SKRIFTER NR. 175

Bouvetøya, South Atlantic Ocean

– Results from the Norwegian Antarctic Research Expeditions 1976/77 and 1978/79 –

NORSK POLARINSTITUTT
OSLO 1981

DET KONGELIGE MILJØVERNDEPARTEMENT

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Contents

Enclosed at the back of this volume:

1. Map of Bouvetøya 1:20 000 (preliminary edition).
2. Special publication copy of Chart 516 of Bouvetøya, at a reduced scale 1:100 000.

Foreword

The uninhabitated volcanic island of Bouvetøya (54°25'S, 3°21'E) is remote from other islands or continents. Few ships pass near it, and it is rarely visited. Norway made it a nature reservation in 1971 by Royal Decree.

Plans for the First GARP Global Experiment (FGGE) comprised extensive meteorological investigations during 1979. Norway decided that one of her major contributions to this international programme would be to operate an upper air station at Bouvetøya during the first Special Observing Period of FGGE, from 5 January to 5 March 1979, and thereafter provide observations by two automatic weather stations for the remainder of the year. The Norwegian Antarctic Research Expedition (NARE) 1976/77 visited the island from 23 to 25 February 1977, in order to select a location for the upper air station, and an automatic weather station was established on Nyrøysa on the western side of the island. We were in particular anxious to obtain information on the wind conditions likely to be encountered. Various other research activities were also carried out on the island and in its vicinity. This work is described in Norsk Polarinstitutt Skrifter Nr. 169 and elsewhere.

This volume presents mainly research from NARE 1978/79, with some results from NARE 1976/77. Both expeditions were organized and led by Norsk Polarinstitutt and used the small Norwegian icebreaker M/V «Polarsirkel». The expedition first worked by Bouvetøya from 21 December 1978 to 5 January 1979 using helicopters to fly personnel and equipment to the island. At this time the upper air station was established and five men were left ashore. Extensive research was conducted on and around the island in spite of a mishap where a trawl got caught in the propeller. After return to Cape Town for exchange of scientific crew and for minor repairs, M/V «Polarsirkel» visited Bouvetøya again from 21 to 23 January. An automatic weather station was established on the upper slope of the island. The final visit to the island was from 5 to 8 March 1979. The upper air station was closed down and the five men taken on board. Two automatic weather stations, three small huts and some emergency provisions were left behind on the island.

This research during NARE 1978/79 involved altogether 24 scientists. It has resulted in improved topographic and hydrographic maps of the island and its environs, in descriptions of the flora and fauna, in micro-earthquake, magnetic and geological studies, as well as in better knowledge of the meteorological, oceanographic, and glaciological conditions. Most of the results from these studies are described in the eleven articles in this volume.

Oslo, 1 July 1981

Olav Orheim
Expedition leader,
NARE 1976/77 and 1978/79.

New map of Bouvetøya*

By Sigurd G. Helle

The programme of the Norwegian Antarctic Research Expedition 1978/79 included mapping of Bouvetøya. The best map available until then was the South African chart *S.A. 1 Bouvetøya* from 1967.

The mapping of the island was done from M/V «Polarsirkel» from 21 December 1978 to 5 January 1979. Ola Steine, Norsk Polarinstitutt, was in charge of the surveying, and Bjørn Fossum, Institutt for Kontinentalsokkelundersøkelser, of the satellite positioning. They used Bell 206B helicopters for transport.

The isolated position of Bouvetøya and the difficult weather conditions there made it impossible to obtain conventional vertical photography from aircraft. The only practical solution was to mount a camera for terrestrial photogrammetry in a helicopter and photograph the island towards the coast. A Zeiss UMK 10/1318 universal photogrammetric camera with 10 cm focal length and for 13 × 18 cm glass plates was rented for this purpose. The camera was mounted on a platform with the lens faced through an open window. It was planned that the island should be photographed from 1500 m and 750 m elevations from straight flight lines, respectively about 3 km and 1.5 km from the coast, and with an inclination of — 15°. These plans could not be followed in the field. For instance, the flight elevation had to be reduced to about one-fourth because of prevailing low clouds covering parts of the island. The inclination of the camera was set to 0°. Some photogrammes were out of focus, possibly because of vibration. Figs. 1 and 2 show two of the photogrammes later used in the map compilation.

Three fixed points marked on the enclosed map were positioned by Doppler satellite receiver (see Fossum 1981). These results were used without geodetic connection between the points. Some trigonometric points were measured at Nyrøysa and its vicinity. The points mentioned and the photographic glass plates were the material available for the map construction, which was done on a Wild A7 autograph at Norsk Polarinstitutt.

The construction of Slakhallet — the eastern slope of the island — could not be carried out because its even snow surface gave inadequate stereoscopic

* Publication No. 37 of the Norwegian Antarctic Research Expeditions. (1978/79).

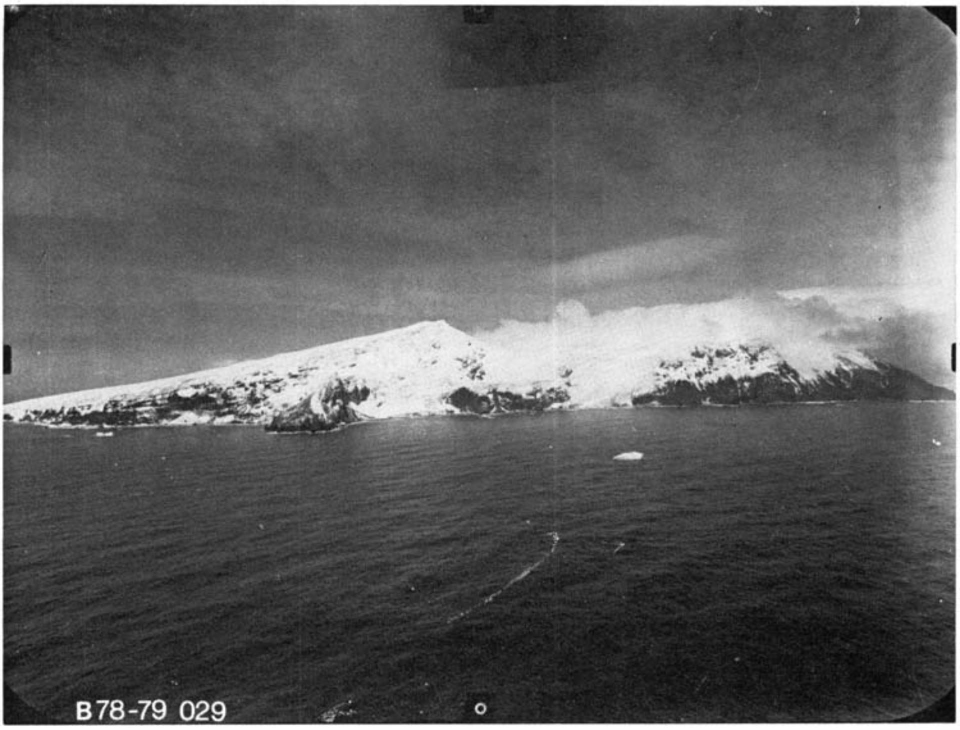

Fig. 1. *Bouvetøya, seen from the north.*

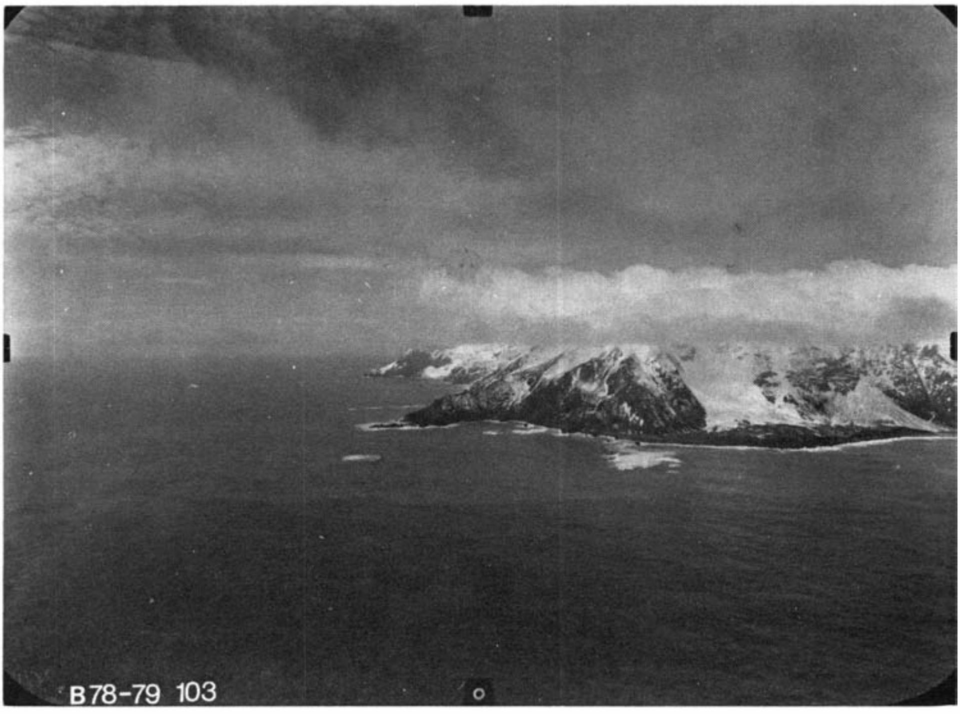

Fig. 2. *Northwestern part of Bouvetøya, seen from the west.*

effect. The photographs show, however, that the slope is fairly even (see Fig. 1 and Orheim 1981, Fig. 1). The upper western part of the island which was always covered by clouds could unfortunately not be compiled.

Bouvetøya is found to be located about 3.7 km WNW of the position shown on the South African chart.

A future, more complete surveying may indeed give a new map which may deviate from the enclosed.

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Fossum, Bjørn, 1981: Geodetic determination of Bouvetøya. *Norsk Polarinstitutt Skrifter* Nr. 175: 11—12 (this volume).

Orheim, Olav, 1981: The glaciers of Bouvetøya. *Norsk Polarinstitutt Skrifter* Nr. 175: 79—84 (this volume).

South African Hydrographic Office, 1967: *Bouvetøya — Bouvet Island/Bouveteiland, 1:30,000. Chart S.A.1.*

Geodetic determination of Bouvetøya*

By Bjørn A. Fossum[1]

Topographic mapping of Bouvetøya was included in the first part of the Norwegian Antarctic Research Expedition 1978/79. As a part of this work it was necessary to establish fixed reference points in a geodetic datum. The determination was carried out by using satellite doppler observation in the TRANSIT-system. The plan was to establish four geodetic points easily detected by the photogrammetric survey carried out simultaneously (see Helle 1981).

The equipment used was a mobile station consisting of a Magnavox-MX 1502 receiver, two 12 volts 100 Ah accumulators, and a small tent for housing the equipment. This had a total weight of approximately 100 kg and was easily lifted together with two surveyors by the Bell 206B helicopters. To set up a station and check that it runs correctly took typically three hours.

Bouvetøya was a challenge from a satellite point of view. The glacier cap extends out to the steep cliff sides which fall almost directly into the sea, and Nyrøysa is the only beach-like area of some size (se enclosed map). The best location for satellite observation points is on the very edge of the cliffs where a relatively free horizon will enable a fairly even distribution of satellite passes. The easiest accessible points were found on the southern coast and in the Nyrøysa area. It was difficult to find suitable observation areas on the northern coast where the few potential locations were either too close to the rising cliff edge or too exposed to adverse weather. Another limitation was set by the prevailing low clouds which generally covered elevations above 300 m. Occasional cloud-free periods were often too short to establish a station, and the possibility of not being able to recover it made us reluctant to establish stations on the northern coast.

The difficult environmental conditions and the limited time available constrained us to establishing three observation points, two along the southern cost and one at Nyrøysa (se enclosed map).

