The Nature of the Poleward Heat Flux Due to Low-Frequency Current Fluctuations in Drake Passage

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ABSTRACT

Values of poleward heat flux due to low-frequency current fluctuations in Drake Passage are presented for 19 long-term current meter records obtained during 1975, 1976 and 1977. Most of the measurements (10) are in the center of the passage near the historical location of the Polar Front where the flux is found to average 1.7 W cm^{-2}. While the variability is large at this location (range of 0.9–2.8 W cm^{-2} and a standard deviation of 0.7 W cm^{-2}), all measurements are within the same order of magnitude. There is no obvious depth dependence in the measured flux.

The heat flux process is dominated by events with time scales of 5–60 days and longer which occur on the order of 3–10 times per year at any location. In general, three or fewer events contribute most of the flux for the year. These mesoscale disturbances, generally meanders or migrations of the Polar Front or rings formed from it, result in a large spatial variability in the measured flux. For example, current meters operating concurrently and separated by 40 and 13 km gave heat flux values which differ by factors of 2.7 and 2.1, respectively, during 1977.

These findings suggest that caution should be exercised in the extrapolation of mean heat flux values obtained from point measurements in the Southern Ocean. Besides the temporal and spatial problems resulting from the discrete nature and small scale of the heat flux processes, the eventual fate of the mesoscale structures must be determined before the global relevance of the estimates can be evaluated.

1. Introduction

The differential heating of the ocean-atmosphere system by solar radiation results in large transports of energy poleward in both hemispheres. In the Northern Hemisphere the oceanic portion of this transport was found to be important relative to that of the atmosphere only at low to midlatitudes (Vonder Haar and Oort, 1973; Oort and Vonder Haar, 1976). By contrast, estimates of required oceanic heat transport at high southern latitudes have been large. Gordon (1975) calculated a heat flux of $\sim 10^{14}$ W across the Polar Frontal Zone to balance the heat lost by the ocean to the atmosphere farther south. Trenberth (1979) derived oceanic heat transport as a residual from a radiation and atmospheric transport budget and concluded that the required poleward flux by the ocean at 60°S is $\sim 10^{15}$ W.

The mechanism of this oceanic heat transport at high southern latitudes is not well understood. By assuming that the total flux was due to meridional circulation, Gordon (1975) estimated the required northward transport of Antarctic Bottom Water across the Polar Front. Implicit in this calculation is the assumption that the diffusion of heat across the Polar Front is negligible. Joyce *et al.* (1978) confirmed from short-term measurements that the cross-frontal transport of heat by small-scale (50–100 m) mixing is small.

Bryden (1979) made the first estimate from direct measurements of the heat flux across the Polar Front due to low-frequency current fluctuations and found that this component may be large (0.7 W cm^{-2} or a total of $\sim 5 \times 10^{14}$ W for the entire Southern Ocean at 60°S). Bryden's calculations were based on current meter measurements made in Drake Passage during 1975 by the Oregon State University Buoy Group. These measurements, a part of the International Southern Ocean Studies (ISOS) program of the International Decade for Ocean Exploration (IDOE), were continued during 1976 and 1977.

In this paper the calculation of the low-frequency turbulent flux is extended to the 1976 and 1977 data. Values consistent with the 1975 results are found. An examination of the temporal and spatial variability of the heat flux process implies that it is primarily due to a small number of discrete events which take place through the year. The yearly averaged heat flux is usually dominated by three or fewer large events. Some of these events have been

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previously identified as meanders and/or rings of small spatial scale (80–110 km) formed at the Polar Front. The spatial scales and structure of the disturbances result in large differences in measured heat flux over concurrent periods at closely spaced (13 km) locations.

2. The data

The data used are from three, year-long moored current meter arrays in the Drake Passage during 1975, 1976 and 1977. The locations and vertical placement of the instruments are illustrated in Figs. 1a and 1b. The 1975 and 1976 moorings spanned the passage on a line almost north-south (332°T) with an approximate spacing of 80 km during 1975 and 160 km in 1976. In addition, during 1976 two moorings were placed normal to this line on either side of the mid-passage mooring (ANN) with spacings from it of 11 km upstream (mooring 19) and 29 km downstream (mooring 76). The 1977 array was a cross at mid-passage with arms aligned in the across-passage and through-passage directions. The 1977 moorings (designated NORTH, CENTRAL, SOUTH, EAST and WEST) were instrumented at a number of depths and had spacings of 27 and 13 km north to south and 45 and 13 km west to east.

The current meter and associated hydrographic data have been discussed in a number of recent publications where the basic statistics of all the measurements are presented (Nowlin *et al.*, 1977; Bryden and Pillsbury, 1977; Pillsbury *et al.*, 1979; Sciremammano *et al.*, 1980). Drake passage is characterized zonally by four surface water masses separated by sharp fronts. From north to south there are the Subantarctic, Polar Frontal, Antarctic and Antarctic Continental Zones. Gordon *et al.* (1977) discuss the properties of each of the zones in detail. The Polar Frontal Zone is a region of mixing of the Subantarctic and Antarctic waters and is bounded by the Subantarctic Front on the north and the Polar Front on the south. This zonal banding is a feature of the Southern Ocean from Australia to at least Drake Passage (Emery, 1977). The water mass boundaries or fronts are associated with sharp horizontal density gradients which extend down through the water column from the surface to just above the level of bathymetric relief. The resulting flow structure consists of vertically coherent, narrow current cores.

