained by:

$$X_{av} = X_{-24} \cdot 0.25 + X_{-12} \cdot 0.5 + X \cdot 0.25$$

where X_{-24}, X_{-12} and X refer to the values of the element 24 hours ago, 12 hours ago and at present. The 24-hour average values were combined with the values of:

$DSTAS$	change in sensible heat content of the atmosphere
$DSTAW$	change in latent heat content of the atmosphere

These two values were calculated for each 24-hour interval. The sum of $DSTAS$ and $DSTAW$, equal to DST, was used to calculate the net advection, AN, according to:

$$AN = DST + RA + Q,$$

where RA = radiation balance of the atmosphere and Q = sum of the turbulent transport terms.

The advection thus obtained refers to the change in heat content between the surface and the 300mb level. However, this heat amount also varies with the mass changes as reflected in a changing surface pressure. These variations in heat content, due to mass changes, have little influence and in energy budget studies it is more useful to observe the effect of temperature and moisture changes only. The influence of mass changes can be eliminated as follows, obtaining a "corrected" value of advection:

$$ANI = AN - \frac{P - P_{-24}}{P - 300} \cdot ST,$$

where P = surface pressure, P_{-24} = surface pressure, 24 hours earlier, ST = heat storage at the time of P.

The term $DSTG$ is also a complex element. It measures a genuine storage change but also the horizontal heat advection in the water. Oceanographic observations were not available to separate the two effects whose relative importance will change with location. Using sea surface temperatures given by the British Meteorological Office [1], and assuming a depth of seasonal cooling of 200 m, the storage change in January-February amounts to 80—100 ly day^{-1} at 50° N, between 15° W and 35° W.

It is more difficult to estimate the value of ocean heat advection. Using the volume transport for the Gulf Stream given by Sverdrup et al. [6] and assuming a cooling of 5 deg., the mean daily advection over the Atlantic amounts to 66 cal cm^{-2}. Using Model's [4] values for the ocean advected energy used in evaporation between 60° and 30° N, a value of about 90 ly day^{-1} is obtained. These values would apply for the whole ocean and should be much higher in the central part of the Gulf Stream and lower elsewhere, especially in the Canary Current. It is likely that the two components of $DSTG$ are of the same order of magnitude in the area under consideration.

Another complex element is the term $L\downarrow$, the atmospheric back radiation. A certain portion of it is simply re-emission of absorbed terrestrial radiation. Generally, in the following, the components of $L\downarrow$ are not evaluated. Only in a few instances was it of interest to calculate separately the component of the back radiation which was caused by re-emission downward of absorbed radiation from the ground. It was calculated after Vowinckel and Orvig [9].

2. Surface Energy Budget

2.1. The Radiation Balance

The various components of the balance are given in Table 1 for a typical day under this circulation type. The terms $AVERTS$ and $AVERTW$ are the vertical component of atmospheric advection of sensible and latent heat, respectively. The first of these has been combined with the heat released by precipitation (*PR*), the second with the latent heat equivalent of precipitation.

Table 1. *Energy Budget Terms*, 25 January 1967, 12 h
Point 35/33, cal cm^{-2} day^{-1}

	Surface		Atmosphere				Whole System	
		%	Sensible heat	%	Water (heat equiv.)	%	Sensible heat	%
SGA	+115	4.56					+115	2.31
L↑	−784	31.10	+784	13.72				
L↓	+693	27.49	−693	12.12				
QE	−320	12.69			+320	40.40	−320	6.44
QS	−156	6.19	+156	2.73				
DSTG	+453	17.97					+453	9.11
SAA			+53	0.93			+53	1.07
L 300 ↑			−432	7.56			−432	8.69
L 300 ↓			+68	1.19			+68	1.37
AS			+1797	31.44			+1797	36.15
DSTAS			−470	8.22			−470	9.45
AVERTS } *PR*			−1263	22.10			−1263	25.41
AW					+76	9.60		
DSTAW					−252	31.82		
AVERTW } *PR*					−144	18.18		
Total turnover:	2521		5716		792		4971	

The simplest budget is that for the surface, which is shown in Fig. 1 for six days at a point situated east of the central Low. During the period a number of disturbances traversed this region. The most outstanding feature of the radiation balance is the strong dominance of the long wave terms, and their constancy. For the terrestrial radiation this is a reflection of the constancy of the sea surface temperature over synoptic time intervals. The atmospheric back radiation is somewhat less constant, but the lowest value is, nevertheless, still 92 per cent of the highest. The difference between the two extremes, however, amounts to 56 ly day^{-1}, i. e., the same order of magnitude as the short wave component.

The lower part of Fig. 1 compares the net long wave flux with the short wave term. It is clear that the radiation terms are very nearly balanced, in this location and synoptic situation. The greatest difference was —19 ly on the 26th, the day with the least cloud amount and with relatively thin clouds. For the same reason, this was also the day with the highest short wave radiation.

In Fig. 1 the clear sky radiation values are also given, and it can be seen how the presence of clouds dampens the net radiative loss. On the 26th the clear sky net loss would have been —54 ly, but clouds

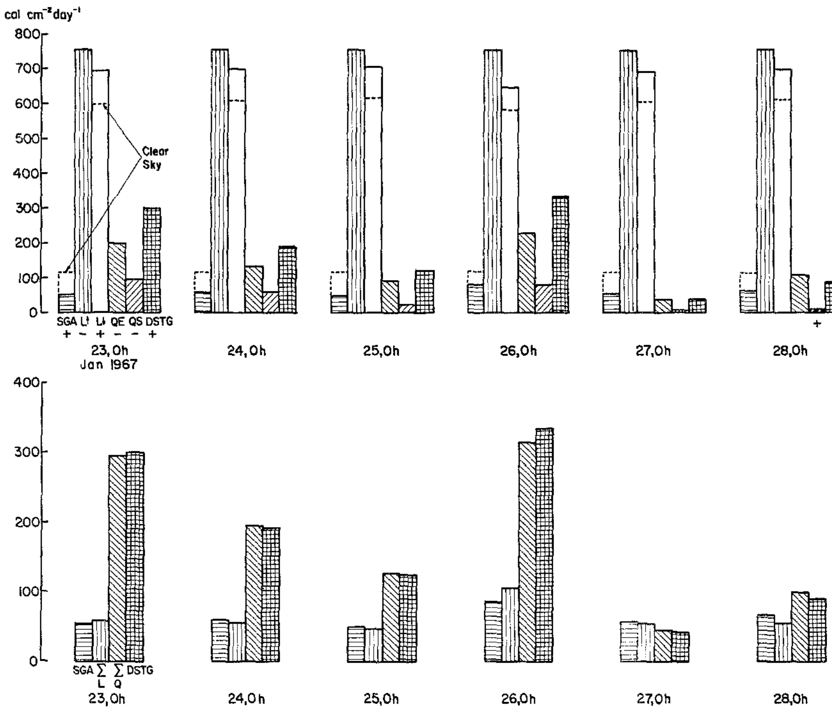

Fig. 1. Surface heat budget, point 31/33, January 23—28, 1967, 0 h

reduced this to —19 ly. On four days the radiation balance was positive, due to greater cloud amount resulting in more heat gain from $L\downarrow$, while the short wave radiation gain was kept up due to relatively high transparency of the clouds.