The preliminary on-site processing by the MX 1502 indicated a 3.7 km WNW shift of the position of the island relative to the position given by the South African chart from 1967. The following results were obtained with reference to the WGS-72 datum:

* Publication No. 38 of the Norwegian Antarctic Research Expeditions. (1978/79).

[1] Institutt for Kontinentalsokkelundersøkelser, Postboks 1883. 7001 Trondheim.

Station name	Observation period	Number of passes	On-site position	Post-processing position	Difference in metres
Nyknausen	26.12.—29.12.	59	S: 54°26′42″.6	S: 54°26′42″.65	1.5 m
			E: 03°24′22″.1	E: 03°24′21″.65	8.0 m
			h: 104.7m	h: 132.8m	28.1 m
Moseryggen	30.12.—02.01.	45	S: 54°26′48″.4	S: 54°26′48″.40	0.0 m
			E: 03°20′37″.6	E: 03°20′38″.00	7.2 m
			h: 291.3m	h: 318.2m	26.9 m
Nyrøysa	09.01.—12.01.	83	S: 54°24′36″.7	S: 54•24′36″.72	7.2 m
			E: 03°17′07″.3	E: 03°17′08″.55	22.5 m
			h: 47.9m	h: 65.4m	17.5 m

The post processing is based on the GEODOP programme, using temperature, humidity, and pressure as observed at Nyrøysa. These computations introduce adjustments to the on-site results but show the necessary consistency. The accuracy for the final positions are all within 3 m. The Nyrøysa determination is the least accurate since the computations are mainly based on passes west of the observation point.

References

Helle, Sigurd G., 1981: New map of Bouvetøya. *Norsk Polarinstitutt Skrifter* Nr. 175: 7—9 (this volume).

Hydrographic surveying around Bouvetøya*

By J.H. Fjørtoft

Abstract

The bathymetry around Bouvetøya was charted during the 1978/1979 Norwegian Antarctic Research Expedition. A nautical chart has been compiled on a scale 1:60,000 covering an area out to about 12 nautical miles from the island.

Introduction

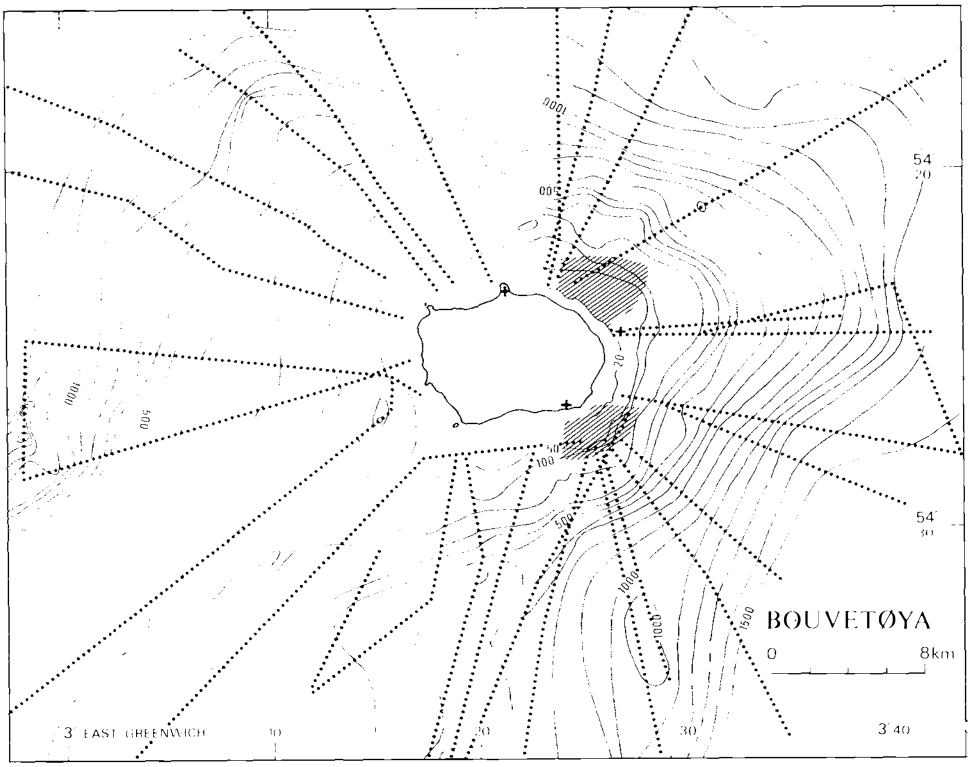
Bouvetøya appears as an isolated volcanic peak in the central southern Atlantic Ocean. The earliest visitors gave accounts of near-shore and landing conditions and the general bathymetry around the island was also known by the 1930's (Mosby 1934). A hydrographic survey was conducted by South African surveyors, mainly east of the island, and published in 1967. Heezen and Tharp (1961), Johnson et al. (1973), and most recently Sclater et al. (1976) have compiled regional bathymetric maps of the area and explored the geological setting of Bouvetøya.

Hydrographic surveying around Bouvetøya was part of a multidisciplinary programme carried out during leg 1 of the 1978/1979 Norwegian Antarctic Research Expedition with M/V "Polarsirkel". Supplementary soundings were collected during visits to the island on leg 2 en route to and from Dronning Maud Land, Antarctica. A bathymetric map and a nautical chart have been compiled covering water depths shallower than 1500 metres.

The hydrographic survey

Survey operations were planned as detailed boat soundings close to the island during daylight and good weather, combined with longer sounding lines run by the expedition vessel M/V "Polarsirkel" during nights and periods of foul weather. The sounding boat (a 6.6 m launch) was equipped with an Atlas model 470 Echosounder and positioned by a Motorola Mini-Ranger system. The transponders were deployed by helicopter and the sites were positioned by a Magnavox 1502 Geoceiver. A lightweight Kelvin Hughes H.E. 30 Echosounder was used as back-up sounding system.

* Publication No. 39 of the Norwegian Antarctic Research Expeditions. (1978/79).



···Density of sounding-lines around Bouvetøya 1978/1979 + Mini-ranger transponder sites

Fig. 1. *Bathymetry of the area surrounding Bouvetøya. Contour interval 100 metres and depths in corrected metres. Survey lines indicated by dotted lines.*

M/V "Polarsirkel" had two Simrad Echosounders (Model EP 2 BN and EK 12 B) and two Navigation Radars (Wave lengths 10 and 3 cm). A dual-channelled Satellite Receiver integrated with log and gyro was used for positioning. Care was taken to obtain at least one satellite-fix on each sounding line run at constant speed and course.

Upon arrival on 23 December 1978, M/V "Polarsirkel" started to run sounding lines radiating from the island out to water depths of around 1500 metres whenever weather conditions were unsuitable for landing operations. On 27 December the expedition vessel was immobilized by a trawl in the propeller and anchored east of the island. For safety reasons the sounding launch was restricted to operate within sight of M/V "Polarsirkel" and this happened to be in the area where the South Africans had laid down most of their work. Surveying was concentrated to the northeast and southwest of Bouvetøya on days with good weather until departure on 5 January 1979.

M/V "Polarsirkel" visited Bouvetøya again on leg 2 for a total of five days in January and March. Additional lines were then run collecting bathymetric and magnetic data, but no survey work was done with the sounding boat.

Results

A final navigation for the survey was worked out by integrating satellite fixes and speed/course information with radar positions of the vessel (Fig. 1). Soundings were computed with corrected sound velocities and plotted at a scale of 1:60,000. Contours were drawn at 100 metre intervals, with the exception of near-shore on the eastern side of the island.

The data were edited and compiled for Norsk Polarinstitutt Nautical Chart No. 516. A reduced copy of this chart in scale 1:100,000 is enclosed with this volume. The final edition printed in colour at a scale of 1:60,00 is available separately.

The morphology of the sea floor around Bouvetøya

The morphology of the platform supporting the Bouvetøya volcano is that of a relatively smooth and gently undulating rise elongated in the NE-SW direction (see chart enclosed), i.e. along the direction of sea floor spreading. Its simple geometry does not indicate any large submarine volcanic centers in the area aside from the island of Bouvetøya itself.

The slope east of the island is built up of several terraces and differs in this respect from other parts of the rise. These terraces may either be constructional features or possibly formed by block faulting.

To what extent sediments smooth the volcanic platform is not known. From limited seismic data, Purdy and Twichell (1978) report that no sediments are present within the map area except pockets in the northern and northeastern part. However, the heavily sediment-laden water observed around the island indicates that a substantial input of erosion products are distributed by currents.

The rise around Bouvetøya is anomalously shallow in relation to the corresponding northeastern flank (minimum depth $\sim$ 1000 metres) of the spreading center east of the island. Also a depth of about 3300 metres is predicted by the depth versus age relationship for a slow spreading mid-ocean ridge (Parsons and Sclater 1977).

The excess accumulation of volcanic material represented by Bouvetøya and its platform has commonly been interpreted as a surface manifestation of a "hot spot" in the earth's mantle (e.g. Morgan 1971).

Acknowledgement

I am grateful to Captain M. Aklestad, officers and crew on board the M/V "Polarsirkel" for their support and good workingf spirit under rather unpleasant weather conditions. Y. Kristoffersen contributed to the discussion on morphology.

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Terrestrial vegetation of Bouvetøya*

A preliminary account

By Torstein Engelskjøn[1]

Abstract

Bouvetøya (54°25'S, 3°18'E) has been surveyed as to vegetation and floristic content. Main vegetation types and localization on the island are summarized. There is a fragmentarily developed Cryptogamic tundra formation of the maritime Antarctic which has phytogeographical relations to the flora and vegetation of more westerly archipelagos like the South Sandwich Islands and the South Shetland Islands.

Previous and present investigations

The nature of the vegetation of Bouvetøya was for a long time subject to speculation due to the infrequency of visits and especially the inaccessibility of the high ground until helicopters became available.

Expeditions during the two centuries after Bouvet's discovery in 1739 were not aware of some extensively vegetated sites on the south and west coasts. Chun (1900 p. 173) stated: "Im Gegensatz zu Bouvet und Lindsay, welche von einem Baumwuchs berichten, verdient hervorgehoben zu werden, dass mit dem Fernrohr keine Spur einer Vegetation (auch nicht aus einer Entfernung von nur zwei Seemeilen) wahrzunehmen war." However, the "Deutsche Tiefsee-Expedition" 1898—99 was unable to land on Bouvetøya, and the quoted statement concerning lack of vegetation must be considered premature as far as cryptogamic vegetation is concerned. The same is the case with the "Norvegia" expeditions 1927—30. The observers, who were not trained botanists, found the island quite barren and reported only thallose algae in some places on the West coast (Aagaard 1930).

Sometime between the visits of S.A.S. "Transvaal" (February 1955) and U.S.C.G.C. "Westwind" (January 1958) the new ground now called Nyrøysa appeared on the northwest coast, leaving an area of about 2 × 0.5 km open for colonization of terrestrial vegetation, and facilitating landing on the island.

* Publication No. 40 of the Norwegian Antarctic Research Expeditions. (1976/77 and 1978/79).

[1] Jøssingveien 25B, 1343 Eiksmarka, Norway.

Holdgate et al. (1968) reported some moss and lichen vegetation on Nyrøysa during their landing 31 March — 2 April 1964. Considering the island at large, these authors held that there were certainly no extensive areas of bryophyte cover.

The South African reconnaissance expedition in 1966 (Muller et.al. 1967) recorded algal, moss, and lichen vegetation in various parts of the island, but no determinations were quoted.

During the landing on 23 February 1977 by the Norwegian Antarctic Research Expedition, Sømme (pers. comm.) collected samples of the notable *Brachythecium — Tortula* vegetation on Nyrøysa.