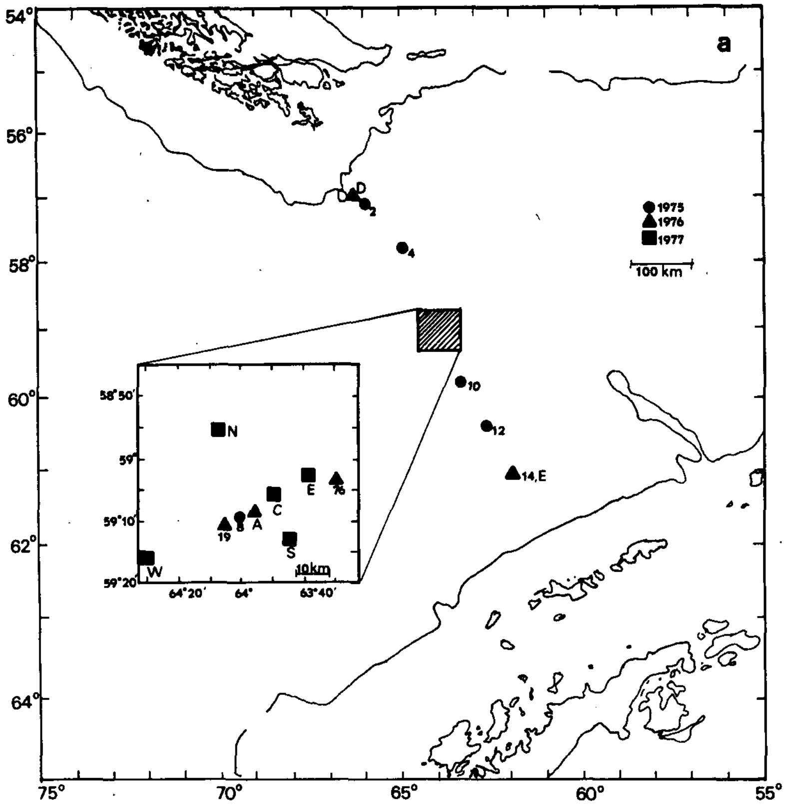

FIG. 1a. Location of current meter moorings in Drake Passage during 1975, 1976 and 1977.

An analysis of the spectral properties of the 1975 data (Pillsbury *et al.*, 1979) has shown that most of the variability in the records is spread over a large band of frequencies in the mesoscale range (5–100 days). Bryden (1979) has shown that the turbulent heat flux is due to motions in this same frequency band. The variability of the flow and the resulting heat flux are at least an order of magnitude less at higher frequencies.

In this analysis 1 h samples obtained from the Aanderaa current meters were low-pass filtered with a 60 + 1 + 60, cosine-Lanczos filter with a half-power point at 40 h. The data were resampled at 6 h intervals after filtering. Time series of fluctuations in temperature and poleward velocity were formed from

$$V'(i\Delta t) = V(i\Delta t) - N^{-1} \sum_{i=1}^{N} V(i\Delta t), \tag{1a}$$

$$T'(i\Delta t) = T(i\Delta t) - N^{-1} \sum_{i=1}^{N} T(i\Delta t), \tag{1b}$$

where $V(i\Delta t)$ and $T(i\Delta t)$ are the poleward velocity and temperature measured over a total time of $N\Delta t$ and sampled at Δt (6 h) intervals. The record-length mean turbulent heat flux is given by the covariance of the poleward velocity and temperature fluctuations, i.e.,

$$\overline{V'T'} = N^{-1} \sum_{i=1}^{N} V'(i\Delta t)T'(i\Delta t). \tag{2}$$

In order to determine the temporal periods during which major contributions are made to the total flux given by (2), daily average values of the product of $V'(i\Delta t)$ and $T'(i\Delta t)$ were calculated and plotted. No loss of information is expected from forming the daily averages because the original low-pass filter smooths the data over a period longer than one day.

Also presented for some records are plots of the eddy kinetic energy defined as

$$\mathrm{KE}(i\Delta t) = \tfrac{1}{2}[U'^2(i\Delta t) + V'^2(i\Delta t)], \tag{3}$$

where $U'(i\Delta t)$ is the eastward velocity fluctuation at time $(i\Delta t)$. Record-length and daily averages of $\mathrm{KE}(i\Delta t)$ were calculated in the same way as those for the heat flux.

