A synoptic background to glacier variations of Heard Island

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Abstract. Among various meteorological parameters and representations of weather used to account for glacier variations, summaries of synoptic processes (especially for the ablation season) have been found to be most closely related to glacier mass budget anomalies (Hoinkes, 1968). For the northern hemisphere such summaries exist in terms of 'Grosswetterlagen' (Baur, 1951; Burger, 1958) or of 'elementary synoptic processes' (Girs, 1967; Dzerdzeevskii, 1968; 1970). The problem is then to select from this complex information the part representing the mesoscale processes affecting a given glacier. In the southern hemisphere the synoptic processes are only just becoming known thanks to satellite information; but it seems possible that the synoptic charts drawn during the past 20 years with the help of single-station time sections and synoptic models may have been sufficiently close to reality to provide some clues to the variations of mountain glaciers on isolated islands in middle and subpolar southern latitudes.

This possibility has been explored for Heard Island where glaciers have been reported to have receded slightly between 1948 and 1954, extensively during the following 10 years; subsequently some glaciers have continued to retreat whilst others have made striking re-advances (Budd and Stephenson, 1970). The synoptic features of these periods are represented in first approximation by the proportion of depressions passing Heard Island on its equatorial side each month. Significant changes in this quantity are shown to slightly precede monthly mean temperature anomalies at both Heard and Kerguelen islands which in turn have the signs and timing expected from the glacier variations. This should make it possible to forecast future glacier variations of the Heard glaciers from synoptic charts.

INTRODUCTION

The effects of weather conditions on glaciers have generally been discussed on two widely separated planes. One of these rests on precise heat and mass budget studies which determine with great detail what has happened to a minute portion of the glacier surface during what we hope are representative periods and then are extra-
polated to the entire glacier and the whole of time. On the other plane broad physical processes and global consideration concerning the exchange between low and high latitudes are invoked in a qualitative way to account for longer-term glacier advances and retreats.

In between these extremes lie the variations of glaciers during specific periods of a few years, up to a decade or two, and the synoptic weather events responsible for them. This field of study is almost a no-man’s-land. Its most notable explorer has been H. Hoinkes who despite the complex mesoscale weather features of mountain regions (especially those which like the Alps extend along the prevailing upper flow, Hoinkes, 1953) succeeded in finding synoptic characteristics clearly related to the variations of certain individual glaciers (Hoinkes, 1968), namely the incidence of certain Grosswetterlagen, or broad weather patterns, for the northern hemisphere (Baur, 1951; Burger, 1958).

Speculations aside, nothing like this sophisticated synoptic tool nor analogous analyses of long-term circulation changes (Girs, 1967; Dzerdzeevskii, 1968, 1970) exist for the southern hemisphere. On the other hand some of its glaciated mountains can be expected to be especially sensitive to synoptic processes. One of these is the conical 2800 m volcano on Heard Island (Fig. 1, from Budd, 1964) situated remote from other mountains in the intense ventilation and precipitation of the ‘furious fifties’. Here if anywhere synoptic charts should contain most of the clues to glacier variations.

Unfortunately the synoptic charts for the southern Indian Ocean so far rest entirely on analysis models and single-station methods. Their limitations are well illustrated in the charts of Fig. 2 which show the Australian analysts’ surmises of events after a trough with two cyclonic centres had passed the longitude of Amsterdam — Kerguelen — Heard early in March 1953. The more southerly depression is shown as having deepened and moved southeast while the other has moved on with little change in intensity. But a ship, the Tottan, happened to be in the path of the second depression and recorded the pressure curve also reproduced in Fig. 2, together with the weather data from the Tottan’s log; these have been added to the charts later.

FIGURE 1. Heard Island (Budd, 1964).
and would of course have suggested major changes in the analysis if they could have been reported at the time. This must be taken as a fairly typical example and a warning against reliance on details of southern ocean charts even quite close to the isolated stations.

There is then little concrete synoptic information available for explaining glacier variations at Heard Island. The same, however, applies to evidence of the glacier variations themselves. The first thorough survey of the Heard Island glaciers was undertaken by Lambeth (1951) who also measured ice flow and the ablation resulting from different dominant processes. Subsequently the glacier variations on Heard have been studied above all by Dr Grahame Budd who in 1954 spent a year on the island as medical officer and subsequently has made use of every opportunity and every type of conveyance (from ice-breaker to sailing boat) to return to Heard and trek around the island for rapid surveys of its glaciers and its wildlife. The last of these operations, in February and March 1971, also brought a resumption of actual measurements on one of the Heard glaciers by I. Allison who with W. Budd reports on them in another paper at this symposium. Further measurements are planned and together with current glaciological programmes at Kerguelen promise before long a more definite picture of glacier variations in this region.