Participating in the Norwegian Antarctic Expedition 1978/79 as a medical doctor and biologist, the present author was in charge of botanical field work on Bouvetøya from 28 December 1978 to 7 March 1979. Nearly 400 collections were obtained of algae, lichens, fungi, and bryophytes from various parts of the island. The material of lichens and bryophytes are revised by a group at Bergen University in cooperation with workers at the Institute of Terrestrial Ecology, Penicuik, Scotland, at the British Antarctic Survey, and at the British Museum. Algae and fungi are dealt with at Oslo University. Studies of vegetation ecology are continued at Oslo University in cooperation with Norsk Polarinstitutt.

A comprehensive taxonomic and phytogeographical account of the Bouvetøya flora will be published in due course. Vegetation communities and ecology are briefly treated in the present paper, whereas a more detailed account awaits publication.

Outline of vegetation types

The classification of Antarctic vegetation proposed by Longton (1967) and modified and extended by Gimingham and Smith (1970), Smith (1972), and Smith and Gimingham (1976) is partly founded on physiognomic criteria like growth form and vegetative appearance (Formations and Sub-formations), partly on floristic similarity (Associations), and on dominance (Sociations). On Bouvetøya, some 100 squares of 1—4 m^2 from various sub-formations and associations were investigated quantitatively, cover degree being estimated according to Hult-Sernander's scale. Summarizing the main vegetation types of Bouvetøya, the island appears to support a more restricted range of communities within each sub-formation than the more extensive and varied land areas elsewhere in the maritime Antarctic. They resemble those described from some of the South Sandwich Islands (Longton and Holdgate 1979), about 1800 km to the west. Some of the more exposed lichen and moss assemblages, on the other hand, come rather close to communities seen in the South Shetland Islands (Lindsay 1971), e.g. a *Placopsis contortuplicata* association and an *Andreaea gainii — Usnea fasciata* sociation. Finally, a few prominent species or species complexes are common to Bouvetøya and continental Antarctica, e.g. *Usnea antarctica, Grimmia* cf. *antarctici,* and *Bryum* cf. *algens* (see Lindsay 1972; Seppelt and Alston 1978).

Table 1.

Bouvetøya – provisional classification of vegetation.

Present on Bouvetøya	*Comparable unit* (Smith and Gimingham 1976):
1. Nearly abiotic, barren ground (more than 95% of total area).	Snow algae sub-formation.
1.1. Glaciers and snowfields, locally with snow algae (*Chlamydomonas* spp.).	
1.2. Screes, precipices, and moraines, without macrovegetation.	
2. Cliff vegetation, from above breaker zone to c. 400 m above sea level.	Crustose lichen sub-formation.
2.1. *Caloplaca* cliff communities.	*Caloplaca-Xanthoria* assoc.
2.2. *Prasiola crispa* cliff communities.	*Prasiola crispa* assoc.
2.3. *Caloplaca* — *Lecania gerlachei* boulder and cliff communities.	
3. Seashore vegetation, in ascending order (from litoral zone up to the reach of breakers).	*Verrucaria* assoc.
3.1. *Rhodymenia palmatiformis* — *Leptosarca* zone.	
3.2. *Porphyra umbilicalis* zone.	
3.3. *Verrucaria* —*Ulothrix* zone.	
3.4. Bird and seal influenced communities (eroded and polluted versions of 2.1., 2.3 and 3.3.).	
4. North and West Coast climax vegetation, 80 — c. 300 m above sea level.	Moss hummock sub-formation; Fruticose lichen and moss cushion sub-formation, but lacking *Andreaea* spp.
4.1. *Bryum* cf.*algens* — *Drepanocladus uncinatus* — *Verrucaria* communities on Kapp Valdivia.	
4.2. *Brachythecium austro-salebrosum* — *Tortula* cf. *excelsa* moss hummock communities.	
4.3. *Usnea antarctica* — *Lecania gerlachei* — *Brachythecium* — *Tortula* communities.	
5. South Coast high ground climax vegetation, 250—380 m above sea level.	
5.1. *Drepanocladus uncinatus* — *Brachythecium* — *Pachyglossa dissitifolia* communities.	
5.2. *Drepanocladus uncinatus* — *Usnea* communities.	
5.3. *Andreaea* — *Usnea* communities.	
5.3.1. *Andreaea gainii* — *Stereocaulon glabrum* — *Usnea fasciata* communities, partially with *Placopsis contortuplicata*.	Fruticose lichen and moss cushion sub-formation, with *Andreaea* spp.
5.3.2. *Andreaea gainii* — *Grimmia* cf. *antarctici* — *Polytrichum alpinum-Usnea* communities, partially with developed moss turf.	
6. Nyrøysa pioneer vegetation on boulders and lava debris, 10—51 m above sea level.	
6.1. *Tortula* — *Brachythecium* — *Bryum* cf. *algens* communities on weathered lava, tuff, and calciferous breccia.	
6.2. *Brachythecium* — *Grimmia apocarpa* — *Caloplaca* —*Usnea antarctica* communities on solid lava stonefields.	
6.3. *Brachythecium austro-salebrosum* community on fumarole heated ground.	

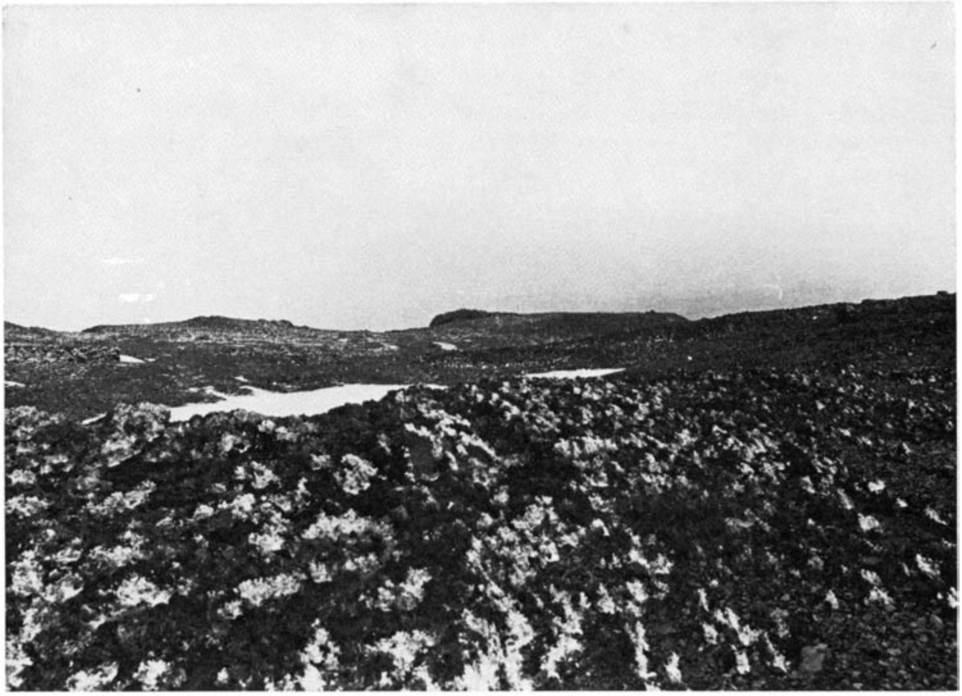

Fig. 1. *Bouvetøya, south coast. Elevated plateau of Rustadkollen. about 350 m above sea level looking south.* Andreaea gainii — Usnea fasciata *communities (lichen with rime), partly cryoturbated. 23 January 1979, 10 a.m.*

The present enumeration (Table 1) is a classification attempt of the particular vegetation types observed on Bouvetøya. Some of the specific determinations are provisional. The correspondence to vegetation units elsewhere in the maritime Antarctic is tentatively noted in the column to the right.

Main vegetated sites on Bouvetøya

As the island is more than 95% ice covered, areas available to terrestrial vegetation are quite restricted. During the present investigation all vegetated sites were visited or photographed from fairly close distance. Four main areas are described here as to appearance and content of vegetation.

1. *Rustadkollen, 340 m above sea level, and surrounding nunataks, 250 — 380 m above sea level. South Coast high ground vegetation.*

Apparently an old and well-established climax vegetation colonizing leached basalt lithosol on exposed plateaus and summit ridges, well away from excessive animal disturbance, marine abrasion, ice avalanches, and volcanic activity. Cryoturbation is considerable on parts of the Rustadkollen plateau.

Already Winsnes (1966) noted the extensive *Usnea* (sect. *Neuropogon)* vegetation. Most of the area (Fig. 1) belongs to the non-vascular cryptogam tundra formation of the maritime Antarctic, chiefly the *Andreaea — Usnea* association, the *Polytrichum alpinum* association, and the *Placopsis contortuplicata* association. The most prominent lichen is *Usnea fasciata* auct. (= *Neuropogon aurantiaco-ater (Jacq.)* Lamb sensu lat. (Jørgensen pers. comm.)) along with *Stereocaulon glabrum, Psoroma* spp., and *Rinodina turfacea.* Important mosses are *Andreaea gainii, Dicranoweisia grimmiacea, Grimmia* cf. *antarctici,* and *Polytrichum alpinum.* However, within such a restricted area the mentioned associations are developed merely as mosaicing fragments. In moist depressions they are replaced by a moss carpet association of *Drepanocladus uncinatus, Brachythecium austro-salebrosum,* the hepatic, *Pachyglossa dissitifolia,* and *Psoroma* spp.

The southern precipices of Rustadkollen and Selodden are colonized by tens of thousands of the southern silver-grey fulmar (*Fulmarus glacialoides*) and the cape pigeon (*Daption capense*). The bird droppings promote extensive covers of the thallose algae sub-formation, presumably dominated by *Prasiola crispa.* As these rock ledges and the promontory of Selodden are practically inaccessible, these sites (from 20 to about 300 m above sea level) are unknown as to possible other components of vegetation.

2. *Rocky slopes and promotories on the west coast, 150 — c. 400 m above sea level.*

Main sites are the elevated slopes southeast of Kapp Circoncision; the mountain ridge with a summit 177 m above sea level north of Nyrøysa, and the crest north of Aagaardbreen, 390 m above sea level. They support a moss hummock vegetation which in places becomes extensive (Fig. 2) and up to 30 cm deep. It is dominated by *Brachythecium austro-salebrosum* and *Tortula* cf. *excelsa.* Minor green patches, presumably of the same species, were also seen on the steep west coast from Norvegiaodden southwards. These oligospecific moss hummocks seem to be a sub-climax stage confined to this sector of the island, which may be related to occurrence of less leached tuff and lava debris. Several species such as *Andreaea gainii* and *Usnea fasciata,* dominating the high ground on the south coast, are entirely absent here.