3. Record-length mean heat flux

The record-length values of $\overline{V'T'}$ for all the Drake Passage current meter records of at least five months duration and for depths of 1000 m or deeper are presented in Fig. 2. The vertical temperature gradients are large ($>10^{-3}$ °C cm^{-1}) above 1000 m in central Drake Passage and depth excursions due to mooring motion (thought to be on the order of 75 m) contaminate estimates of $\overline{V'T'}$. At the deeper meters the vertical temperature gradients are an order of magnitude less ($<10^{-4}$ °C cm^{-1}) and the variations in temperature are due to the advection of horizontal gradients. There is no obvious pattern of depth dependence in the measured values. This is due to the high vertical coherence in both currents and temperatures observed in Drake Passage.

The variability of the measured heat flux is quite large at the center of the passage (inset area of Fig. 1) near the historical location of the Polar Front. The mean heat flux at this location over all three years for all depths > 1000 m is 1.7 W cm^{-2} with a range of 0.9–2.8 W cm^{-2} and a standard deviation of 0.7 W cm^{-2}. Values at the northern and southern ends of the passage do not exhibit the same amount of year-to-year variability as is evident near the Polar Front. Mooring 4 from 1975 was deployed in a canyon (Pillsbury *et al.*, 1979) and its measured heat flux may not be representative of that region of the passage.

The heat flux values shown in Fig. 2 for the 1975 moorings are not the same as those given by Bryden (1979) who used the across-passage (72°T) instead of poleward velocity component. The differences are small, however, and the same general conclusion can be drawn; the poleward heat flux due to low-frequency motions is large in Drake Passage. All the heat flux estimates are of the same order of magnitude which, in light of the variability discussed below, may be the best accuracy we can expect.

4. Heat flux variability

In Figs. 3, 4 and 5 are presented the daily average $V'(i\Delta t)\cdot T'(i\Delta t)$ values for a number of Drake Passage moorings. Fig. 3 is for five deep current meters on moorings that spanned Drake Passage during 1975. Fig. 4 is for two deep current meters on moorings ANN and 76 separated by 29 km in the through-passage direction in the central passage during 1976. Fig. 5 is for three instruments at 2000 m depth on the 1977 NORTH, SOUTH and CENTRAL moorings in the same area. They were separated in the across-passage direction by 27 and 13 km from north to south. The dashed line on each figure is the cumulative mean of the heat flux as a function of time (t) given by

$$\overline{V'T'}(t) = n^{-1} \sum_{i=1}^{n} V'(i\Delta t)T'(i\Delta t) \tag{4}$$

at time $t = n\Delta t$. The last value $\overline{V'T'}(t = N\Delta t)$ is indicated on each figure and is the record-length mean heat flux as shown in Fig. 2.

The processes contributing to the heat flux are dominated by discrete events, especially at the