At this stage, however, from both the glaciological and synoptic points of view a preliminary examination is the best that can be hoped for. We begin with a summary of the reported glacier variations at Heard and Kerguelen (section 2) and place these in relation to the brief climatic record for Heard and the somewhat longer (and happily continuing) one for Kerguelen (section 3). A synoptic parameter is then introduced (section 4) and its fluctuations are compared with those in the local climatic elements as well as with data for the adjacent southern hemisphere continents (section 5).
RECENT GLACIER VARIATIONS ON HEARD AND KERGUELEN ISLANDS

Budd and Stephenson (1970) who visited Heard Island in 1963 for an unsuccessful attempt at climbing its 2800 m mountain, Big Ben, used their own photos and those taken by earlier expeditions to establish three recent stages in the behaviour of the glaciers which ring the mountain (cf. Fig. 1). They found no clear changes before 1947 when the station of the Australian National Antarctic Research Expeditions was set up, but evidence of a minor recession by the time the station was abandoned at the beginning of 1955. The 1963 survey suggested that the recession had markedly intensified during the intervening eight years. Two years later, during a further expedition which saw the ascent of Big Ben (compare, for example, Deacock, 1965) Budd noted signs of readvances by the Winston and Stephenson glaciers (Budd and Stephenson, 1970). On visiting the island again in 1969 he found 'obvious major readvances' by the glaciers of Corinthian Bay but further recession by other glaciers (Budd and Stephenson, 1970, postscript). Current advancing tendencies were confirmed during the latest visit to the island (Allison, personal communication) and will be reported in detail by the members of the 1971 team.

It is interesting that at least one of these stages appears to have had a parallel on Kerguelen. Aubert de la Rue (1967) established from his own explorations in 1929 and 1952 and from aerial photos obtained by Bauer (1963) that the residual glaciers on the Courbet peninsula had greatly shrunk between 1952 and 1962. Further surveys appear to have since been made on the various glacier systems of Kerguelen, but no results have as yet come to our notice.

The information on the recent history of the Heard Island glaciers (and by implication of those on Kerguelen although its size and complex topography presumably create less clear-cut conditions) may therefore be summed up as follows:

- 1947-1955 . . . slight recession
- 1955-1963 . . . marked recession
- 1963-1965 . . . partial readvance
- 1965-1971 . . . continued readvance

CLIMATIC DATA

The climate of Heard Island, first inferred from a year's observations on Kerguelen and at the Gauss winter station (66°S, 90°E) by Meinardus (1912), is now reasonably well defined by both surface and upper air observations obtained by the Australian National Antarctic Research Expeditions during the period February 1948 to December 1954. These observations have been published in detail in the ANARE Reports, Series D, Meteorology, but have not received a great deal of analysis or discussion. The same applies, by and large, to the observations made continuously since 1951 by French meteorologists at Port-au-Français on Kerguelen and published in the form of monthly averages until 1958 in Annales des Services Météorologiques de la France d'Outre-Mer and since then in the TAAF Revue Trimestrielle, with a brief gap covered by the US Weather Bureau's Monthly Climatic Data of the World series.

The most important of these data are the temperatures. Ahlmann (1948) has shown that in maritime subpolar latitudes the turbulent heat transfer is much more significant for the glacier heat budget than radiation. By sample measurements on Heard Island during periods when only a single effect was active, Lambeth (1951) confirmed this to be true for Heard Island, although he found rain to produce the greatest ablation. But precipitation is difficult to measure and therefore uncertain in windy and mountain regions.

All available monthly mean temperatures for Heard and Kerguelen are shown in
FIGURE 3. Monthly mean temperatures at Heard Island and Kerguelen Island. Note: The unjoined dots give the Kerguelen temperatures for the first two years of the Port-au-Français record which were not available when the paper was written. They were made available by R. Bost and agree with Heard's abnormally high winter temperatures for 1951 and 1952.
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Fig. 3. The winter temperatures at Heard are from 3 to 5°C lower than those at Kerguelen. In summer this difference increases to almost 10°C; this reflects the greater land mass of Kerguelen as well as the seasonal southward shift of the main baroclinic zone which brings the subtropical jet stream almost to the latitude of Kerguelen in summer. The relationship between monthly mean temperature anomalies at Kerguelen and at Heard Island is therefore not very close (Fig. 4).