Wind-exposed crests bordering on the moss areas support a more stony and open fruticose lichen and moss cushion vegetation of *Usnea antarctica, Brachythecium austro-salebrosum, Bryum* cf. *algens, Tortula* cf. *excelsa,* and *Lecania gerlachei.*

Precipices and cliffs unsuitable for extensive moss growth are partially covered by crustose lichens of the genera *Buellia, Caloplaca, Lecanora,* and *Verrucaria,* in some places also foliose species like *Physcia dubia* and the squamulose *Lecania gerlachei.* Especially the dolerite dykes have a marked *Caloplaca* cover, the predominant species being *C. cirrochrooides* and *C. sublobulata. Verrucaria tesselatula* is ubiquitous on all shore cliffs, but may extend to a couple of hundred meters above sea level, along with *Verrucaria dispartita.* These associations of the crustose lichen sub-formation occur all around the ice-free cliffs of Bouvetøya, even at Kapp Meteor on the east

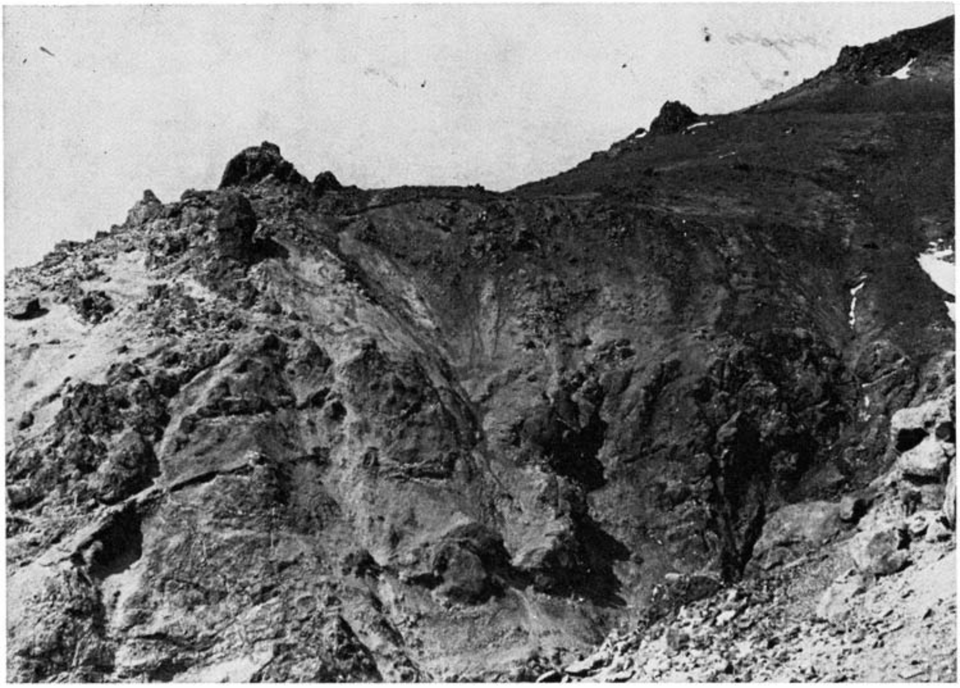

Fig. 2. *Bouvetøya, northwest coast. Headland north of Nyrøysa, about 200 m above sea level. Upper slopes with extensive* Brachythecium — Tortula *vegetation. 16. January 1979, 2 p.m.*

coast, and at quite high levels, at least above 400 m. In avalanche areas, however, the cliffs are devoid of macroscopic vegetation. The *Prasiola crispa* sub-formation is conspicuous as dark-green areas around the bird rookeries, even at considerable altitudes on the crest north of Aagaardbreeen, 390 m above sea level. Such sites, close to the glacier cap, seem to be preferred habitats of genuine antarctic birds such as the snow petrel *(Pagodroma nivea)* and brown petrel (*Thalassoica antarctica*). The accompanying sparse crustose lichen and thallose algae vegetation was only studied from a distance.

3. *Communities of the Kapp Valdivia rhyolite, North Coast.*

Kapp Valdivia forms a promontory projecting about 1 km from the general trend of the north coast and is quite competent against marine abrasion, being built of columnar rhyolite. The vegetation of its top surface, about 80 — 150 m above sea level, is a scattered, oligospecific assemblage of the apparently most frugal species occurring on Bouvetøya. Although the ice-free area is extensive and stable, the impression is desert-like (Fig. 3). Wind action seems to be excessive. A few gullies eroded by meltwater brooks support small stands of *Drepanocladus uncinatus.* Rhyolite slabs are partly covered by *Verrucaria dispartita* and *V. tesselatula,* a little *Buellia latemarginata,* and *Caloplaca cirrochrooides.* Silty ground between the slabs are colonized by compact, old cushions of *Bryum* cf. *algens,* and a little *Prasiola crispa.*

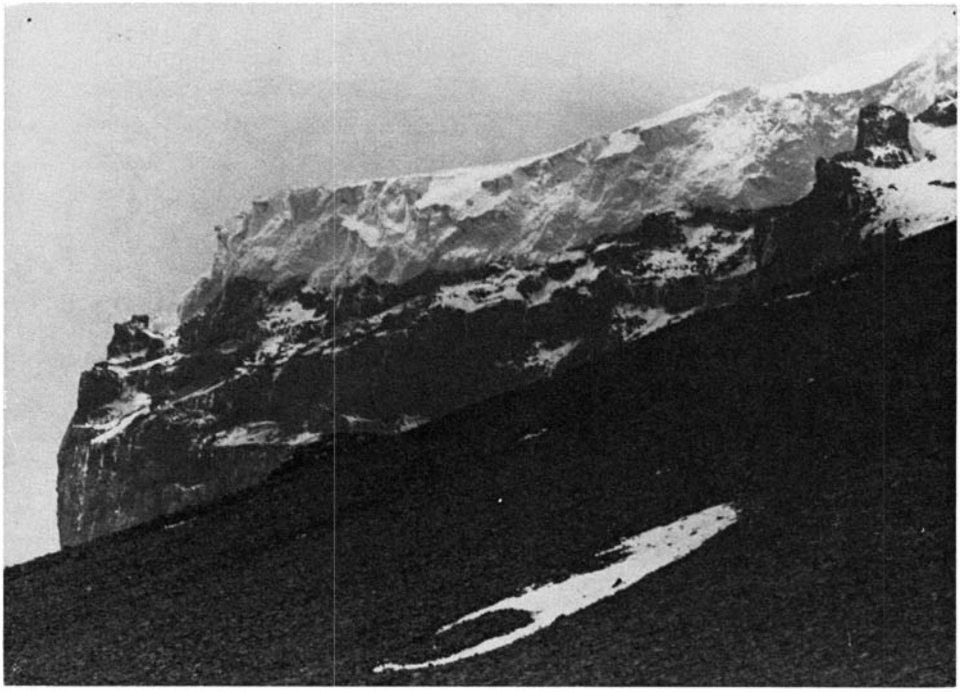

Fig. 3. *Bouvetøya, north coast. Slopes of Kapp Valdivia, about 100 m above sea level, looking east. Almost barren rhyolite stonefield with* Bryum *cf.* algens. *Background: precipice with glacier cap. 30 December 1978, 1 p.m.*

4. *Recent pioneer vegetation of Nyrøysa, 10 — 51 m above sea level.*

The new ground of Nyrøysa including Westwindstranda was consolidated in the period 1955 — 58 after an extensive landslide (Prestvik and Winsnes 1981). Its present expanding vegetation is evidently recruited from the nearby mountains and headlands. Depending on local topography, ground stability, extent of surface weathering, and geothermal heat, the extent and species content of the vegetation is rather heterogeneous. Solid and smooth-surfaced lava surfaces are colonized by *Caloplaca sublobulata* in great amounts, furthermore *Buellia babingtonii, Physcia dubia, Usnea antarctica, Grimmia apocarpa,* and the ubiquitous *Brachythecium austro-salebrosum.*

Easily weathering tuff and calcite-bearing volcanic breccia are overgrown by *Tortula* cf. *excelsa, Bryum* cf. *algens, Brachythecium austro-salebrosum,* and the bryophilic ascomycete *Lamprospora miniata.* We also noted accidental colonization of *Drepanocladus uncinatus* in moist depressions, and quite sporadically, rare species like *Dicranoweisia* cf. *antarctica* and *Leptogium* cf. *puberulum.*

The climax vegetation on such recently invaded ground would seem to be a moss hummock community dominated by *Brachythecium* and *Tortula,* with *Usnea antarctica* on protruding boulders. Most species of the *Andreaea — Usnea fasciata* association described from Rustadkollen are absent.

The expanding fur seal and penguin colonies compete with the pioneer

Fig. 4. *Fur seal area north of Nyrøysa, about 5 m above sea level. Seal pups on the ridge, partly eroded* Brachythecium *hummock. 23 February 1979, 2 p.m.*

vegetation of Nyrøysa. The penguin area of the northern shore expands centrifugally, as shown by moss peat below penguin sludge. Also the fur seals destroy vegetation, but sloping moss hummocks are left intact (Fig. 4). The highest point of Nyrøysa is an agglomerate hillock about 50 m above sea level. It is a nesting place of cape pigeons and fulmars, and *Tortula* carpets are overgrown by *Prasiola* due to excessive dunging.

Finally, the seaward side of Nyrøysa is eroded by the breakers at an astonishing rate, amounting to 1 — 2 m annually (Snuggerud pers. comm.).

Environmental factors

Only a few points are discussed here, whereas biometeorology and soil studies will be dealt with in a later account.

Regional climate

As shown by Vinje (1978), Bouvetøya has a pronounced maritime Antarctic climate. There is an excessive glaciation in spite of the low latitude. Air humidity is high, and there are frequent foggy days. However, clear days have a great solar radiation intensity which leads to considerable desiccation of the porous lava soils.

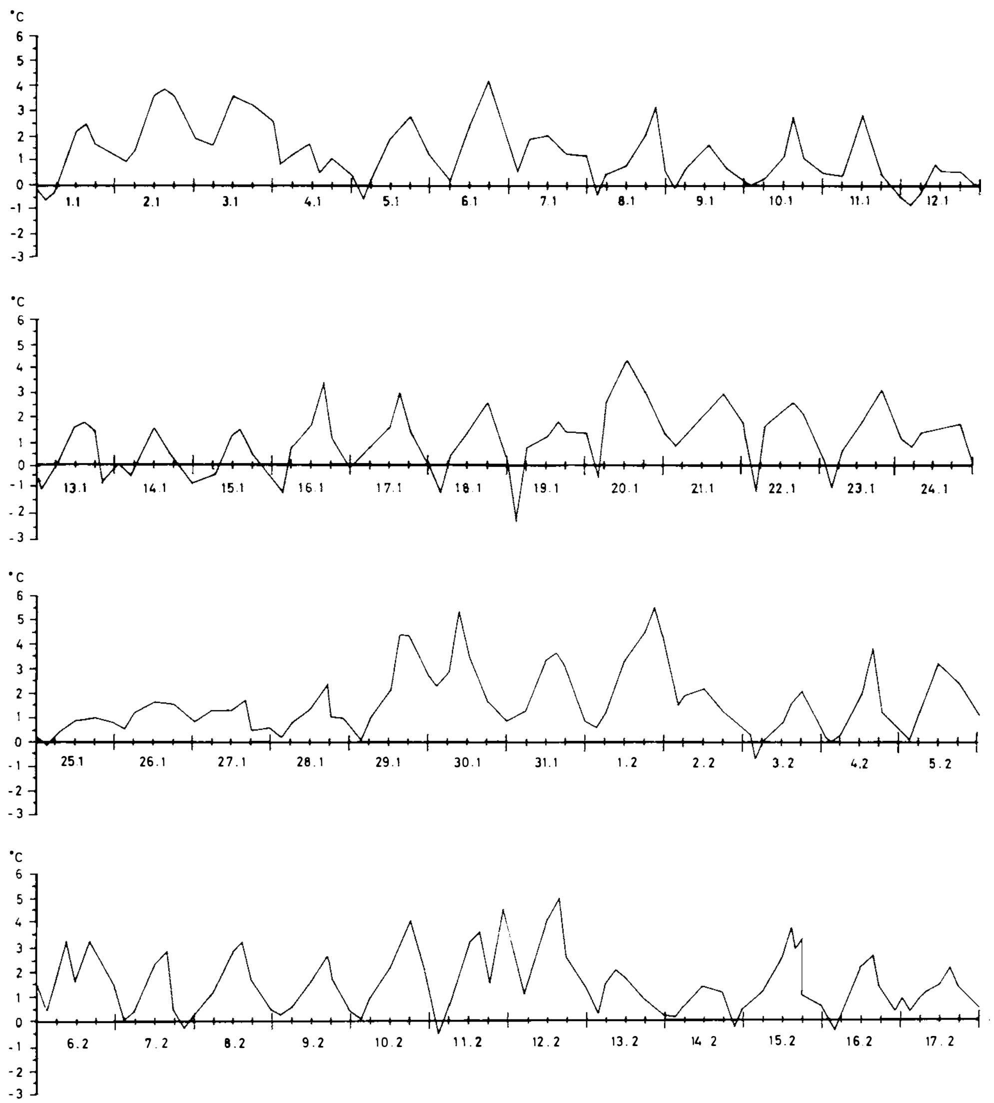

Fig. 5. Diurnal air temperature fluctuations at the Nyrøysa station, 35 m above sea level, 1 January — 17 February 1979. Data by courtesy of T.E. Vinje, Norsk Polarinstitutt.