Fig. 2 shows a cross section of net radiation for clear sky and actual cloud conditions on the western side of the Low. The variations in clear sky net flux are caused solely by the air mass changes. In the southerly latitudes, where the short wave radiation determines the net total, the effect of warm (moist) air advection is to decrease the net radiation. Cold air advection will increase it. In the north the reverse holds true. It is noteworthy that the latitude is rather constant for the change from negative to positive flux under clear sky. The average position of the zero-line for this circulation type, for clear sky conditions, is:

Long.	°W	50	45	40	35	30	25	20	15	10	5
Lat.	°N	46	46	47	47	47	48	50	50	51	51

The position is about 5 degrees lat. farther south in the cold part of the Low than in the warm part. The position of this line must change

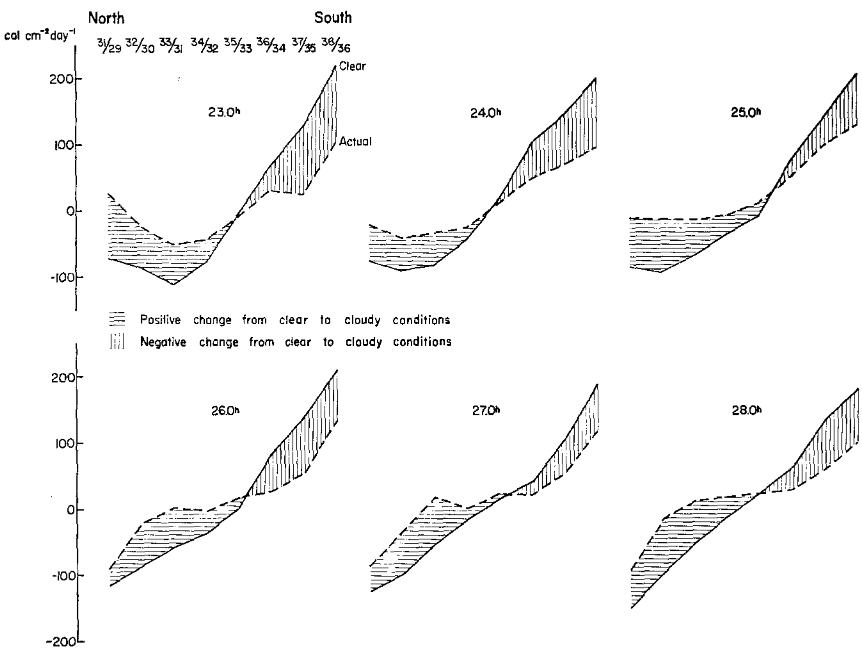

Fig. 2. Cross sections of net total radiation, surface, for clear and cloudy conditions, January 23—28, 1967

with the season. As a first approximation it will depend on solar altitude. The approximate position of the zero-line during the year over the North Atlantic will be:

	15 Jan.	15 Feb.	15 March	15 Sept.	15 Oct.	15 Nov.	15 Dec.
Lat. °N	49	58	74	79	63	51	44

The main changes in the radiation balance, however, are those caused by the cloud conditions. Negative clear sky budgets are made less negative, or even positive, and strong positive budgets are reduced, as is seen in Fig. 2. The influence of clouds on the long wave budget is always to increase the heat gain at the surface, and clouds will always reduce short wave heat gain. The difference in atmospheric back radiation with clear sky ($L\downarrow C$) and with overcast of low clouds ($L\downarrow$) is governed by two factors:

First, the difference is greater the drier the air, because less radiation originates in clear, dry air, and introduction of clouds will be relatively more effective. Secondly, the difference will be smaller with steeper lapse rate. Over the open ocean, surface inversions are rare and the lapse rate below cloud level generally uniform. The result is that this second factor will cause only small changes in back radiation with overcast, over a wide range of air masses and latitudes.

The net effect is that the difference between $L\downarrow$ (overcast) and $L\downarrow C$ varies little, numerically, and the difference will decrease towards the south, where moister air is generally found. The following average cross section shows a maximum in the centre of the cold air, and a gradual decrease southwards:

Point	N	30/30	31/31	32/32	33/33	34/34	35/35	36/36	S
$L\downarrow - L\downarrow C$: ly day^{-1}		+118	+127	+132	+136	+133	+117	+94	

For short wave radiation, however, the cloud depletion is a certain fraction of the clear sky value. Hence, the actual amount lost is not constant but varies with latitude.

These results can be summarized as follows:

a) The positive influence of a cloud cover on the net radiation is restricted to the area poleward of where *SGC-SGA* has a numerical value equal to the maximum gain by clouds in the long wave budget, i. e., where the depletion of short wave radiation by clouds equals the maximum increase in long wave radiation caused by the cloud layer.

b) The positive influence of a cloud cover on net radiation over open water will increase polewards to a maximum value of about 120 ly day^{-1} as the influence of solar radiation vanishes.

c) The reducing influence of clouds on net radiation in more southerly latitudes will progressively increase, as *SGC* increases. The highest reduction in net radiation which can be obtained in the Atlantic Subtropics, in summer, is about 400 ly day^{-1}.

The situation under study demonstrates that the cloud distribution of the Low has the effect of increasing the radiation balance in the north and reducing it in the south. This is due to the particular location of the cyclone, and to the time of year. Later in the season, the influence of the Low would have become gradually more negative. Similarly, with a more northerly position, the Low would have increased the radiation balance. Fig. 3 shows that a position of the

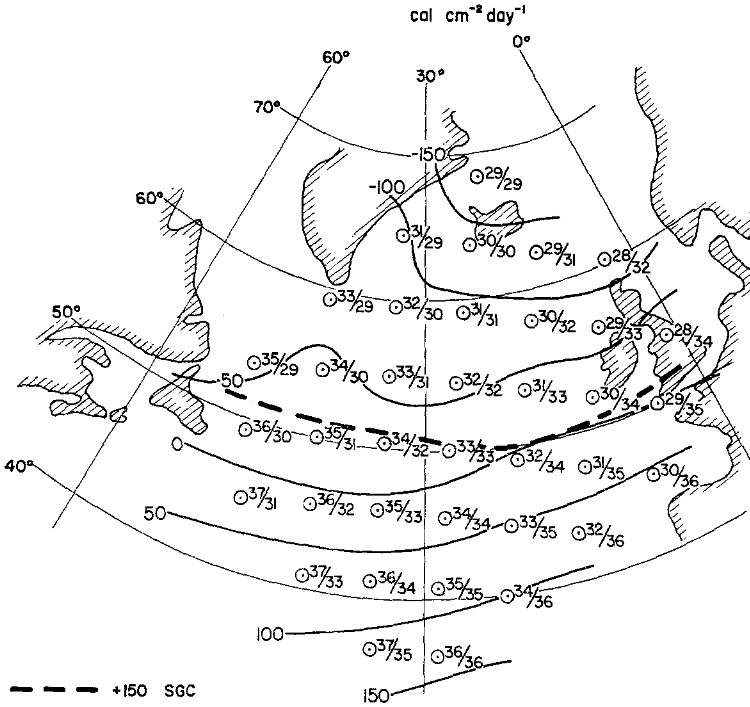

Fig. 3. Net total radiation, surface, clear sky, mean for period January 23—28, 1967, in cal cm^{-2} day^{-1}

whole system north of 50^0N would have resulted in an increased radiation balance in all parts of the cyclone (50^0N is the approximate position of the isopleth for $SGC = +150$ ly day^{-1}, which is the position where is obtained a difference SGC-SGA of about 135 ly day^{-1}).