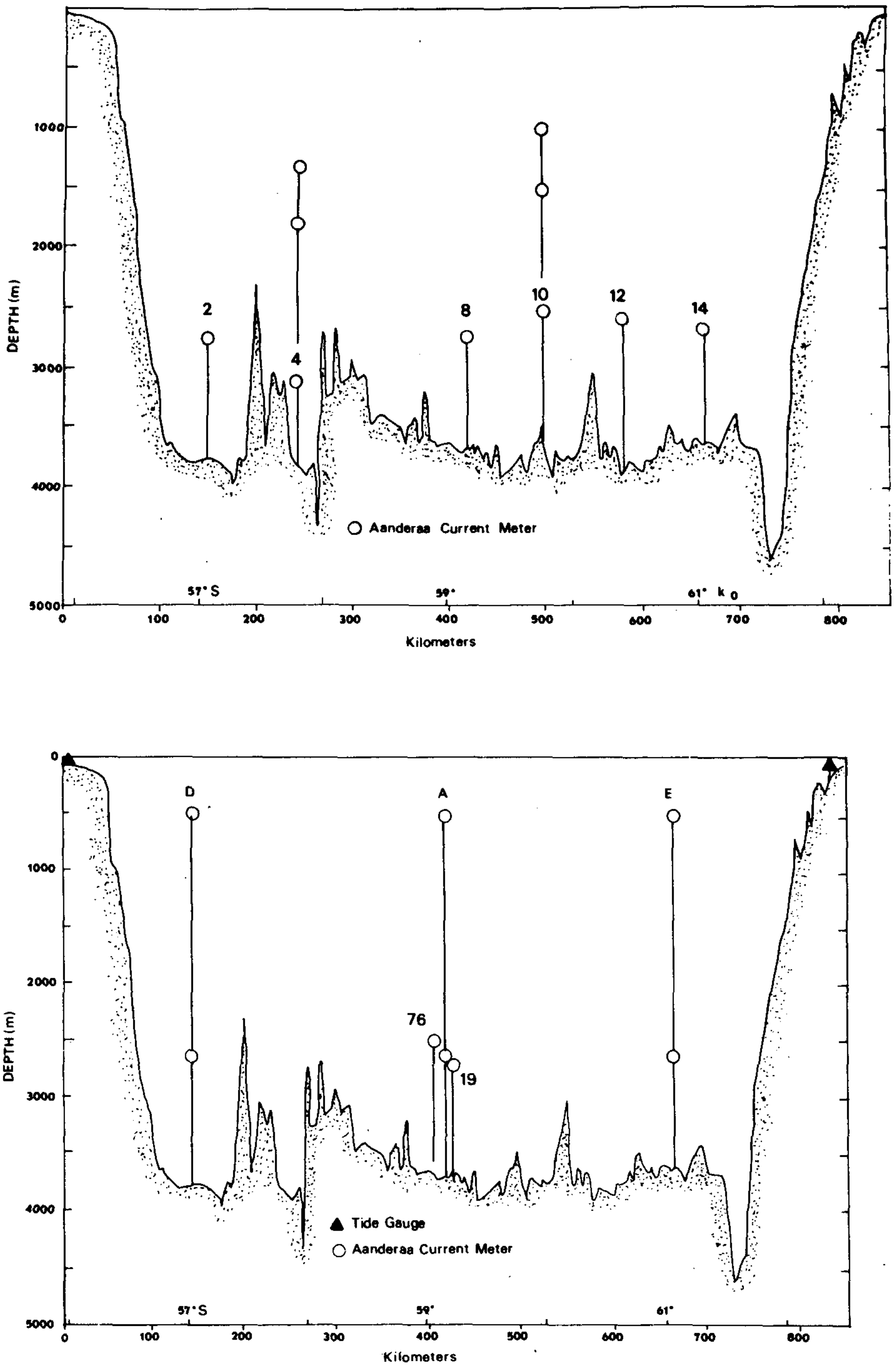

FIG. 1b. Vertical placement of the instruments during 1975 (top), 1976 (middle) and 1977 (bottom).

central passage moorings. Note the relative lack of activity at moorings 12 and 14 and the shorter period, higher frequency events at mooring 2. This same pattern was found in the 1976 records in these areas. The high variability at mooring 2 may be due to the rough local bathymetry (Pillsbury *et al.*, 1979). The influence of the current core associated with the Subantarctic Front, which is generally located near the mooring site, may also contribute.

The time scales of the individual events vary. Periods of the order of 5–60 days and longer are found and agree with the dominant frequency bands

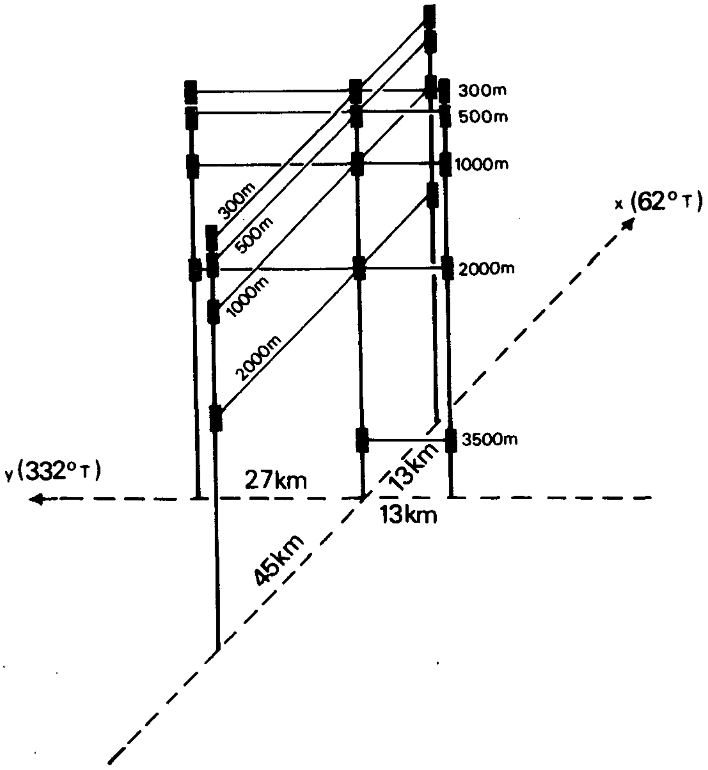

FIG. 1b. (*Continued*)

found in spectral studies of the current variability. The cumulative mean value of the heat flux is strongly affected by the occurrence of the events, even at the latter parts of the records where we expect them to have less influence.

By using the daily average values, a quantitative measure of the contributions to the record-length mean heat flux by individual events can be obtained. This analysis confirms the significance of the discrete events to the mean flux. As an example, the three dominant heat-fluxing periods for mooring 8 occurred for 8, 22 and 13 days during March, April–May and August of 1975, respectively. These events are readily identifiable in Fig. 3 and account for