The most striking feature of the Heard series is the sudden and sustained increase in winter temperatures around 1950. By contrast the summer temperatures showed little change throughout the period of observations. At Kerguelen lower winter temperatures prevailed in most winters between 1959 and 1964, but the summer temperatures also fluctuated appreciably and sometimes (e.g. 1962) in the opposite direction, suggesting increased 'continentality'. Clearly the annual mean temperatures give only part of the picture. This is especially so since for glaciological purposes the temperature changes must be interpreted in terms of melting.

From this point of view the rise in winter temperatures at Heard and the subsequent decrease at Kerguelen were probably more significant than any of the changes in summer temperatures which invariably remained high enough at both places to produce extensive melting. For Heard the influence of melting throughout the year can be deduced directly from published temperature frequency analyses (ANARE Reports, Series D, Meteorology) which bring out the main features of the Heard climate.

The proportion of positive temperatures in the meteorological screen at Atlas Cove, Heard Island for each month of the period February 1948 to December 1954 has been plotted against the corresponding mean temperature deviation $\Delta T$ from the seven-year mean for the month in Fig. 5, where the numbers denote the months. Three separate groups of months emerge from Fig. 5. Five of these (December to April) had melting temperatures throughout, while another five (June to October) had much the same proportion of melting temperatures for a given mean monthly temperature deviation. The two remaining months (May and November) sometimes belonged to the first and sometimes to the second group. These data suggest a division of Heard's climatic year into summer (December to April), autumn (May), winter (June to October) and spring (November). Moreover a 1°C change in monthly mean temperature appears to change the proportion of positive temperatures in winter by about 20% in winter and rather
more in the transitional months, while having no effect on the incidence of melting in summer.

These deductions hold strictly for sea level only. Their vertical extension is made possible by the radiosonde observations made at Heard. Figure 6 gives monthly mean vertical temperature gradients, or ‘lapse rates’, computed from the overall mean temperatures for the entire period of upper air observations (Maher and McRae, 1966); this procedure, while open to meteorological objections, will be adequate for the glaciological purposes of this interdisciplinary study. In the lowest 800 m (100 mbar) the lapse rate shows a marked annual variation, presumably related to changes in storminess and predominant air mass. On the average in winter the temperature decreases by about 7.5°C in the lowest kilometre and a little more slowly in the next 1700-1800 m — that is, right up to the height of Big Ben.

Now from Fig. 5 it can be seen that melting at sea level ceases altogether when the monthly mean temperature drops to about 3°C below the seven-year average. If the frequency distribution does not change significantly in the lowest kilometre or two then melting in winter would also be expected to cease when the combined temperature decrease due to altitude and to the monthly mean temperature anomaly reach that amount. Using a mean lapse rate of 7.5°C for the lowest kilometre in winter this suggests that, with the average winter temperature, melting ceases at 3/7.5 km or 400 m, and that this altitude increases or decreases with the monthly mean temperature anomaly by somewhat more than 100 m per degree C. The conclusion that melting at sea level should cease for $\Delta T = -3°C$ agrees with Lambeth’s (1951) snow line observations for 1948. No later observations of this kind appear to have been made.

A similar argument suggests melting up to the 500 m level for $\Delta T = 0$ in the transitional months. For the summer months it is necessary to make use of the observed upper air temperatures. Frequency analyses have been published for the 850 mbar (1200 m) and 700 mbar (2800 m) levels only, and the relatively small number of observations produces a great deal of scatter except for March. The dependence of the melt frequency at 850 mbar on the surface mean temperature
deviation in March is shown by the dots in Fig. 5 which closely parallel the trend of the surface values for winter and, in view of the lapse rates above 800 m (Fig. 6), suggest that a negative temperature anomaly of a little over 1°C will terminate all melting at the 1200 m level in summer. Under average conditions melting would extend to about 1500 m and move vertically by 250 m for a 1°C change in monthly mean temperature.

The above provides some rough estimates of the extent and variations of the ablation region on the Heard glaciers. To estimate mass balances comparable precipitation or accumulation data would be needed, but these do not yet exist. A synoptic explanation of the glacier variations must therefore account mainly for the temperature variations although the observed precipitation at sea level should serve as collateral evidence.

A SIMPLE SYNOPTIC PARAMETER FOR THE HEARD ISLAND REGION

A regular series of daily surface weather charts covering the southern ocean between about 60°E and 180°E was started soon after the establishment of the Australian weather station on Heard Island and has been continued in one form or another ever since. Corresponding South African charts were published in the periodical *Notos* from December 1949 until June 1957 in the form of grid point pressures and since July 1957 as daily surface and 500 mbar charts; this historic series at present ends in March 1964. Another series of experimental charts for a substantial portion of the southern hemisphere was prepared by the International Antarctic Analysis Centre in Melbourne for the period from 1959 to 1965.