Such simple conditions can only exist over the ocean, with its conservative surface temperature, low and fairly uniform cloud level, as well as relatively uniform temperature gradients in the air near the surface.

The synoptic variations of the radiative terms, caused by the passage of a peripheral Low, are shown in Figs. 4a—c. The first of these shows short wave radiation actually absorbed at the surface (SGA).

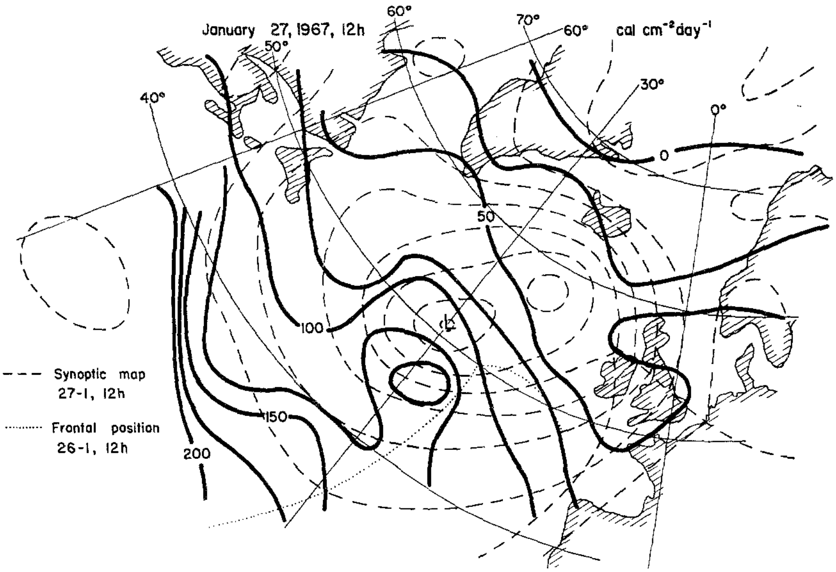

Fig. 4a. Short wave radiation absorbed at the surface, January 27, 1967, 12h

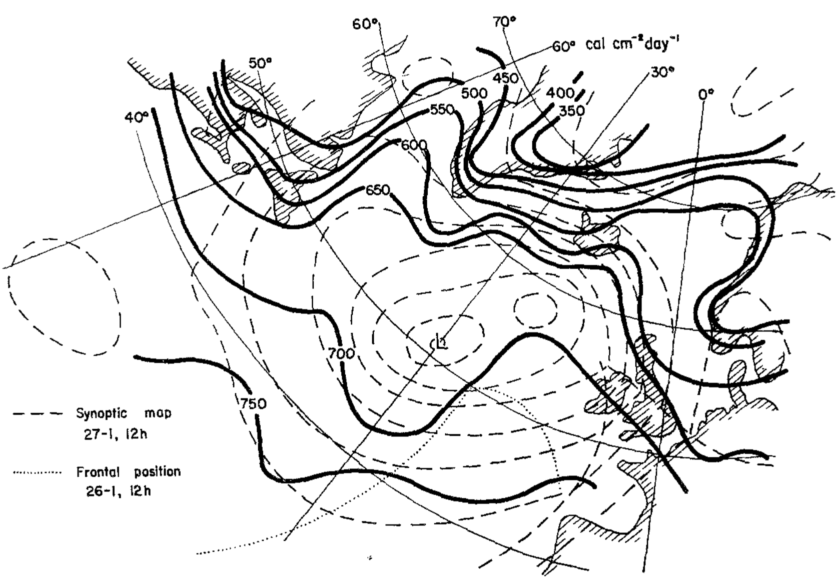

Fig. 4b. Atmospheric back radiation, January 27, 1967, 12h

Under the heavy cloud shield ahead and to the north of the moving cyclone, *SGA* decreased, while it increased in the clearing area behind the cold front. Fig. 4b shows the opposite: back radiation ($L\downarrow$) increased ahead and to the north of the peripheral cyclone,

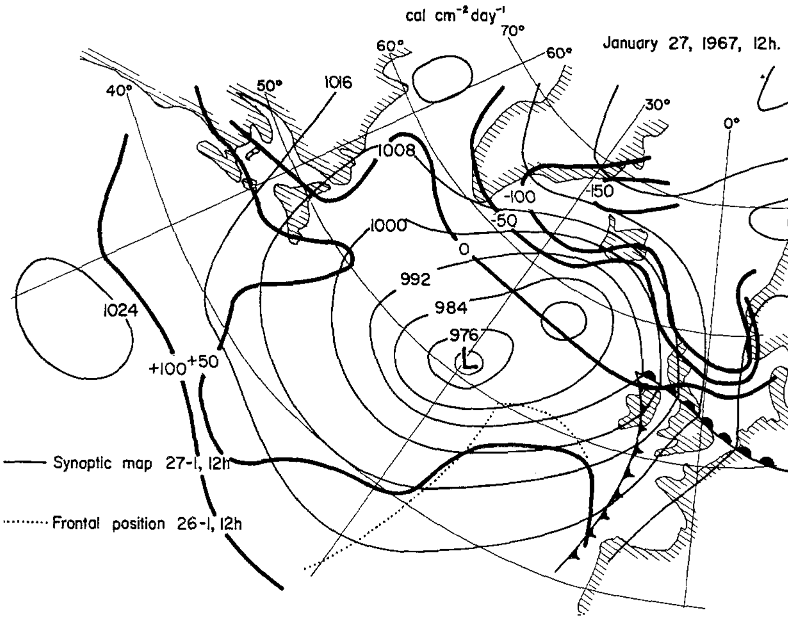

Fig. 4c. Net total radiation, surface, January 27, 1967, 12h

while it dropped in the rear. The net effect, shown in Fig. 4c, is a weak gradient in net radiation over the whole area, with a tendency for positive deviations ahead and to the east, and negative in the rear and west.

It thus seems to be of crucial importance for the surface radiation balance over the ocean that $L\uparrow$ is, essentially, constant and not affected by the synoptic patterns. Accordingly, the variations in the radiation budget are likely to be significantly greater than over land surfaces, where $L\uparrow$ quickly adjusts to the variable sum of *SGA* plus $L\downarrow$.

It should be stressed that, for the surface radiation budget, a strong cyclonic system such as the one under study, is not the most favourable. It is best for the surface balance to have little or no Nb and Ns clouds, and mainly middle and high clouds, because the reduction in short wave radiation would be less and this would more than compensate for the decrease in $L\downarrow$ due to the lower radiating temperature of the clouds.

Finally, it is of interest to assess the amount of energy actually radiated from the atmosphere to the ground when excluding the greenhouse effect (that part of $L\uparrow$ which is absorbed and re-radiated downwards). The areal distribution of such atmospheric radiation for the average conditions of the central Low turns out to show a rather slight latitudinal variation, and the values are very large — about 200 to 260 ly day^{-1}. This is more than the short wave contribution to the surface radiation balance. Long wave radiation is thus the method used by the atmosphere to transfer heat to the surface, and it is in this way that the energy is made available to the ground which has been advected from lower latitudes as sensible or latent heat. Advected heat is, of course, essential for maintaining the ground temperature, and hence $L\uparrow$, at a relatively high level in winter.

Even in low latitudes, including the tropics, the atmosphere radiates appreciably to the surface. This indicates only that the atmosphere is everywhere warmer than its radiative equilibrium state. It is thus evident that the non-radiative, turbulent, processes must transport considerably more energy into the atmosphere than the amount required in poleward heat advection.