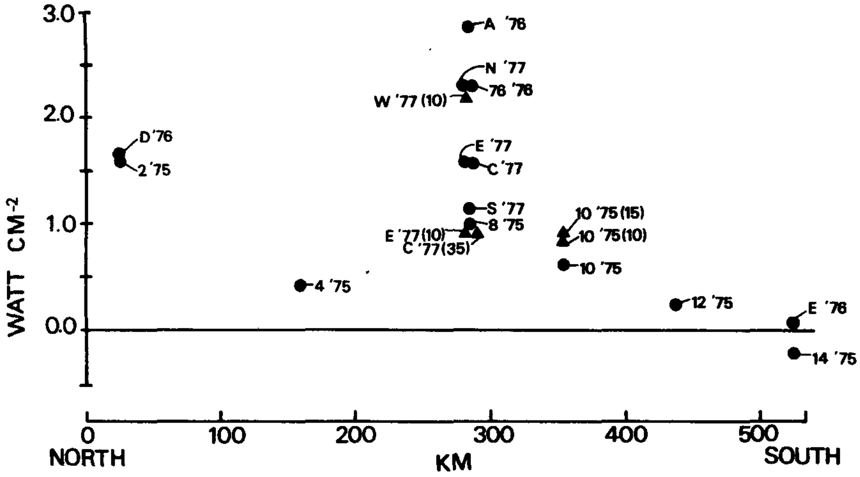

FIG. 2. Record-length mean poleward heat flux for all current meters at 1000 m depth or below: (●) current meters between 2000 m and 2800 m, (▲) current meters at other depths (depth indicated in parentheses in hundreds of meters).

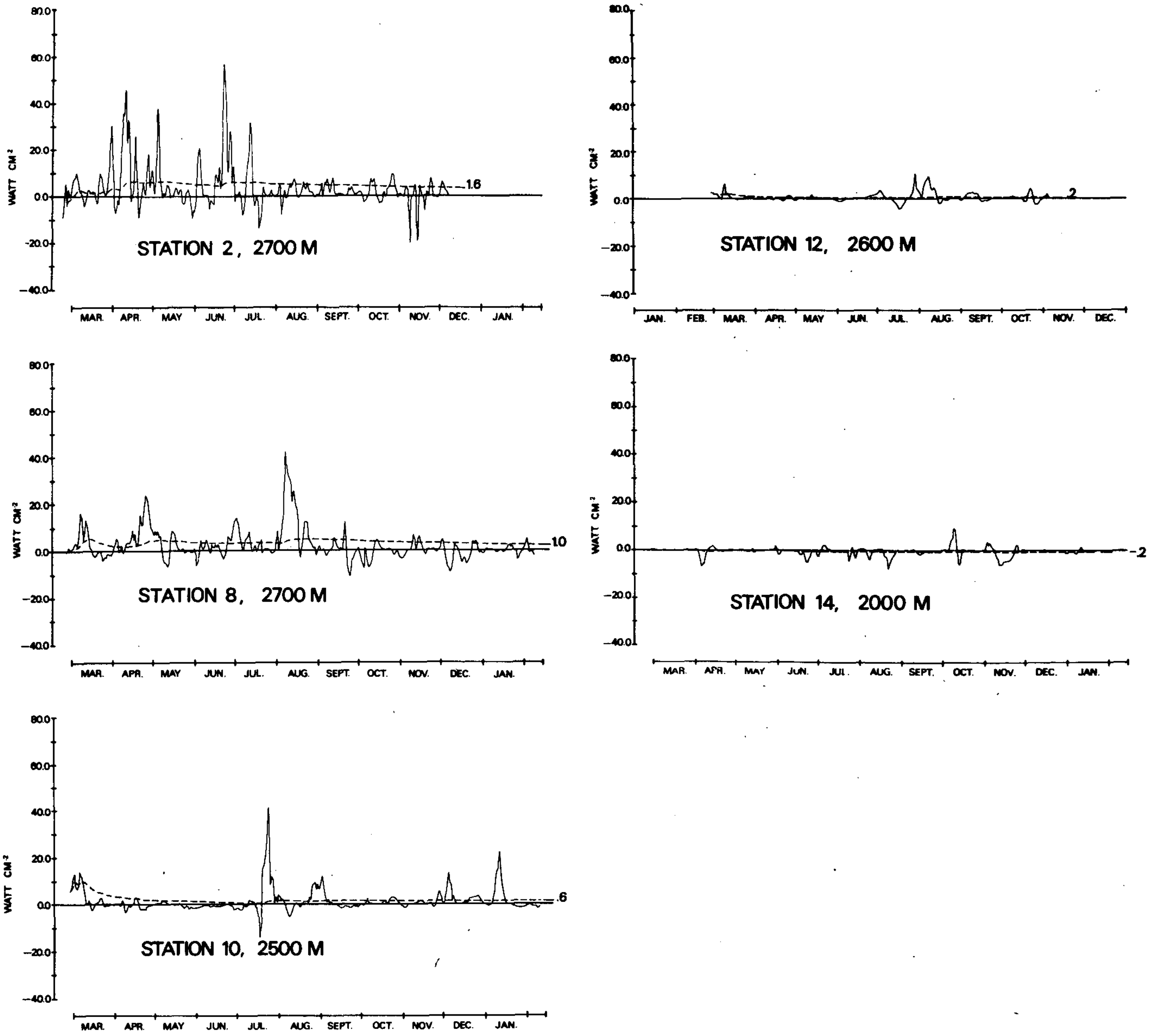

FIG. 3. Daily averaged $V'(i\Delta t)T'(i\Delta t)$ for five deep-current meters for 1975. Dashed line is cumulative mean heat flux.