Local climate

Hourly temperature registrations were performed at various sites on Nyrøysa to study the diurnal temperature regime in the air as well as soil and vegetation. Fig. 5 gives an idea of the diurnal temperature fluctuations in the air above Nyrøysa in January and February 1979. Nightly frost and snowfall is frequent, but snow seldom persists for more than a few hours. Sunny days lead to rapid melting and considerable heating of the ground. On north facing cliffs temperatures above 20° C were measured regularly. Up to 33° C was registered 5 January 1979 (Fig. 6).

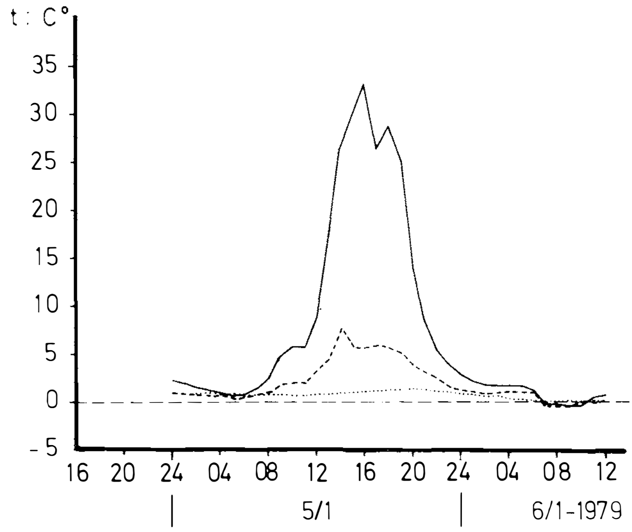

Fig. 6. *Surface temperature fluctuations on a sunny day (5 January 1979) and the following cool night, with snowfall after 6 a.m.*
—— : *Superficial temperature of north facing lava boulder on the middle elevation of Nyrøysa, 30 m above sea level, with* Caloplaca *sp. and* Usnea antarctica.
– – – : *Air temperature below the same boulder (some direct radiation after 12).*
. . . . : *Soil surface temperature below the same boulder, completely shaded.*

Fumarole areas

In view of the contrast between geothermally heated and unheated ground, temperature registrations were also made in a fumarole heated area in the middle of Nyrøysa. Some places have a stable and elevated temperature of 10 — 15° C (Fig. 7 a, b). In addition to solar radiation this favours early thawing and continuous growth of vegetation, which is clearly seen in a local, luxuriant development of *Brachythecium* hummocks.

Recently ice-free areas

The ice-cap mode of glaciation has been described by Holtedahl (1929) as typical of Bouvetøya. According to Winsnes (pers. comm.) striae on the edges of the Rustadkollen plateau indicate a more extensive glaciation in the past. Based on observations from March/April 1964, Lunde (1965) holds that the glaciers are in a bad state as regards net accumulation. However, he concluded that there had been a small advance on the east coast since the thirties. The contrary is evident on the west coast. Comparing photographs in Holtedahl (1929) with 1978/79 observations of the area west of Rustadkollen, glacier lobes have retreated. Finally, nunataks have been exposed on the glacier north of Rustadkollen. It would be of great interest to follow the succession of vegetation in these recently ice-free areas.

Discussion

The scattered vegetation of Bouvetøya belongs to the non-vascular cryptogamic formation of the maritime Antarctic. As to floristic contents, it is an impoverished version of the maritime Antarctic flora at large. There are still too many dubious points in the Antarctic cryptogamic taxonomy to allow a detailed assessment of its phytogeographical affinities. Most, if not all of the

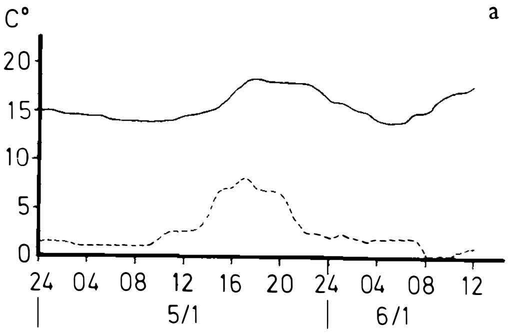

Fig. 7 a. *Air and subsurface temperature 5—6 January 1979 in a fumarole heated area on Nyrøysa, 15 m above sea level. See also Fig. 6 for weather specification. Data by courtesy of L. S. Sømme.*
——: *5 cm deep in a* Brachythecium *cushion.*
– – –: *Air temperature below a boulder (some direct sun radiation after 12).*

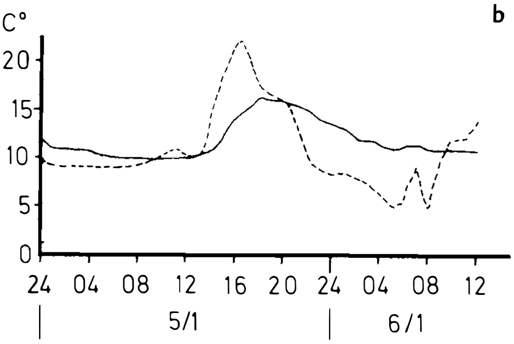

Fig. 7 b. *Surface and subsurface temperature 5—6 January 1979 in a fumarole heated area on Nyrøysa, 15 m above sea level. See also Fig. 6 for weather specification. Data by courtesy of L.S. Sømme.*
——: *6 cm deep in a* Brachythecium *cushion.*
– – –: *superficially (photosynthetizing layer) of another* Brachythecium *cushion.*

nearly 20 bryophyte and about 50 lichen species are widespread in maritime Antarctic localities to the remote west and southwest.

These patterns are compatible with the view that most species have reached Bouvetøya by way of trans-oceanic dispersal since the emerging of the island during the Pliocene and Pleistocene. The question of their survival during more extensive glaciations remains open.

Acknowledgements

I should like to thank the companions of the Norwegian Antarctic Expedition 1978/79 for their keen interest and support in the botanical field work on Bouvetøya. My co-workers at the Universities of Bergen and Oslo have made essential contributions to the results entered in this report.

I am especially indebted to the Norwegian Polar Research Institute for giving me the unique opportunity of exploring Bouvetøya. Thanks are also extended to the Norwegian Research Council for Science and the Humanities for supporting the present study.

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A census of penguins and seals on Bouvetøya*

By Svein Haftorn[1], Lauritz Sømme[2] and John S. Gray[3]

Abstract

By means of aerial surveys and ground counts the total population of penguins on Bouvetøya in Dec. 1978 — Jan. 1979 was estimated at 117,500 birds. Macaroni penguins (*Edyptes chrysolophus)* comprised more than 100,000 individuals, chinstrap penguins (*Pygoscelis antarctica)* 10,000, and Adelie penguins *(Pygoscelis adeliae)* a few hundred only. Altogether five rookeries were cencused; the largest at Kapp Circoncision contained 66,400 penguins. The total penguin population on Bouvetøya has increased dramatically in recent decades, especially in the third largest rookery at Nyrøysa. The population of fur seals (*Arctocephalus gazella*) was estimated at 4100 individuals, and elephant seals (*Mirounga leonina*) at 350 individuals with the largest concentration at Westwindstranda, Nyrøysa.

Introduction

Observations were made of the populations of penguins and seals on Bouvetøya during the Norwegian Antarctic Research Expedition 1978/79. The expedition arrived at Bouvetøya on 21 December 1978, but owing to stormy weather did not come ashore until 24 December. It departed on 4 January 1979.

With the exception of the penguin rookery at Nyrøysa, including Westwindstranda, information on the sizes of the different rookeries was scarce. Neither the exact number of rookeries nor their distribution on the island were known. A census of the penguin population was therefore given a high priority.

Three penguin species breed on Bouvetøya: the chinstrap penguin (*Pygoscelis antarctica*), the macaroni penguin (*Eudyptes chrysolophus*), and the Adelie penguin (*Pygoscelis adeliae*), the latter in limited numbers only. In addition, the island is occasionally visited by the king penguin (*Aptenodytes patagonica*), of which two individuals were observed at Nyrøysa in January

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1979. The species was observed at Bouvetøya for the first time in 1977 (Fevolden and Sømme 1977), but there is no indication that it has ever bred on the island. Altogether penguin rookeries were recognized in five different places, from Posadowsky-breen in the north to Larsøya in southwest.

Following the formation of Nyrøysa, possibly by a volcanic eruption between 1955 and 1958 (Baker and Tomblin 1964), or a landslide (Prestvik and Winsnes 1981), a rookery consisting of 800 chinstrap, 150 macaroni, and 56 Adelie penguins was observed by Soljanik (1959) in 1958. Holdgate et al. (1968), visiting Nyrøysa in March/April 1964, counted about 600 chinstraps and 100 macaronis. The size of the rookery in February 1977 was estimated at about 7500 penguins (Fevolden and Sømme 1977), most of them chinstraps. At the same time estimates were made of the rookeries on Larsøya and Kapp Circoncision.

Olstad (1929) found both fur seals (*Arctocephalus gazella*) and elephant seals (*Mirounga leonina*) on Bouvetøya. Lunde (1965) and Winsnes (1966) reported that the above species were present in 1964 and 1966. Winsnes (1966) gave figures of 20—30 elephant seals and 500—600 fur seals at Westwindstranda. Holdgate et al. (1968) estimated that the same locality had about 500 fur seals. In 1977, the populations of Bouvetøya were estimated at about 1000 fur seals and 200 elephant seals (Fevolden and Sømme 1977). While Fevolden and Sømme (1977) did not observe fur seals from their rubber boat when circulating Larsøya, a population of about 300 animals were seen on photographs taken from helicopters during the present study.

Methods

All the rookeries were photographed from two helicopters. Photographs of whole rookeries were obtained using a 35 mm camera with 55, 200 and 300 mm lenses. Enlarged copies (usually 24 × 18 cm) of overlapping "close-up" photographs provided a basis for counts. In addition, the rookery at Nyrøysa was photographed from the ground.

Aerial photography was carried out on two occasions, on 30 December 1978 at about 0930 — 1100 hrs, and on 1 January 1979 at about 1330 — 1500 hours.

The numbers of penguins given below refer to fullgrown individuals. Nestlings, at the actual time only a few days old, were not counted.

The populations of fur seal and elephant seal were counted partly from the ground and partly from counts based on aerial photographs taken during the penguin surveys and on other occasional helicopter flights.

Penguins

Posadowsky-breen

The rookery was situated on the steep rocky slope close to the western border of the glacier and consisted probably entirely of macaroni penguins. 5473 birds were present in the rookery at the time of photography.

Kapp Circoncision

This rookery, lying on the huge saddleformed headland on the northwestern part of Bouvetøya, was by far the largest of the rookeries on the island, estimated to contain 66,400 penguins at the time of photography. This estimate was based on a census covering 26.6% of the colonized area, and gave a total of 17,682 individuals. Macaroni penguins dominated the rookery. It is impossible to make a detailed determination of the penguins to the species level from the photographs taken.

Nyrøysa (Westwindstranda)

This rookery consisted of two subcolonies, one on the recently formed rocky beach and the other, a much smaller one, on a plateau about 150 m above sea level on the steep cliff behind the northern part of the beach.