Comparing the distribution of total atmospheric back radiation ($L\downarrow$) and the part of it ($L\downarrow A$) which is not due to absorption of terrestrial radiation, it is found that the patterns are very similar. Their ratio remains remarkably constant: $L\downarrow A/L\downarrow$ varies between 0.3 and 0.4.

2.2. The Turbulent Fluxes

The striking feature of these terms is that their magnitudes show little similarity to the radiative budget. This is evident in Fig. 1. The second characteristic is their great variability. The range in values, at each point for the whole period, along a W—E cross section for the various surface budget terms, is shown in the following (ly day^{-1}):

Point	38/30	37/31	36/32	35/33	34/34	33/35	32/36
SGA	79	27	48	72	56	63	37
$L\uparrow$	25	26	8	7	7	3	4
$L\downarrow$	38	48	49	59	71	80	52
QE	137	79	176	323	299	150	234
QS	117	65	98	192	86	93	73
$RNET$	35	32	24	33	35	27	34

From Fig. 1 it can be seen that the disparity between the turbulent and other terms would have been even greater if the values were expressed in per cent of the mean of each element. The lack of similarity between radiative and turbulent fluxes is opposite to the results obtained over land or ice surfaces, as shown for example by VOWINCKEL [8]. The two modes of energy transfer are physically different but linked by the requirement that the total budget must balance. As the ocean is a larger heat reservoir, the energy requirements can almost always be met by drawing on storage. There are cases where a certain relationship may be seen between radiative and turbulent terms. The 26 January, in Fig. 1, shows a situation where the negative radiation balance and the turbulent flux reached their maximum values. The storage change term therefore also reached its highest value. This can happen if a cold air mass is advected over the ocean, causing increased evaporation and sensible heat flux as well as cloud and moisture conditions effecting reduced back radiation. If a position were chosen at a lower latitude, a high positive radiation balance would occur with high turbulent flux.

In general, the geographic distribution of the turbulent fluxes shows a similar picture to that described in other studies (CHISHOLM [2]; VOWINCKEL [7]). The differences are caused by the fact that the present period was dominated by a central Low. The main belt of evaporation then remains fairly stationary in the SW quadrant, although the peripheral disturbances cause changes in the gradient, and the associated air masses create expansions and contractions in the zone of maximum evaporation. Points in the SE sector of the central Low showed markedly lower evaporation rates. Table 2

Table 2. *24-Hour Heat Equivalent of Evaporation and Time of Passage of Peripheral Lows, in Two Quadrants*

January	21 12 h	22 0 h	22 12 h	23 0 h	23 12 h	24 0 h	24 12 h	25 0 h	25 12 h	26 0 h	26 12 h	27 0 h	27 12 h	28 0 h
SW														
QE ly day^{-1}			522	274	269	336	396	319	307	399	445	411	289	241
Low passing point 36/32:	X				X				X					X
SE														
QE ly day^{-1}			210	283	228	98	107	186	128	41	6	24	79	61
Low passing point 31/35:				X				X				X		

gives the evaporation heat equivalent for 24 hours, centered at the indicated time, and the passage of peripheral Lows over point 36/32 in the SW sector and over point 31/35 in the SE quadrant.

The lower evaporation in the SE sector is clearly demonstrated, and the peak in evaporation after each Low passage is seen to occur sooner in the SE than in the SW. The drop in evaporation ahead

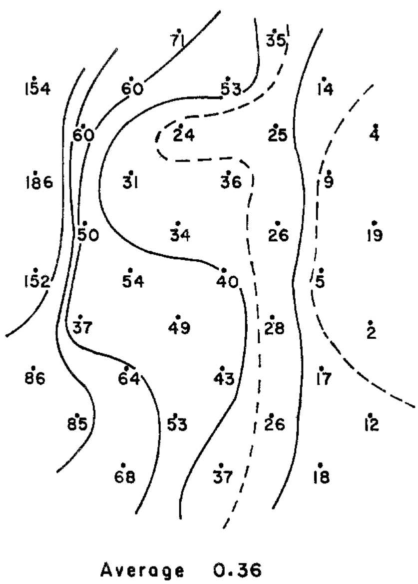

Fig. 5. The Bowen ratio QS in per cent of QE, mean for period

of the disturbance results in lower values in the SE than in the SW. The flow of air will then be south or southwesterly over the East part of the ocean.

The sensible heat term, QS, follows the same pattern as QE, although it remains much smaller. Fig. 5 shows the mean Bowen ratio. QS takes on greater relative importance on the cold side of the Low.

2.3. Time Sequences of Surface Terms

Fig. 6 shows detailed 12-hourly time sequences for all surface terms for three points around the central Low.

Point 33/35, to the south, saw the passages of well developed Lows with different air masses. The sequence begins on the 22nd, on the rear side of such a Low. In the strong wind field both QE and QS are very large, requiring a high $DSTG$. The SGA term was only moderately high due to extended clouds behind the disturbance. By the 24th a new Low had passed, bringing warm air advection ahead of it, with clouds and rather low SGA but rising value of $L\downarrow$ and drastic reduction in the Q terms. The rear of this Low brought similar conditions to those on the 22nd, except that the cloud amount was less. This resulted in an increase in SGA and decrease in $L\downarrow$. It should be noted that $L\uparrow$ remained unaffected by all this activity. The 25th and 26th brought another Low passage, with even stron-

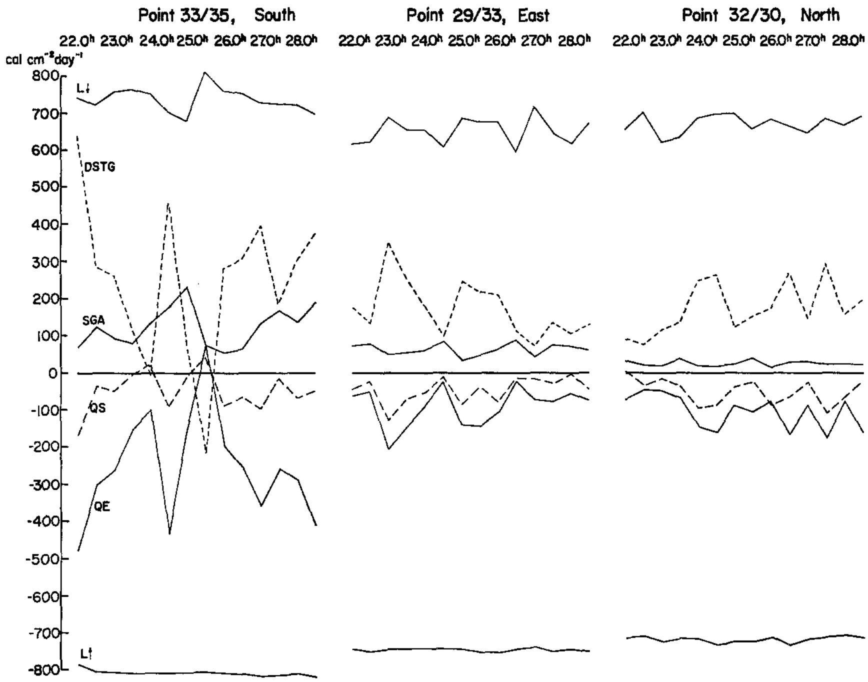

Fig. 6. 12-hourly time sequences of surface terms at three points around the central Low

ger warm air advection. Turbulent heat transport took place from air to surface. Although the radiation balance actually became less favourable, nevertheless there was an increase in heat storage.