81% of the total poleward heat flux in just 12% of the total record length. Mooring 10, during the same year, had all of its poleward heat flux carried in five events whose total period accounts for only 17% of the record length. Mooring 76 follows a similar pattern in 1976 with 82% of its heat flux occurring over 21% of the total record length. Similar results were obtained for the 1977 records.

The heat-fluxing events are also associated with increases in eddy kinetic energy. Fig. 6 shows the daily average and cumulative mean eddy kinetic energy from moorings 76 and NORTH during 1976 and 1977, respectively. Increases in eddy kinetic energy occur simultaneously with periods of increased heat flux evident in Figs. 4 and 5. An analysis of the heat flux and eddy kinetic energy time series shows that they are highly correlated at all moorings during all three years of measurement.

In addition to the discrete nature of the heat flux process, a large spatial variability is evident in Figs. 3, 4 and 5. An analysis of the horizontal scales and structure of the mesoscale variability near the Polar Front in Drake Passage from the available current meter data has been presented elsewhere

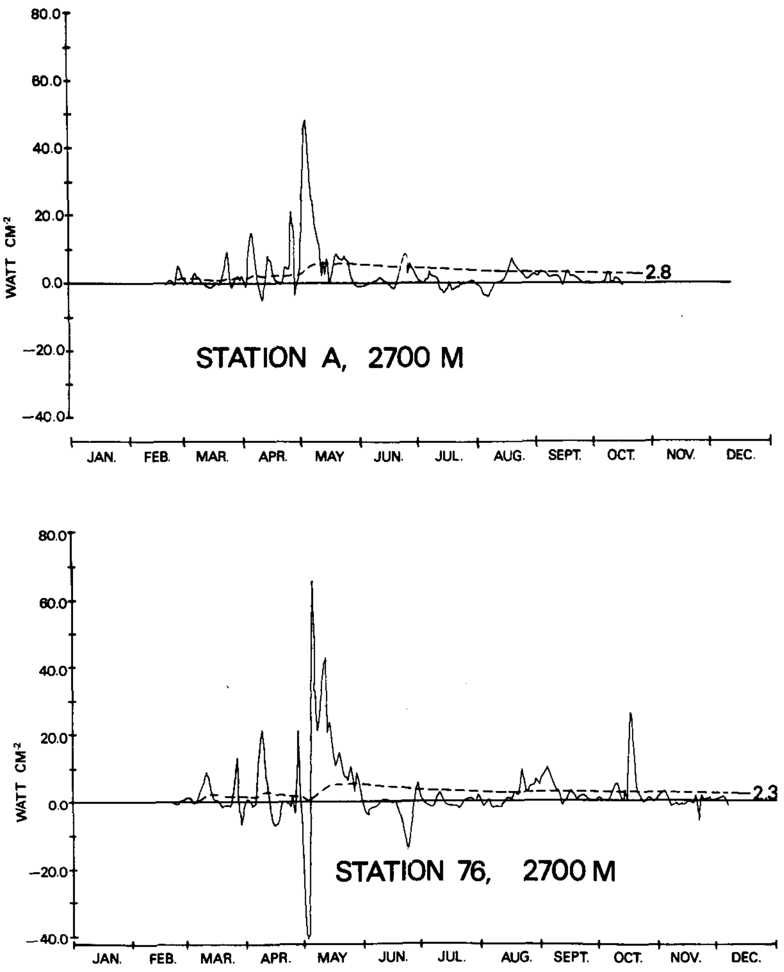

FIG. 4. As in Fig. 3 except for two current meters during 1976.

(Sciremammano *et al.*, 1980). It suggests that the fluctuations are generally in the form of meanders or lateral migrations of the Polar Front or of cold-core rings formed from the meanders. The horizontal extent of the resulting cold or warm water pools was found to be on the order of 80–110 km. These disturbances generally move in a northeastward direction (55°T) through the area sampled by the current meter arrays.

This 80–110 km spatial scale accounts for the large variability evident in Fig. 3. Only a marginal relation between events at moorings 8 and 10 (80 km separation) can be seen. The heat flux for individual events at these moorings is generally strong at one and weak or nonexistent at the other. In contrast, events are readily identifiable at concurrent periods between moorings ANN and 76 (29 km separation) and between moorings NORTH, CENTRAL and SOUTH (27 and 13 km separations) in Figs. 4 and 5, respectively.

Even though the occurrence of individual events can be traced through the closely spaced moorings of 1976 and 1977, some spatial variability is still present. This is due to the disturbances being in the form of meanders or rings which causes the heat flux to vary over very small scales. We have performed a simulation of a cold-core ring passing near closely spaced current meter locations at a common depth using the model of Henrick *et al.* (1979) for the ring velocity and temperature fields. Various trajectories of the ring center past the hypothetical current meters were run. Quantitative comparisons are not possible due to a lack of detailed knowledge of the ring characteristics but qualitative features similar to those in Figs. 3–5 are observed including the small-scale spatial variability. The measured heat flux is found to be critically dependent on the trajectory of the ring relative to the measurement point.