The subcolony on the beach (Fig. 1) contained, according to the aerial photographs, 14,826 individuals. By counting the birds in the foreground (altogether 5683 individuals) on 114 photographs taken at ground level (covering the whole subcolony), the proportions of the three species in this subcolony were calculated to be 55.5% chinstrap, 44.1% macaroni, and 0.4% Adelie penguins. Based on these percentages, the numbers of the different species were estimated at 8228 chinstraps, 6538 macaronis, and 60 Adelies. All three species were more or less intermingled on the breeding ground, but the greatest concentration of macaronis was at the highest elevation on the seaward side, whereas the chinstraps mainly bred at the lower levels. The few Adelies were scattered all over the subcolony, with only 1 — 3 pairs at each place.

The number of penguins (apparently only macaronis) breeding on the plateau was estimated from aerial photographs at 1400 individuals. To reach the nesting places they followed a zigzag path made by the birds themselves up the steep cliff. The substratum was loose and the birds were in constant danger of a landslide.

Kapp Norvegia

From aerial photographs covering the whole rookery, 7683 penguins, probably macaronis only, were counted. They nested on the narrow headland ridge and down along the steep sides.

Larsøya

This is the second largest rookery on Bouvetøya, estimated to contain 21,700 penguins, of which 9792 were counted with precision from an area estimated to cover 45.1% of the colony.

It was impossible to distinguish the species on the aerial photographs, but pictures taken of the rookery by geologist Thore Winsnes show crowds of macaronis, flanked by a few chinstraps. The proportional composition of species is probably much the same as in 1928, when Olstad (1929) visited Bouvetøya. He found that macaronis made up the bulk of the penguins.

Chinstraps were less numerous and occurred especially in the outskirts of the rookery, whereas Adelies were few. No Adelies appear on Winsnes' photographs, which, however, cover only parts of the rookery.

Seals

At the time of the present study the population of fur seals at Bouvetøya comprised a total of about 4100 individuals, and of elephant seals about 350 individuals. The seals were observed in four localities.

Nyrøysa

Seals were found on both the northern and southern beach of Westwindstranda. At the southern beach a total of 478 fur seals were counted, of which about 150 were pups. The number of elephant seals was 105. Based on aerial photographs and ground counts the population of fur seals at the northern part of Westwindstranda was estimated at about 2700 individuals, of which about 800 were pups. A total of 160 elephant seals were counted on this beach.

Kapp Norvegia

From air photographs, about 600 fur seals and 60 elephant seals were counted on the beach on the northern side of Kapp Norvegia.

Larsøya

No elephant seals were observed on Larsøya, but about 300 fur seals were counted from air photographs.

Svartsandstranda

Around 30 elephant seals and 10 isolated individual fur seals were counted. This beach is probably used as a resting site and not a whelping area, since it is narrow, influenced by falling ice from the glacier abutting the beach and by strong wave action, the sea completely flooding the beach in stormy weather.

Discussion

The total number of fullgrown penguins ashore during our visit in December 1978 — January 1979, was estimated at 117,500 birds, of which 56,856 (48%) were counted from aerial photographs. Three species are breeding on the island, the macaroni penguin, chinstrap penguin, and Adelie penguin. The macaroni was by far the most numerous species, counting probably more than 100,000 birds, whereas the Adelie population numbered at the most a few hundred. The number of chinstraps present at the time of photography probably did not exceed 10,000 birds, of which about 8200 were at Nyrøysa. Besides Nyrøysa and a small population on Larsøya we have no information on chinstraps nesting at other places on Bouvetøya.

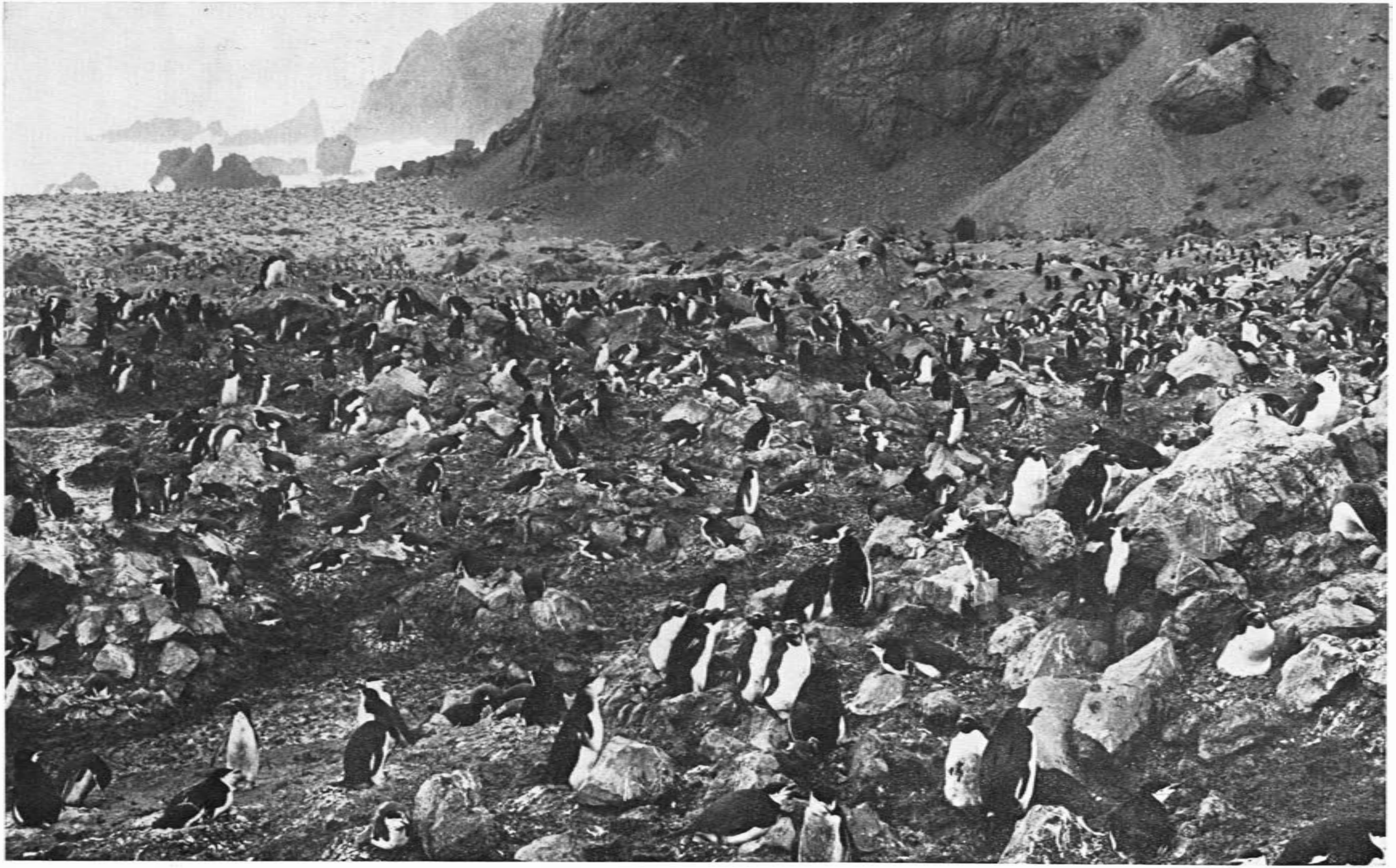

Fig. 1. *The northern part of Nyrøysa, showing chinstrap and macaroni penguins in the rookery. 27 Dec. 1978. Photo: Haftorn.*

The numbers given are estimates or total counts of birds present during daytime. The number of birds belonging to the rookeries, but out feeding at sea at the time of photography, was not estimated. Judging from the great masses of macaronis and chinstraps which, every evening, came in from sea and sought their respective nesting territories at Nyrøysa, the number to be added to obtain a grand total must for Nyrøysa alone be one thousand. The movement of birds was in the opposite direction in the early morning hours, but although there was a clear concentration of birds leaving Nyrøysa at this time, both seaward and landward movements occurred throughout the day.

On our arrival on 24 December hatching had just begun in the chinstrap nests at Nyrøysa, but the majority of birds was still incubating two (sometimes one) eggs. Most eggs were hatched during the next few days, thus suggesting a synchronization of egg laying.

Hatching of macaroni eggs occurred on an average several days after the chinstrap hatching. All observed macaroni nests contained one egg. The species normally lays two eggs, of which one is nearly always lost in a still unknown way (Warham 1975). The first nests with newly-hatched young were observed on 29 December (one of the nestlings by then already 2 — 3 days old).

Thus, the penguin census took place at a time when numerous nests contained small young, while others still held eggs.

According to Warham (1975) the female macaroni penguin is responsible for feeding the nestling during the first 3—4 weeks of its life, while the male stays on guard, brooding the chick and protecting it against severe weather conditions and attacks by predators. Most of the females seem to feed their nestlings daily, and may visit them at any time of the day, but most frequently in the afternoon. However, at the time of hatching and the following 2 — 3 days, the pair remains together at the nest.

Also in the chinstrap penguin the sexes share the duties at the nest, one parent remaining while the other is collecting food at sea.

Observations at Nyrøysa in the middle of the day showed that a greater proportion of the chinstrap penguin nests was attended by one parent only than was the case in the macaroni penguin nests. Thus, only 50 (9.7%) out of 515 chinstrap penguin nests observed on 1 January at 10 — 11 hrs, were attended by both parents, compared with 154 (70.3%) out of 219 macaroni penguin nests observed. Although the counts are small, the trend is statistically significant (X^2-test, $p < 0.001$), a result confirmed by the photographs taken. This difference is probably due to the above-mentioned interspecific difference in hatching time.

Lacking reliable conversion factors, no estimates of the total number of penguins attached to the rookeries on Bouvetøya are given, and the numbers quoted should be regarded as lower limits.

Circumstantial evidences indicate that the penguin population at Bouvetøya has increased strikingly during the recent decades. The increase of the rookery at Nyrøysa since establishment in the 1950's is indisputable. When Fevolden and Sømme (1977) visited the beach on 23 February 1977, they found the rookery to contain about 7500 birds, consisting of two species, chinstraps and macaronis, of which the former appeared to be most numerous. Although their figures may be too low, the present census in December — January 1978/79, giving a total of about 15,000 birds, indicates that the rookery is still growing.

When Olstad (1929) visited Bouvetøya in 1928, he found penguins on three sites only, Larsøya, Kapp Norvegia, and Sjøelefantstranda (Elephant Seal Beach). Olstad (1929) may not have been aware of the large colony on Kapp Circoncision, which was actually visited by members of the "Norvegia" expedition in 1929.

At many breeding grounds in the Antarctic and Subantarctic, penguin numbers have increased markedly recently (Conroy 1975). Evidently this general population trend also applies to the penguins at Bouvetøya. According to Conroy (1975) three factors are believed to be important in explaining these changes in population size: 1) climatic changes, 2) recovering in numbers following persecution by man, and 3) increase due to surplus of food following depletion of whale stock.

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Supercooling in two Antarctic terrestrial arthropods from Bouvetøya*

By Lauritz Sømme[1]

Abstract

The effect of acclimation at —5 and —10° C on supercooling was studied in two Antarctic species of terrestrial arthropods collected at Bouvetøya in January 1979. Mean supercooling points of the Collembola *Cryptopygus antarcticus* were —25.1° C in specimens acclimated at —5 and —27.4°C after two weeks at —5 and two weeks at —10°C. Acclimation at —10° C also lowered the supercooling points of the oribatid mite *Alaskozetes antarcticus* more than at —5° C, and a mean supercooling point of —30.2° C was found in mites given two weeks at each temperature. Low concentrations of glycerol were present in mites from both temperatures.

In principle two mechanisms of cold-tolerance are found in terrestrial arthropods exposed to temperatures below the freezing point of their body fluids (Salt 1961; Asahina 1969). Some species are able to survive the actual ice formation within their haemolymph, while others are rapidly killed by freezing even at temperatures only a few degrees below freezing point. It is of vital importance for species in the last group to remain unfrozen, which is achieved by the supercooling of their body fluids. The degree of supercooling is regulated by several factors, of which the elimination of nucleating agents from the gut and the formation of cryoprotective substances in the haemolymph are of particular importance.