The second point, 29/33, lies on the east side. The peripheral Lows are still discernible, with the cold sides passing on the 22nd, 24th and 26th. Although they in principle exhibit the same phenomena, the differences are less marked. The air masses involved in this location had been modified. Even the cold air arrived from the south-west, and no warm sectors were present. Also the wind, which partly governs the Q terms, was weaker.

The third point, 32/30, lies on the north side of the central Low. It is just possible to notice the remnants of the distinct cloud fields of the peripheral Lows. It can be seen that the variability of the various terms changes drastically from the first to the third point, except that the change is less pronounced in the back radiation. The reason is that the differences in cloud amount and type between front and rear of a cyclone remain more important than those of the air masses and wind fields.

2.4. The Circulation Type

The large-scale synoptic situation remained essentially unchanged between the 23rd and 27th. This period therefore depicts a circulation type. Although the discussion has shown that the energy budget

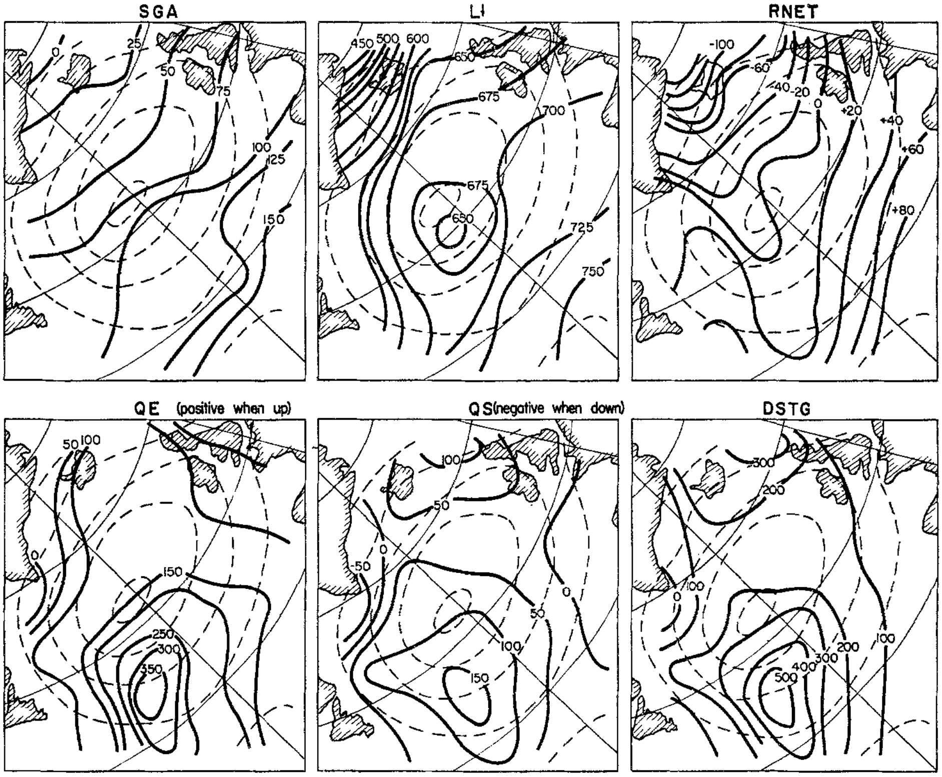

Fig. 7. Distribution of average surface energy balance terms, January 23—27, 1967, cal cm^{-2} day^{-1}

will vary substantially with the passage of individual Lows, it is nevertheless justified to average over the period. Thus only the net effects of the moving Lows is maintained. Fig. 7 shows the areal distribution of various elements for this circulation type. Most of the features have already been discussed. Of particular interest is the minimum of $L\downarrow$, situated southwest of the centre of the central Low, caused by the fairly clear sky in this area. It is a situation often observed in satellite photographs, that the clouds seem to swirl around a Low with a minimum developing near the centre. Extended cloud sheets usually reappear further to the northeast of the Low centre.

The map of *DSTG* appears as a pattern similar to that of the turbulent terms. The ground storage change may be considered to be the amount of energy expended in excess of income. Only in the most northern part of the Low do radiational energy requirements contribute significantly to heat release from the ocean.

The average values are shown in the following, of the surface budget terms in different sectors of the Low, and for the system as a whole (ly day^{-1}):

Sector	*SGA*	$L\uparrow$	$L\downarrow$	*QE*	*QS*	*DSTG*
NW	+53	−691	+635	−84	−31	+117
SW	+102	−757	+678	−244	−113	+334
SE	+106	−775	+709	−146	−20	+126
NE	+45	−733	+659	−111	−53	+193
Whole Low	+80	−745	+675	−147	−52	+189

These values show that a weather pattern such as that described will put the greatest demand on storage in the SW sector. Assuming a demand of about 350 ly day^{-1} by a winter atmosphere with this circulation pattern, and further assuming that at least 50 m of water will be affected due to turbulent mixing, the result will be a cooling of this water column of about 1 degree C in two weeks. It is thus apparent that the heat release from storage can be maintained at the required level for as long as the weather pattern is likely to persist.

It is also apparent, however, that a similar surface energy budget could not be maintained over another surface, whether ice or land, as no such energy amounts could be made available at those surfaces.

3. Atmospheric Energy Budget

3.1. The Radiation Balance

The atmospheric budget is more complicated than that of the surface, because additional terms appear, both for long wave radiation and advection. Long wave radiation is received from above and below and again emitted in both directions. In the present investigation the total of $L\uparrow$ was considered as a gain for the atmosphere, and the total of $L\,300\uparrow$ as a loss, although in reality part of $L\uparrow$ passes directly through the atmosphere. As this method counts the transmitted energy first as a gain and secondly as a loss, the resultant turn-over of long wave radiation will be exaggerated. However, the error will be small over the Atlantic, since cloudy conditions prevail and all terrestrial radiation ($L\uparrow$) is absorbed under overcast sky.

Fig. 8 shows a N—S cross section of radiative terms on a day when a deep peripheral Low was present. The income side of the atmospheric radiation budget is completely dominated by $L\uparrow$ which is practically constant with time and which increases gradually towards the South. Even more constant is $L\,300\downarrow$, although observa-

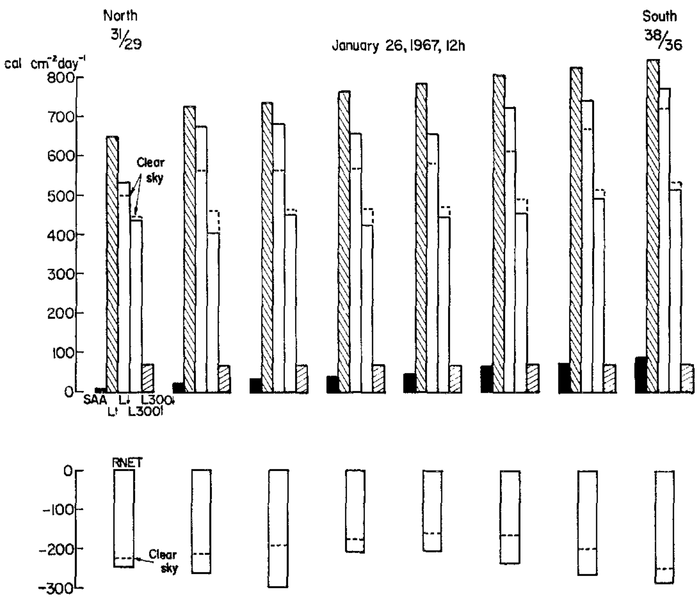

Fig. 8. N—S cross section of atmospheric radiative terms, January 26, 1967, 12h

tions above 300 mb were lacking in this investigation and little significance should be attributed to these values. It is, however, unlikely that the actual variations in this term will have much importance.