All these charts are a monument to the diligence and ingenuity of southern hemisphere meteorologists and their struggle with an extremely difficult data situation. They must now be re-examined in the light of the new evidence which the American satellites have supplied in the last few years through cloud photos both in the visible and in the infrared; and above all with the upper air temperatures obtained by new remote sensing systems such as SIRS. This is a major task which we could not
contemplate tackling in the context of the present study. Instead our limited glacio-
logical and climatic information called for some equally simple synoptic parameter
which had a chance of being correctly assessed more often than not from charts based
on the observations of the three stations in the area of interest — Amsterdam Island,
Kerguelen Island and Heard Island (compare Fig. 2).

One such parameter suggested itself from earlier studies of the upper zonal flow
(Radok and Grant, 1957; Berson and Radok, 1960) which showed that the subtropical
jet stream has different modes and often changes rapidly from one to the other. These
changes are reflected in the behaviour of the surface depressions and especially in their
preferred tracks. Local weather phenomena will of course depend greatly also on the
intensity, speed of movement, and development of the depressions. However, for
average effects over periods of the order of a month it may be expected that the most
important single feature would be the relative proportions of lower and higher latitude
tracks. The number of depressions passing Heard Island on its equatorial and polar
sides respectively could then be a suitable synoptic parameter here. This is a feature
which may be deduced with some confidence even from tentative charts drawn once a
day.

We have therefore determined for each month the ratio

\[ R = \frac{n_N}{n_N + n_S} \]  

(1)

where \( n_N \) is the number of depressions passing north of Heard Island and \( n_S \) that of the
depressions passing to the south. Statistically such a ratio defines a binomial
distribution and in absence of other than random effects would be expected to have
the variance \( R(1-R)/(n_N + n_S) \) which varies with \( R \) itself as well as with the monthly
number of depressions. The first of these variations can be eliminated by the 'angular'
transformation (see, for example, Mather, 1943, ch. 13)

\[ R = \sin^2 R_a \]  

(2)

The parameter \( R_a \) when expressed as an angle has the variance \( 820.7/(n_N + n_S) \) which
depends only on the size of the monthly depression 'sample'. \( R_a \) will be used in the
next section to describe the synoptic fluctuations accompanying the climate and
glacier changes discussed previously. Here the statistical nature of \( R \) remains to be
examined.

The monthly depression numbers and proportions of northern tracks are given in
Table 1. The frequency distribution of \( R \) may be compared with that expected in
samples from a binomial distribution

\[ (p^i)(1-p)^{n-i} \quad (i = 1, 2 \ldots n) \]

where \( n \) can be normalized for simplicity to a constant value of 10, say, and \( p \) is a
representative mean value of \( R \). The annual averages in Table 1 show that southern
tracks predominated until about 1959 when a marked change to northern tracks took
place. The comparison with binomial expectation therefore has been made separately
for these two subperiods, with \( p = 0.15 \) and 0.38 respectively. Table 2 suggests
significant discrepancies from a random binomial process and confirms the impression
of two contrasting synoptic regimes, which may be tentatively ascribed to the 'single'
and 'split' modes of the subtropical jet stream (compare Radok and Grant, 1957). The
question is now whether the broad changes in synoptic conditions represented by the
\( R \) values or their angular-transforms \( R_a \) were related to the observed changes in
temperature and precipitation at Heard and Kerguelen Islands.
SYNOPTIC AND CLIMATIC ANOMALIES

To compare the fluctuations in the synoptic parameter $R_d$ with those in the meteorological data for Heard and Kerguelen all the monthly values were converted to 'anomalies', or deviations from the corresponding means for the entire period of record. These anomalies are deliberately shown as discrete points, rather than continuous lines, to emphasize that especially the $R_d$ anomalies are subject to considerable uncertainties, and that at best parallel tendencies rather than firm relationships are anticipated. The principal interest then attaches to broad trends and sequences of anomalies with the same sign, or the absence of such sequences. In this connection it is useful that runs of successive anomalies with the same sign provide a simple test of significance. For a symmetric anomaly distribution the probability of a sequence of $k$ independent anomalies of the same sign (positive or negative) is (Feller, 1951) $0.5^k/(1 - 0.5^k) = (2^k - 1)^{-1}$. This probability drops below 2% for $k = 6$ and to less than 0.1% for $k = 10$; a run of six or more anomalies of the same sign can therefore be regarded as a hint of changed conditions. In view of the unreliability of
TABLE 2. Binomially expected numbers of months with different $R$, $M(i^{10})R^{10-1}(1-R)^i$ ($M$ = length of period in months), and observed numbers (from Table 1)

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the data tested such a simple criterion seems preferable to more sophisticated tests that could be constructed around the actual magnitude of the anomalies, which may, however, be given separate consideration.