A review of the available data (Sømme 1979a) shows that alpine species of Collembola, as well as species from the Arctic and the Antarctic, depend on supercooling to survive low temperatures. No freezing-tolerant species have been found so far. The same strategy has been evolved in oribatid mites from the Norwegian mountains (Sømme and Conradi-Larsen 1977), the Austrian Alps (Sømme 1979b) and from the Antarctic (Block et al. 1978; Young and Block 1980).

Data on the cold-tolerance of species from the Antarctic, however, are relatively scarce. The limits of supercooling in the Collembola *Cryptopygus antarcticus* Willem were studied in specimens from Signy Island (Block et al.

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1978) and from Bouvetøya (Sømme 1978). In both cases animals devoid of gut content had supercooling points in the range of —25 to —30° C. Bouvetøya specimens previously acclimated at 0 and —5° C had mean supercooling points of about —26° C (Sømme 1978). Acclimation at 12° C for one or two weeks resulted in slightly higher supercooling points. The ability to supercool was strongly influenced by feeding or starvation of the animals concerned (Block et al. 1978). In *C. antarcticus* allowed to feed, the average supercooling point rose to about — 7° C.

A more detailed study on cold-hardiness in an Antarctic mite was carried out with *Aslaskozetes antarcticus* (Michael) by Young and Block (1980). They concluded that food material in the gut greatly reduced the ability to supercool in this species as well. When freezing occurred at relatively high temperatures, it was considered that food material was retained in the gut of the animals. In specimens with empty guts, supercooling points decreased from about —27° C in those stored at 0° C down to about — 30° C following acclimation at —5 and —10° C. The increased ability to supercool was accompanied by the accumulation of glycerol in adult mites, and possibly by other polyhydric alcohols as well in the nymphs.

The present study is based on specimens of *C. antarcticus* and adult *A. antarcticus* collected at Bouvetøya during the Norwegian Antarctic Research Expedition 1978/79. To investigate the extent of supercooling in these animals, they were exposed to various kinds of acclimation in the laboratory. The results support and supplement previous data for both species, and demonstrate a striking similarity in specimens from Bouvetøya and Signy Island.

Material and methods

Moss samples were collected on Bouvetøya in January 1979 and stored at about 5° C in the cold room of the expedition vessel. After arrival in Oslo in April, Collembola and mites were extracted in Tullgren funnels. Live specimens were collected from the funnels in chilled tubes placed in thermos bottles filled with ice. Following extraction, all specimens were initially stored at 0° C for periods of fifteen to forty days without access to food.

Prior to measurements of their ability to supercool the animals were acclimated for various periods of time at —5 and —10° C. Supercooling points were measured with copperconstantan thermocouples connected to a Hokushin recording potentiometer. The animals were attached to the thermocouple with petroleum jelly, and cooled at a rate of 1 — 2° C per minute (Salt 1966). Analysis of glycerol according to Metzenburg and Mitchell (1954) was carried out on samples of *A. antarcticus* acclimated at —5 and —10° C.

Results and discussion

The distribution of the supercooling points of *C. antarcticus* acclimated at —5 and —10° C is presented in Fig. 1. The data agree with previous results from 0 and —5° C acclimated specimens of this species from Bouvetøya (Søm-

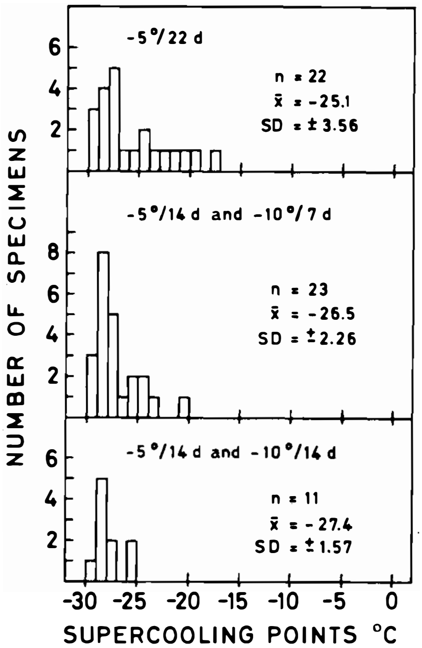

Fig. 1. *Histograms showing the distribution of the supercooling points of* Cryptopygus antarcticus *acclimated at —5 and —10° C.*

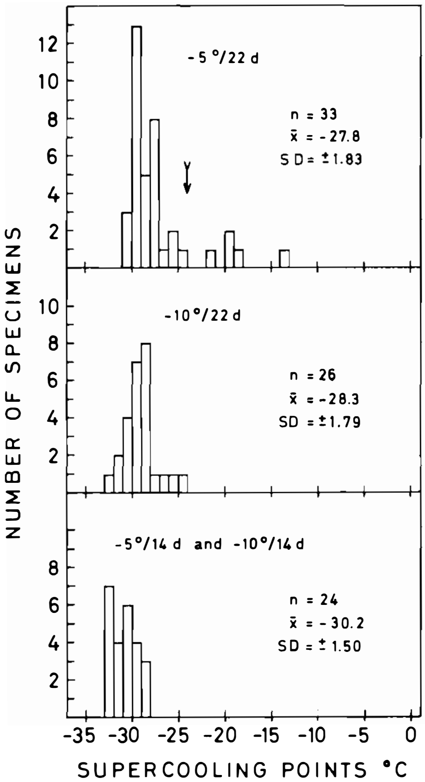

Fig. 2. *Histograms showing the distribution of the supercooling points of* Alaskozetes antarcticus *acclimated at —5 and —10° C Only values below —24° C, indicated by an arrow, were used to calculate mean supercooling points.*

me 1978). From Fig. 1 it appears that specimens acclimated at —10° C have even lower supercooling points than those from —5° C. The reason for this decrease is not known at present. No trace of glycerol was detected on paper chromatograms, but preliminary studies with gas liquid chromatography indicate that other cryoprotective substances may be present.

Results from acclimation experiments with *A. antarcticus* are presented in Fig. 2. As discussed by Young and Block (1980) freezing at temperatures above —24° C may be caused by food residues in the gut. They found that supercooling points are lowered below this level when the guts are emptied, and further by acclimation at —5 and — 10° C. To analyse the effect of acclimation at low temperatures, only supercooling points with values below 24° C were considered. Excluding values above —24° C, specimens from the present study acclimated at —5° C had en average supercooling point of —27.8° C. The average values were slightly lower in specimens from —10° C, and significantly lower ($P < 0.01$) in those acclimated for two weeks at — 5° C and for two weeks at — 10° C. These results

Table 1.

Average concentration of glycerol in Alaskozetes antarcticus *following acclimation at —5 and —10° C.*

Acclimation	*No. of samples*	*Glycerol μ g/mg fresh wt.*
—5° C/23 d	2	5.6
—5° C/14 d and —10° C/14 d	3	16.1

are in close agreement with those of Young and Block (1980). In their experiments animals acclimated for two weeks at —5° C and for four weeks at —10° C had an average supercooling point of —29.7° C. Specimens acclimated at —5° C had average supercooling points between —28 and — 29° C, and of —30.5° C if the humidity was lowered to 50% RH during storage.

In *A. antarcticus* from Bouvetøya the presence of glycerol was demonstrated in specimens acclimated at —5 and —10° C (Table 1). The concentration was highest in those kept at the lowest temperature. Young and Block (1980) found a significant correlation between supercooling points and the concentration of glycerol.

The results of Young and Block (1980) and those of the present study both show that a decrease in supercooling points takes place at —5 and —10° C. This is related to the accumulation of a cryoprotective substance, which is produced even at these low temperatures.

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Geology of Bouvetøya, South Atlantic*

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Abstract

The volcanic structure of Bouvetøya (54°25′ S, 3°21′ E) consists of two formations: a lower hydrothermally altered sequence of mainly pyroclastic rocks and an upper formation of predominantly lava flows. The transition between these formations is believed to represent the time when the structure was rigid enough to prevent seawater from entering the vents. K-Ar dating indicates that the island is at least some 1 Ma old. The age obtained on rocks from Nyrøysa (0.4—0.5 Ma) shows that this platform, which formed between 1955 and 1958, represents a landslide rather than a recent eruption. The predominant rock type of Bouvetøya is a transitional basalt, but mugearite, trachytic icelandite, and comendite (relatively young) are also found. The present volcanic activity of Bouvetøya seems to be restricted to abundant fumarolic activity along the north-western and northern coasts. The volcanic activity of the island is now probably in a declining phase.

Introduction

Bouvetøya is an oceanic volcano located at 54°25'S and 3°21'E in the South Atlantic Ocean, close to the Bouvet triple junction. According to the distance (c. 45 km) from the central part of the Bouvet ridge and a half spreading rate of 1.0 — 1.3 cm/a between anomalies 2' and 3' and 0.83 cm/a from anomaly 2' time to Recent (Sclater et al. 1976), the age of the oceanic crust beneath the island is c. 4.5 — 5.0 Ma. This is thus a maximum age of the volcanic activity responsible for the Bouvetøya cone.

The island is 10 km long (east-west) and 7.5 km wide (north-south), and the summit area (crater/caldera rim) in the north-western part of the island reaches a height of almost 800 m a.s.l. (Fig. 1). The assymetrical shape of Bouvetøya is influenced by the wave action caused by almost permanent westerly wind in the area. Most of the island is covered by permanent ice. However, rocks are well exposed in a few outcrops along the coast (Fig. 1), and deeper parts of the cone can be studied in the steep cliffs along the northern, western and southern sides of the island.

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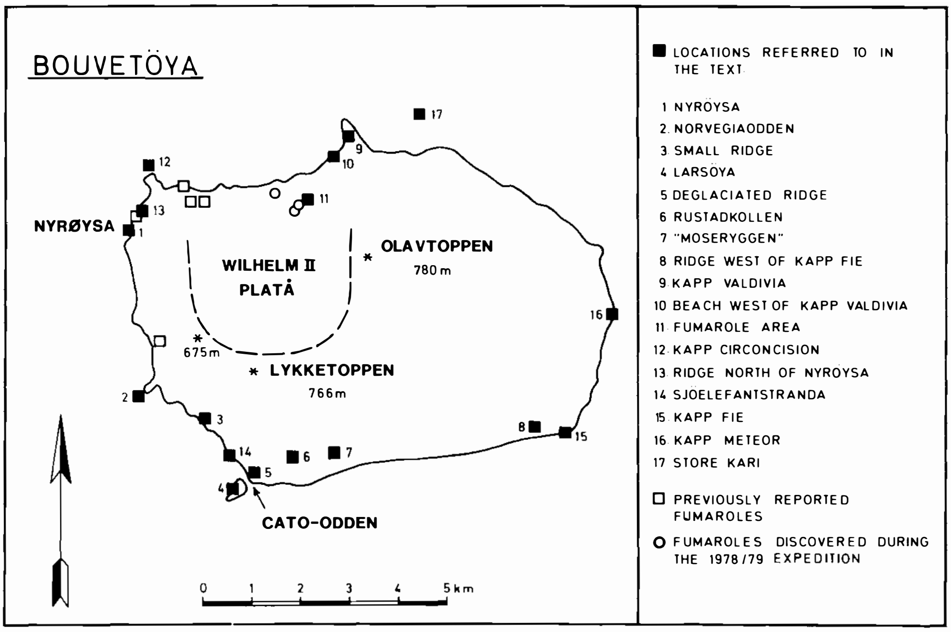

Fig. 1. *Sketch map of Bouvetøya showing sites of locations described in the text.*

General comments

The Norwegian Antarctic Research Expedition of 1978/79 visited Bouvetøya during the period 21 December, 1978, to 5 January, 1979. During twelve days from 24 December, 1978, helicopter transportation was available for geological mapping and sample collection when weather conditions were appropriate.