The short wave contribution shows the expected rise southwards, although it remains small. It is interesting that its southward increase is less than that of $L\uparrow$, so that its per cent contribution in fact decreases from North to South. It is apparent that the positive side of the radiation budget will remain rather stable, regardless of the weather pattern over the area. It will therefore be the expenditure side which will be decisive for the budget.

In general, $L\downarrow$ increases with temperature and moisture content. With higher moisture content the effective radiation level lies closer to the surface and, with the usual lapse rate, the higher will be the radiative temperature. The relation between $L\uparrow$, the dominant gain term, and $L\downarrow$ is therefore determined by the relation between stability in the lower atmosphere and its moisture content. For the cross section in Fig. 8, $L\downarrow C$ (clear sky back radiation) is related to $L\uparrow$ as follows:

	North							South
Point:	31/29	32/30	33/31	34/32	35/33	36/34	37/35	38/36
$L\downarrow C$ in % of $L\uparrow$:	77	77	77	74	74	76	81	86

In the northern part of the system, conditions are rather stable under the influence of highly modified air circulating around the Low. Accordingly, relatively high values are obtained, in spite of generally cool temperatures. At points 34/32 and 35/33, unstable fresh cool air near the centre of the Low shows lower values. Further southwards the values rise again as the temperature and moisture content increase. Fig. 8 shows that the presence of clouds enhances the value of $L\downarrow$. Towards the southern edge of the system the decreasing cloud amount will counteract the increase in moisture and temperature.

Conditions are quite different for $L\,300\uparrow$. With clear sky this radiation shows a gradual rise southwards, which becomes steeper on the south side of the cyclone, but which remains smaller than the increase in $L\downarrow C$. While the latter increases by a total of 232 ly day^{-1}, the value of $L\,300\uparrow C$ gains only 83 ly day^{-1}. The influence of clouds on $L\,300\uparrow$ is opposite to that on $L\downarrow$; clouds reduce the former because no radiation can reach 300 mb from the surface and warm air of the lower atmosphere. The cloud top temperature becomes dominant. The effect of clouds on $L\,300\uparrow$ depends on the height of cloud tops, the highest clouds causing the most pronounced effect.

Considering now the net radiation, the cyclone has a significant influence, exercised through both the cloud and air mass distributions. The atmosphere radiation balance is always negative. Under average conditions its magnitude should increase gradually southwards. The cyclone, however, causes the net values to increase in the north, with a minimum in the centre and SW sector of the Low. Fig. 9 shows two W—E cross sections. Here the latitudinal effect is largely excluded. The more southerly section shows the larger negative values of net radiation on the warm, moist side of the

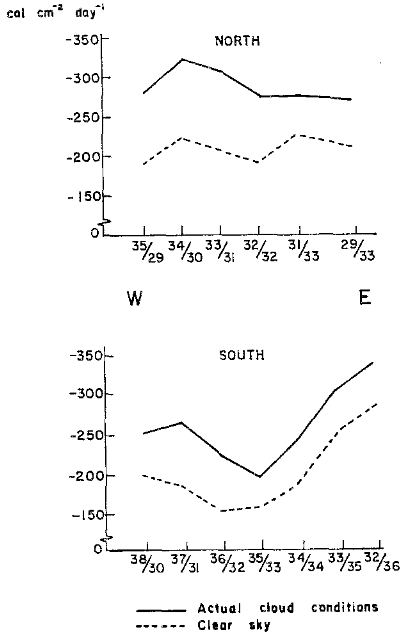

Fig. 9. W—E cross sections of atmospheric net total radiation, January 27, 1967, 0 h

peripheral Low, and smaller negative values some distance behind the cold front. Here is found the coldest and driest air. From that minimum can be seen a gradual increase in net radiation westwards into warmer air. The influence of clouds is most pronounced in the west, in the rear of the moving cyclone, as the difference in emissivity between overcast and clear sky is greatest if the latter is found with dry and cold air.

The northerly cross section cuts through the central Low only. The clear sky net radiation shows little longitudinal change, but the actual balance had a markedly higher negative value in the west, over the area with the most extensive cloud sheets. The cloud amount in the west was 9.0—9.5, while in the east it was only 5.5.

Fig. 10 shows the average geographical positions of maxima and minima in the radiation balance. In the general circulation pattern of a deep central Low there are two areas of maximum loss: in the south and southeast, caused by warm air surges carried by peripheral disturbances, and in the northwest, due to warm air and

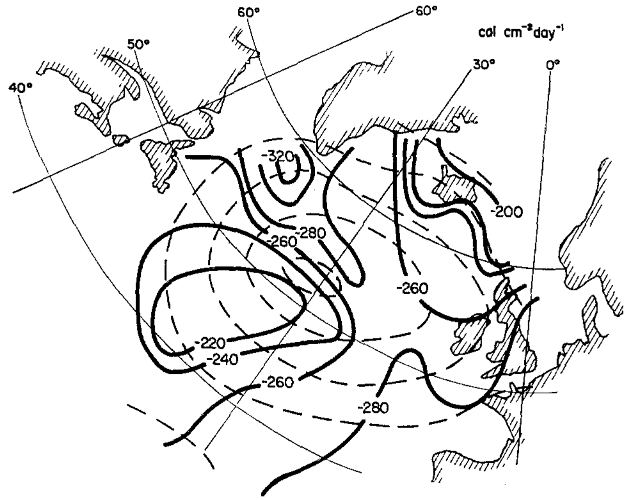

Fig. 10. Net total radiation, atmosphere, mean for period

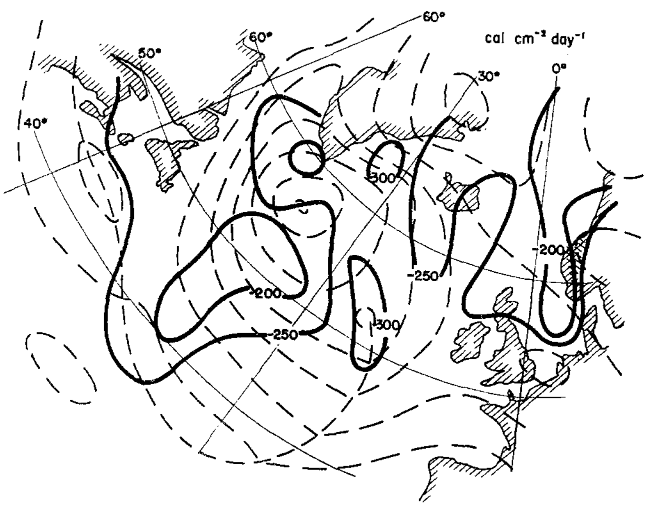

Fig. 11. Net total radiation, atmosphere, January 24, 1967, 12 h

cloud decks carried around the Low. The average for the period shows that the NW maximum was the stronger, being more persistent in its position and characterized by lower energy supply from below due to a colder sea surface. Fig. 11 shows the atmospheric radiation balance on a particular day, when the SE maximum was as strong.