Figures 7-9 show the various anomaly plots. In Fig. 7 we compare the anomalies in $R_a$ with those of the monthly mean temperature anomalies $\Delta T$ at Heard Island, the anomalies in the number of precipitation days $\Delta N$, and the ratios $P/P$ where $P$ are the precipitation amounts recorded at Atlas Cove in individual months and $\bar{P}$ the corresponding means for the entire period of observation. Figure 8 shows a similar comparison for Kerguelen, using temperature anomalies only, while Fig. 9 compares the $R_a$ anomalies for 1950-59 with those of the rainfalls in Western Australia and eastern South Africa. In each of these diagrams runs of six or more anomalies have been indicated for the following summary of principal features.

The main association suggested by Fig. 7 is that of lower-than-average values of $R_a$ (or proportions of northern depressions) for 1951, and possibly for the entire period 1951-54, with above-average temperatures. A less distinct but related trend was present in the number of precipitation days, whereas the precipitation amounts only showed transitory association in 1951. It is interesting that the temperature anomalies more often than not appear to have lagged behind those in $R$. Both are of the sign needed to explain the observed glacier tendencies up to 1954.

For Kerguelen (Fig. 8) the 1951 discontinuity unfortunately could not be demonstrated without the Post-au-Français observations for 1951 and 1952 (see footnote page 4). However, there is similar evidence of above-average temperatures associated with below-average $R_a$ values up to 1955, and again in 1958 before a very distinct return to northern tracks and below-average temperatures after 1960. Both the
pronounced recession observed in Heard and Kerguelen by 1963 and the subsequent readvances of the Heard glaciers are thus accounted for.

Finally some evidence of related changes has been sought in the precipitation recorded on the continents bordering the Indian Ocean. To this end rainfall anomalies have been constructed separately for groups of coastal and inland stations in Australia and South Africa from the quintile data published in the US Weather Bureau’s series *Monthly Climatic Data of the World*, using a technique developed by Radok (1960) for the combination of observations from different climatic regions. Figure 9 shows the $R_a$ anomalies for the period 1950-59 flanked by the rainfall anomalies for eastern South Africa and western Australian coasts and interiors, in terms of a standard normal variate $Q'$ representing the rainfall quintiles (see Radok, 1960, for details). The corresponding rainfall anomalies for the other sides of these continents and for South America have also been constructed but will not be reproduced here.

Figure 9 suggests a measure of association between the changes in depression tracks near Heard Island and rainfall anomalies in both Western Australia and southern Africa. Further away almost simultaneous anomaly runs occurred in western South America and eastern Australia in 1958 and 1959, that is before the Heard depression tracks started their distinct northward shift. It will be necessary to examine other meteorological elements before such coincidences can be accepted as evidence of hemisphere-wide connections.
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FIGURE 9. Synoptic anomalies $\Delta R_d$ in the southern Indian Ocean (centre) and rainfall anomalies in Western Australia (top) and eastern South Africa (bottom).
CONCLUSION

There appears to be some justification for claiming that the preferred tracks of depressions explain the temperature conditions and thereby the changes of the glaciers in the Heard Island region. This should make it possible to forecast future glacier variations from synoptic charts. With the use of satellite photos these charts moved towards greater realism shortly after the end of the series here considered, and undoubtedly they will be further improved when the remote sensing of upper air temperatures from satellites becomes operational for the southern hemisphere. The various associations sketched here must then be re-examined, but we believe that they give at least a first glimpse of the synoptic background to the glacier variations on Heard Island.

ACKNOWLEDGEMENTS

We are indebted to the Bureau of Meteorology for access to their southern ocean charts, to Lynne Armitage for her laborious analysis of those charts and other calculations used in this study, and to Dr Grahame Budd not only for help with locating data for Kerguelen but above all for his great exploratory effort on Heard Island.

REFERENCES

Dzerdzeevskii, B. L. (1970) Tsirkulyatsionnye mekhanizmy v atmosfere severnogo polushariya v XX stoletii (statisticheskii dannye dlya polushariya i mesti ego sektoroy).
Radok, U. and Grant, Alison M. (1957) Variations in the high tropospheric mean flow over Australia and New Zealand, J. Meteorol., 14, 141-149.