An example from the data of the spatial variability

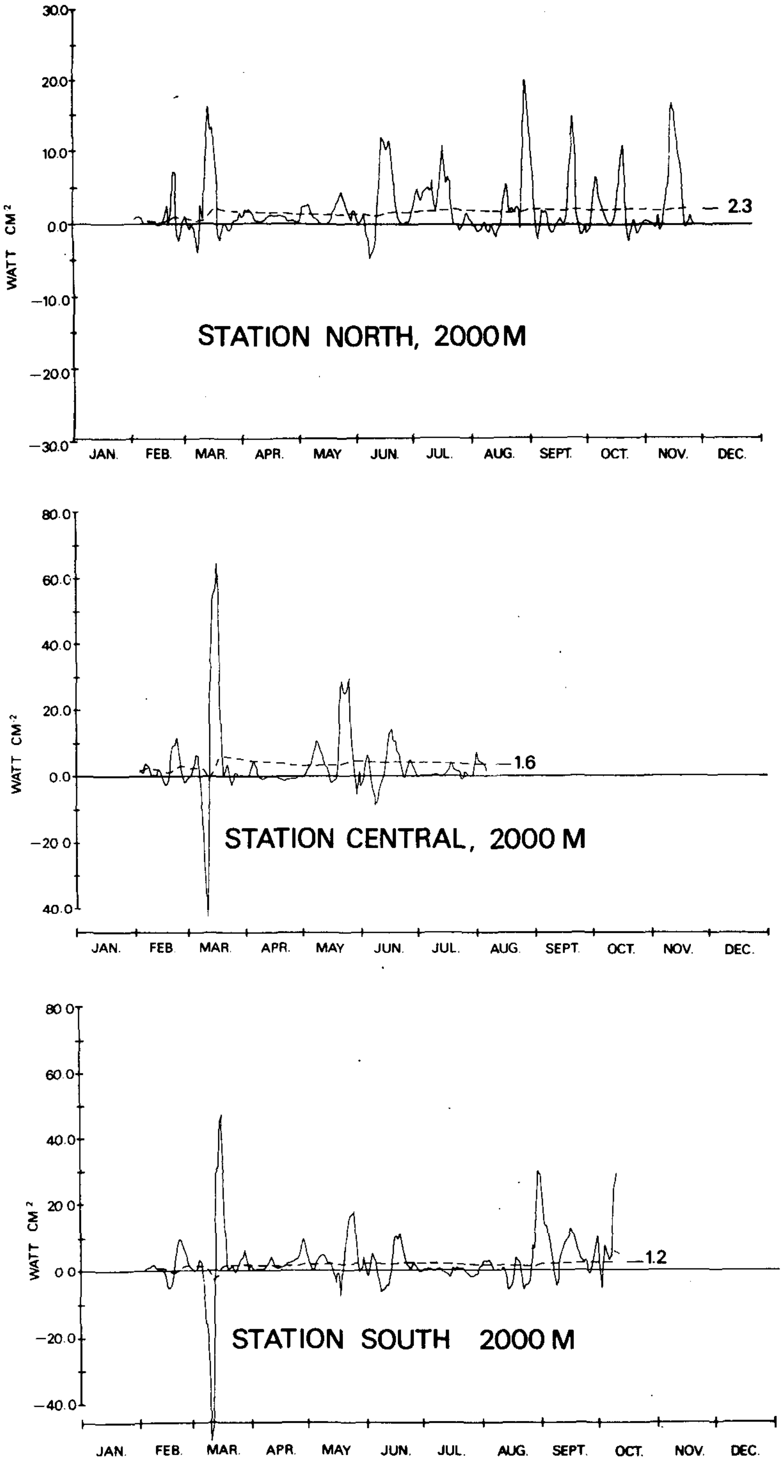

FIG. 5. As in Fig. 3 except for three current meters at 2000 m depth during 1977.

of the heat flux resulting from a single disturbance is provided by the large event occurring in March 1977 (Fig. 5). An examination of the flow field and temperature structure from this event [see the discussion in Sciremammano *et al.* (1980)] indicated that it is a cold-core ring whose center passed just south of the CENTRAL mooring.

The heat flux pattern at the SOUTH mooring during this event is more or less symmetric with an equatorward flux followed by a poleward flux. The