A pronounced minimum occurs in the SW quadrant, in the average as well as in individual cases, due to the predominant cold air advection and relatively small cloud amounts.

3.2. Non-Radiative Terms

The turbulent components are the only other parameters which do not require energy transport from outside. Their magnitude is the same as for the surface budget, but their sign is reversed: loss at the surface appears as gain in the atmosphere. If the turbulent flux values are added to the radiation budget, the result will be the amount of energy gain or loss which would occur in the atmosphere, if there were no advection. The values for three cross sections are as follows, for 27 January at 0 h.

W-E, southerly section:		38/30	37/31	36/32	35/33	34/34	33/35	32/36
$RA+Q$ (ly day^{-1}):		−129	−37	+444	+341	+62	−248	−406
W-E, northerly section:		35/29	34/30	33/31	32/32	31/33	29/33	
$RA+Q$ (ly day^{-1}):		−188	−205	−184	−139	−233	−182	
N-S:	31/29	32/30	33/31	34/32	35/33	36/34	37/35	38/36
$RA+Q$ (ly day^{-1}):	−194	−63	−184	−11	+341	+277	+192	−69

It is apparent that the turbulent fluxes are sufficiently strong to more than compensate for the atmospheric radiative loss in the rear of the cyclone, particularly in the SW quadrant. This is due not only to high turbulent values, but also to the fact that the negative radiation balance is relatively small in this area.

It was said in the Introduction that energy budget calculations are better served by using for advection a value corrected for the influence of mass changes in the column from surface to the top (*ANI*) rather than the value for net advection (*AN*). The latter is the quantity usually discussed in meteorological literature. A comparison of the two values is given below, for a N—S cross section. The values are totals for the two advection terms for six days at each point, in cal cm^{-2}.

	N						S
Point:	31/29	32/30	33/31	34/32	35/33	36/34	37/35
AN:	−174	−421	−823	+1019	+310	+445	+652
ANI:	−974	−732	−394	−402	+474	+1339	+1837

In general, *ANI* is numerically greater than *AN*, which should be expected as cold air advection is usually related to rising pressure, and vice versa.

The radiative and turbulent terms showed essentially unchanged patterns from day to day. The synoptic situation influenced only their magnitude. This was not the case for *ANI*, nor for the change in sensible and latent heat content of the atmosphere (*DST*). When discussing advection and storage change it is, therefore, best to consider the

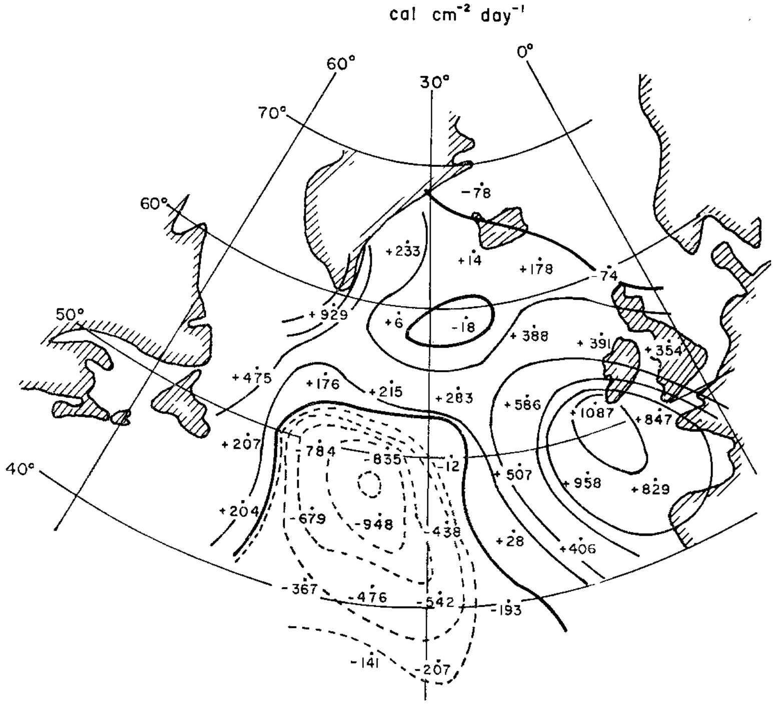

Fig. 12. Advection, mean for period

net effect of the circulation type, rather than distributions for individual days. Fig. 12 shows the mean advection for the period, and Fig. 13 the mean sensible and latent heat storage change. These illustrations show that both distributions display a rather similar pattern, i. e., the change in atmospheric heat content is the result of advection, in agreement with synoptic experience. The result of a circulation type such as the present is thus to accomplish accumulation of heat in the northern parts of the system and a decrease in heat storage in the SW sector.

The advection figures will only take on meaning when considered in conjunction with the other atmospheric budget terms. The follow-

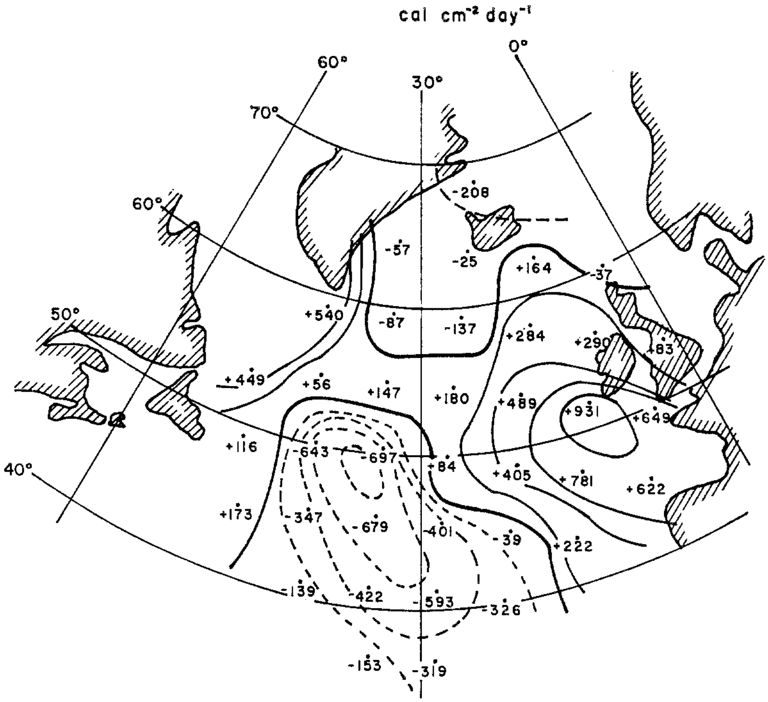

Fig. 13. Atmospheric heat storage change, mean for period

ing values show the budget terms for the whole Low and for the four sectors (positive sign for *DST* means storage increase).

Sector	*DST*	*ANI*	*Q*	*RA*	(ly day^{-1})
NW	+175	+339	+115	−279	
SW	−330	−460	+357	−227	
SE	+212	+316	+166	−270	
NE	+143	+233	+164	−254	
Whole Low	+60	+116	+201	−257	

It is seen that, in the Low as a whole, the advection alone would not be able to compensate for the loss by radiation, not to mention the small increase in heat storage. Only in the NW and SE sectors is the advection sufficiently strong to compensate for the radiative loss without assistance. For the system as whole, the contribution of advection is considerably less than that of the turbulent fluxes.

It can therefore be said that the main result of a weather system such as the present over the ocean is, primarily, a redistribution of the heat storage within the system. This is made possible, however, by the pronounced effect exerted by the system on the turbulent terms. In the absence of advected energy import, the atmospheric budget ($RA + Q$) would be -56 ly day^{-1}, which is only about one fifth of the radiation balance. It is of interest to note that under clear sky conditions, $RA + Q$ would actually be very nearly balanced in the system. RA for clear sky would be -207 ly day^{-1}, compared to the Q value of $+201$. An optimum balance for the atmosphere would therefore be reached under a strong circulation system, such as that being studied, but without clouds. It is obvious that this cannot be realized under oceanic conditions. The nature of this circulation type is therefore such that a part of its effect in releasing energy via turbulence and transporting northward via advection will be lost for the atmosphere by the automatic increase in cloudiness.

Also, the effect of clouds will be more pronounced the colder the air mass and less its moisture content. With dry air the cloud free atmosphere will radiate less, and hence the increase will be greatest when clouds are introduced. Thus, the cyclonic cloud development will degrade the energy budget most when the system is located in a far northerly position, and when it is a winter situation.

4. System's Energy Budget

The details of the atmospheric energy budget are rather different from those of the surface. Neither of these can stand alone, however, and it is necessary to consider the energy budget for the whole earth-atmosphere system. If heat loss from ocean storage ($DSTG$) is considered to be a loss for the system, the energy balance can be written as:

$$-DSTG + DST + ANI + SGA + SAA + L\,300\downarrow - L\,300\uparrow = 0.$$

The term $DSTG$ can also be regarded as an income term if heat is given up by the ocean. The system is then defined as extending from 300 mb down to just below the surface.

The average values (ly day^{-1}) for the earth-atmosphere system are (positive sign for *DSTG* means heat release from the ocean):

Sector	*DST*	*ANI*	*RNET*	*DSTG*	*DST+DSTG*
NW sector	+175	+339	−282	+117	+58
SW sector	−330	−460	−204	+334	−664
SE sector	+212	+316	−230	+126	+86
NE sector	+143	+233	−283	+193	−50
Total system	+60	+116	−246	+189	−129

Thus, if the whole subsurface column is included in the system, the central Low causes a decrease in stored energy, located almost exclusively in the SW sector.

Over ocean areas, where *DSTG* includes ocean advection and where the heat reservoir is very great indeed, it seems more appropriate to regard *DSTG* as potential energy, available to the system if conditions are favourable. Solar energy is somewhat similar. Then, the energy budget of the system is positive for the Low, as *DST* is positive.

The essential point to be made for the system as a whole is that the atmospheric part is highly mobile, while the surface — even over the ocean — is essentially stationary. Atmospheric storage change is therefore reversible, but this is not true for ground storage. Neither turbulent nor long wave processes can cause any appreciable amounts of heat to be transported down into the ground. The rare occasions when such transport does take place are restricted to certain localities and the downward transport is always very small, compared to the values of upward transport situations. Terrestrial radiation is so efficient in removing turbulent and long wave heat from the surface that the only possible re-charging of ground storage is by absorbed solar radiation and, in the ocean, by currents. The latter contribution can be regarded as a constant, since its variations are much smaller than those of atmospheric advection. In the present discussion it is disregarded. It is then apparent that the re-charging of ground storage will be seasonal, i. e., it will be negative throughout the winter.

The atmospheric advection is highly variable and readily adjustable to the radiation budget requirements. A weather type which reduces the radiational heat loss from the surface will be the most energy conserving for the radiation budget. Thus, the role of advection in the energy budget is, essentially, to supply the energy for $L\downarrow$ and $L\,300\uparrow$. A large value of $L\downarrow$ is most favourable for the long term conservation of the non-replenishable energy source which is ground heat storage. That this also implies a large upward loss, $L\,300\uparrow$, is incidental and only states that conservation of ground heat storage is coupled to a strong demand for energy via atmospheric advection.

All energy fluxes discussed above are summarized in Fig. 14. This shows the various fluxes for two sectors of the Low in a manner

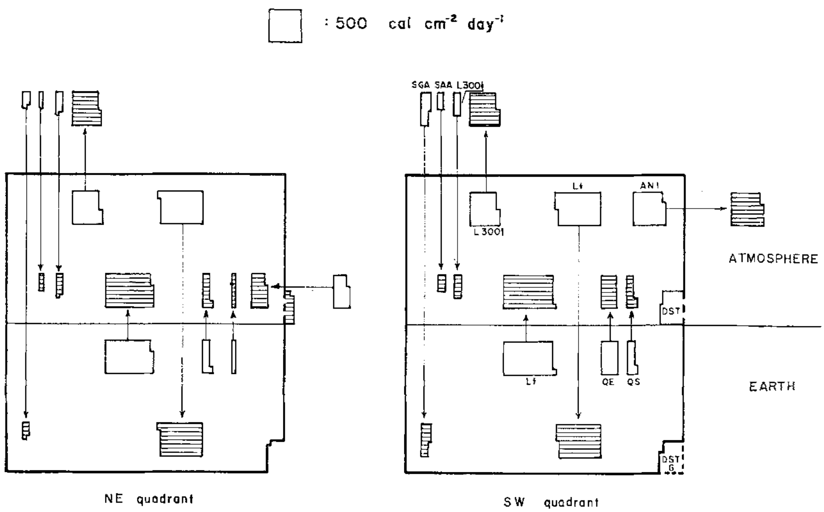

Fig. 14. The energy balance for two sectors of the Low

which gives a visual impression of the relative magnitudes of the exchange between surface and atmosphere, and between atmosphere and space.

References

1. British Met. Office: Monthly Meteorological Charts of the Atlantic Ocean. M. O. 483 (1948).
2. Chisholm, W. J.: Factors Contributing to Evaporation over the North Atlantic. McGill Univ., M.Sc. thesis, 80 p. (1966).
3. Manabe, S.: On the Modification of Air Mass over the Japan Sea when the Outburst of Cold Air Predominates. J. Met. Soc. Japan, Ser. II, **35**, 311—326 (1957).
4. Model, F.: Warmwasserheizung Europas. Ber. Deutsch. Wetterdienst US-Zone, **12**, 51—60 (1950).
5. Petterssen, S., D. L. Bradbury, and K. Petersen: Heat Exchange and Cyclone Development on the North Atlantic Ocean. Univ. of Chicago, Weather Forecast Res. Center, AFCRL **807**, 76 (1961).

6. Sverdrup, H. U., M. W. Johnson, and R. H. Fleming: The Oceans. New York, 1087 p. (1954).
7. Vowinckel, E.: The Energy Budget over the North Atlantic January 1963. Part I: Energy Loss at the Surface. McGill Univ., Publ. in Met. **78,** 38 (1965).
8. Vowinckel, E.: The Surface Heat Budgets at Ottawa and Resolute, N. W. T. McGill Univ., Publ. in Met. **85,** 27 (1966).
9. Vowinckel, E., and S. Orvig: The Greenhouse Effect of the Arctic Atmosphere. Probl. Arkt. i Antarkt. **25,** 71—76 (1967). (In Russian.)
10. Vowinckel, E., and S. Orvig: Climate Change over the Polar Ocean II. A Method for Calculating Synoptic Energy Budgets. Arch. Met. Geoph. Biokl., B, **17,** 121—146 (1969).

Authors' address: Prof. Dr. S. Orvig and Dr. E. Vowinckel, Department of Meteorology, McGill University, Montreal, Canada.