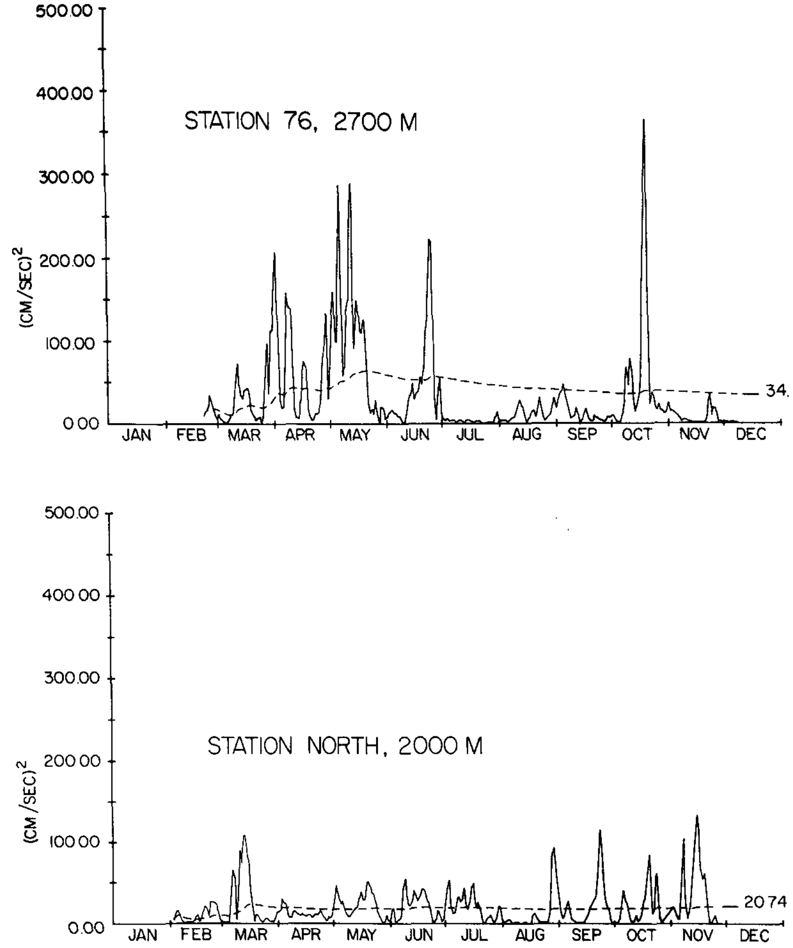

FIG. 6. Daily average eddy kinetic energy for one deep-current meter during 1976 and one during 1977. Dashed line is cumulative mean eddy kinetic energy.

value of the mean poleward heat flux over the ring's approximately 16-day passage was 0.6 W cm^{-2}. Over the same period the slight asymmetry apparent at the CENTRAL mooring resulted in a mean 5.4 W cm^{-2}, while the strong asymmetry and weaker response at NORTH resulted in a mean 4.6 W cm^{-2}. This one event accounts for 42% of the difference in the mean heat flux between the CENTRAL and SOUTH moorings over their period of concurrent operation.

The large differences possible in the heat flux measured for the same disturbance at closely spaced stations is significant in light of the importance of these events to the record-length mean heat flux. This is seen quite clearly by comparing the cumulative mean heat flux values for the records displayed in Fig. 5 over their period of concurrent operation. Until 5 August 1977 the mean poleward flux was 2.0, 1.6 and 0.75 W cm^{-2} at moorings NORTH, CENTRAL and SOUTH, respectively. Thus, we have factors of 2.7 and 2.1 between the measured heat flux at moorings separated by 40 and 13 km, respectively. This difference occurred in spite of the fact that almost every major event affecting these moorings is simultaneously identifiable in all three.

5. Discussion

These findings suggest that caution should be exercised in the use of mean heat flux values obtained from point measurements in the Southern Ocean. There is the obvious temporal and spatial sampling problem associated with the discrete nature and small scale of the process involved. Beyond that, the fate of the individual mesoscale disturbances must be determined before any conclusions on heat flux can be reached. There is some evidence (Sievers and Emery, 1978) that cold-core rings formed at the Polar Front migrate northward across the Polar Frontal Zone and are absorbed at the Subantarctic Front. There is also a hint of this migration in the structure of the correlations of current meter records separated over large distances in Drake Passage (Sciremammano *et al.*, 1980). If such a scenario holds for all the rings that propagate past the measurement point, the mean heat flux will be reasonably estimated. However, if the rings move southward downstream of the measurement point and rejoin the Polar Front, the heat flux will be seriously overestimated.

Meanders of the Polar Front present these same problems. Legeckis (1977) has shown from satellite imagery that numerous meanders occur on the Polar Front. The passage of one such meander can be seen in the current meter records from 1976 (see Sciremammano, 1979). The meander occurred in October 1976 and is clearly evident in the heat flux shown in Fig. 4. It accounted for 14.5% of the mean heat flux measured at that mooring. This point-sampled heat flux will only be representative of the true flux if the meanders are pinched off into a ring and propagate north. If instead the meander amplitude dies out and the Polar Front becomes more or less zonally aligned, the flux will be overestimated.

The eventual fate of the mesoscale disturbances is essentially a zonal sampling problem and is especially relevant to the measurements made in Drake Passage. It is an anomalous region of the Southern Ocean where the Antarctic Circumpolar Current is constrained laterally and forced over shallow and rough bottom topography. All the current meter measurements to date have been in a small area which may or may not be representative of the entire passage, let alone the entire Southern Ocean.

A time series of synoptic measurements of the mesoscale field in Drake Passage and other regions of the Southern Ocean will be needed before the global relevance of the present heat flux estimates can be evaluated. As demonstrated by Sciremammano (1979), the high vertical coherence of the flow in this area makes possible the synoptic mapping of the disturbance field from satellite sea surface temperatures. This may be the only practical way to make the required measurements.

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