During the twelve days stay on shore, eleven different localities on the island were visited, seven of these (Nos. 3, 5, 7, 8, 9, 10, and 11 on Fig. 1) for the first time. Rustadkollen (Location 6, Fig. 1) was visited later in the summer, during a two-day stop at the island. The material collected includes 115 rock samples and a gas condensate from one of the fumaroles. In addition, observations were made and pictures taken at other places along the coastline of the island. Unfortunately, the weather conditions were never so good that the summit of the island with the caldera could be observed or visited.

Previous work

The "Valdivia" expedition in 1898 resulted in some information about the petrology of Bouvetøya from a few dredged samples (Reinisch 1907). Members of the two "Norvegia" expeditions in 1927/28 and 1928/29 landed on Bouvetøya, and they annexed the island for Norway in December 1927. During these two expeditions considerable information and geological material from both onshore and offshore locations were collected. Based on this material, Holtedahl (1929) described the physiography and geology, and Broch (1946) the petrology of the volcanic rocks of the island. A joint British/

South African expedition in March 1964 resulted in several papers of geological interest. Baker and Tomblin (1964) and Lunde (1965) discussed the geology and mode of formation of the new platform (now called Nyrøysa) on the north-western coast of the island, and Baker (1965, 1967, 1973) described the geology and petrology of Bouvetøya. A South African expedition in March 1966 worked under very good weather conditions for five days and results were reported by Starke (1966), Winsnes (1966), Snape (1971), Verwoerd (1972), and Verwoerd et al. (1976). Later Imsland et al. (1977) and Prestvik (1981) reexamined material from the "Norvegia" expeditions together with some material from the 1966 South African expedition and gave accounts of the petrology and trace element geochemical features of rocks from the island. Two geological reports (Furnes and Løvlie 1978, Løvlie and Furnes 1978) resulted from the Norwegian Antarctic Research Expedition of 1976/77.

Thus, much information on the geology and petrology of Bouvetøya existed prior to the 1978/79 expedition. However, some problems remained to be solved.

Two important ones concern:

a) the mode of formation of Nyrøysa, a platform that appeared on the north-western coast of Bouvetøya between 1955 and 1958.
b) the present volcanic activity and the age of the island.

Geologic features of Bouvetøya are described and discussed below, based on previously known information and the new data collected during the 1978/79 expedition. The rather detailed descriptions of Locations 1 —12 (Fig. 1) are given because the information obtained from a remote island such as Bouvetøya should be made available for members of subsequent expeditions.

Discussion of geological features and distribution of rock types

Bouvetøya is covered (95%) by permanent ice, and exposed rocks occur mainly along the shoreline and in cliffs and ridges. The best sections are found in the north, west, and south-southwest. Locations that have been visited and sampled in situ by this and previous expeditions are marked on the location map, Fig. 1.

The peaks on the top of the island lie along a caldera rim (Imsland et al. 1977) which is broken towards the north. Verwoerd et al. (1976) mentioned that exposed rocks could be seen on the inner caldera walls, but weather conditions during the 1978/79 expedition did not permit observations and sampling of this feature. It is uncertain wether there has been any eruptions within the caldera after its formation. Outrops of basaltic rocks at Location 11 (Fig. 1), which is supposed to be within or on the northernmost wall of the caldera, show no conclusive evidence to confirm that these represent post-caldera eruptions.

Oblique aerial photographs of the island (Fig. 2) show that the thin ice cap and probably the underlying lava flows as well dip gently (8°) eastwards all the way from the top of the caldera rim. Gently dipping (15 — 17°) lava flows and pyroclastic deposits are also seen in situ along the southwestern

Fig. 2. *Oblique aerial photograph of Bouvetøya from the north. Numbers represent: 1. Olavtoppen, 2. Kapp Valdivia, 3. Fumarole area (Location 11 above), 4. Posadowskybreen, and 5. Kapp Circoncision.*

Photo: Norsk Polarinstitutt.

coast of the island (Fig. 3). Holtedahl (1929) and Baker (1967) suggested that parasitic cones might occur on the island and mentioned Rustadkollen as one example. However, both the cliffs above Cato-odden and Rustadkollen (Locations 5 and 6, Fig. 1) are made up of gently dipping lava flows or flow units, indicating that the vents were in or close to the crater or caldera area. The only good evidence for parasitic vents is to be found at Kapp Valdivia (Location 9, Fig. 1) where a silicic dome occurs and probably at Larsøya, which is dominated by a rhyolitic lava flow. The eventual continuation of this flow to Cato-odden on the mainland could not be investigated. Broch (1946) reported rhyolite from Sjøelefantstranda close to Cato-odden, but it is not known whether this rock was found in situ. However, the rocks from both Kapp Valdivia and Larsøya are extremely fresh compared to most basic rocks from Bouvetøya, indicating that they may represent late-stage parasitic or flank eruptions. Silicic rocks are scarce outside of these two locations. They are sporadically found in domes at Nyrøysa and in the hydrothermally-altered rocks behind Nyrøysa and south of Westwindstranda (Fig. 4), as well as in the steep seaward slopes of Nyrøysa, where they occur as dikes cutting lavas or volcaniclastic breccias.

Intermediate rocks (trachytic icelandite/benmoreite) have been reported from Nyrøysa (Baker 1967; Verwoerd et al. 1976; Imsland et al. 1977; Furnes

Fig. 3. *Area between Norvegiaodden and Cato-odden. The solid line represents the transition between a lowermost section of predominantly tuffaceous rocks (hyaloclastites) and an uppermost section of mainly lava flows.*

and Løvlie 1978). Imsland et al. (1977) analysed two trachytic icelandites reported to come from Larsøya, but the actual locality of these samples has not been proven. Their composition is almost identical both petrographically and chemically to the Nyrøysa rocks, but their identity is somewhat unclear because no intermediate rocks were found on Larsøya during this expedition.

Verwoerd et al. (1976) found that the aphyric lava cropping out at Kapp Fie on the southeastern coast was a mugearite, the only occurence of a rock intermediate between transitional basalts and trachytic icelandites reported from Bouvetøya previously. During the 1978/79 expedition a hydrothermally altered lava of approximately mugearite composition was found in the steep seaward cliffs of Nyrøysa where it underlies the trachytic icelandite of the platform.

The predominant rock type of Bouvetøya is a traditional basalt or hawaiite characterized by rather high TiO_2 (2.7 — 3.7%) and by moderately high K_2O (0.9 — 1.5%) and total FeO (10 — 12%) content. A few somewhat more "primitive" rocks reported by Broch (1946), Verwoerd et al. (1976, anal. No. 1), and Imsland et al. (1977, anal. Nos. 1, 6, 7, 10) contain variable amounts of plagioclase megacrysts that may have been accumulated. Unpublished analyses (Furnes pers. comm.) from Kapp Meteor show that the lavas exposed along the eastern shore are also evolved hawaiites.

Fig. 4. *Vertical rhyolitic dikes in transitional basalt. Southern end of Westwindstranda (south of Nyrøysa).*

In a recent paper, O'Nions and Pankhurst (1974) reported trace element data on rocks from Bouvetøya. Two of their samples were reported as tholeiites low in K_2O and Rb, indicating that much less evolved basalts occur on the island. These "tholeiites" (BV-5, BV-17) are even much less evolved than the rift tholeiites of this area reported by Dickey et al. (1977). Two of these samples from Nyrøysa (BV-3, BV-5) were also analysed for Sm and Nd isotopes (O'Nions et al. 1977). Sample BV-3, which has K_2O and Rb contents within the range of the common transitional basalt, has Sm = 7.75 ppm and Nd = 32.51 ppm. This Sm value is very similar to the Sm values published by Prestvik (1981) for transitional basalts from the island. However, their sample BV-5, which has K_2O = 0.22% and Rb = 3.3 ppm, shows Sm = 17.00 ppm and Nd = 61.91 ppm and is thus enriched by a factor of 2 in these elements compared to the more evolved sample BV-3. This feature is opposite to what is expected during normal fractionating processes. Basaltic rocks from the cliffs behind Nyrøysa are, however, invariably altered, and analyses of such rocks (T. Prestvik unpublished) show considerable depletion in elements such as K_2O and Rb. Furthermore, studies by Menzies et al. (1979) show that REE concentrations in basalts may be enhanced by hydrothermal alteration when the water/rock ratio is high. We therefore suggest that sample

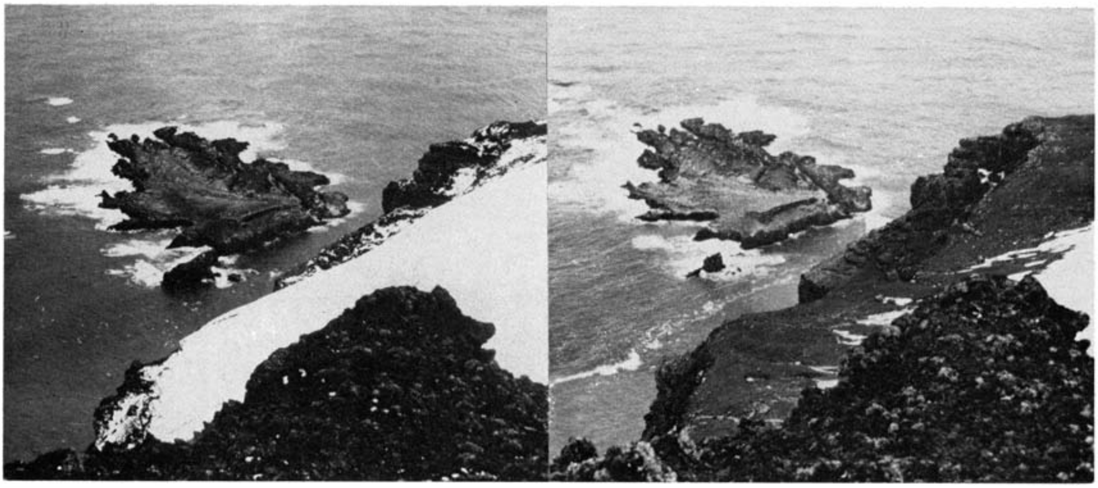

Fig. 5. *Wave abrasion at Larsøya and retreat of glacial cover west of Rustadkollen 1966 to 1979.*

BV-5 and problably BV-17, which both were sampled at Nyrøysa (Baker and Tomblin 1964), represent hydrothermally altered transitional basalt rather than low-K tholeiite.

Glacial cover and wave abrasion

The top of the front on the east side of the island is 50 — 70 m above sea level and the uneven glacier surface with a lot of crevasses indicates a fairly thin ice cover on the slope. A reduction in ice thickness from 1966 to 1979 was observed on several localities. The ridge west of Kapp Fie (Location 8, Fig. 1) and the ridge above Cato-odden (Location 5, Fig. 1) were covered by ice and not seen in 1966. Older photographs of the last location show that the ice was about 40 m thicker here (Fig. 5). On the other hand, behind Nyrøysa, in a cliff which was free of ice before and just after the landslide, a small glacier is now forming, mostly by material from ice avalanches.

The wave action steadily undercuts the rather soft pyroclastic rock, and changes in the coastline can easily be seen by comparing new and older photographs. The beach east of Norvegiaodden is now completely washed out, the inner side of Larsøya is much changed (Fig. 5), and the tip of Kapp Valdivia has changed completely in the last thirteen years. Throughout the ages there must have been a lot of undercut cliffs which resulted in landslides such as the one that formed Nyrøysa. In the same way as seen there, the wave action is rapidly removing the scree and beaches on the windward side.

Geological features of different locations

Location 1. Nyrøysa

Nyrøysa is the name of the new platform on the northwestern coast of Bouvetøya. The platform is fan-shaped and lies in front of a recess in the cliffs behind it. It is composed of a mixture of blocky lava of mainly trachytic

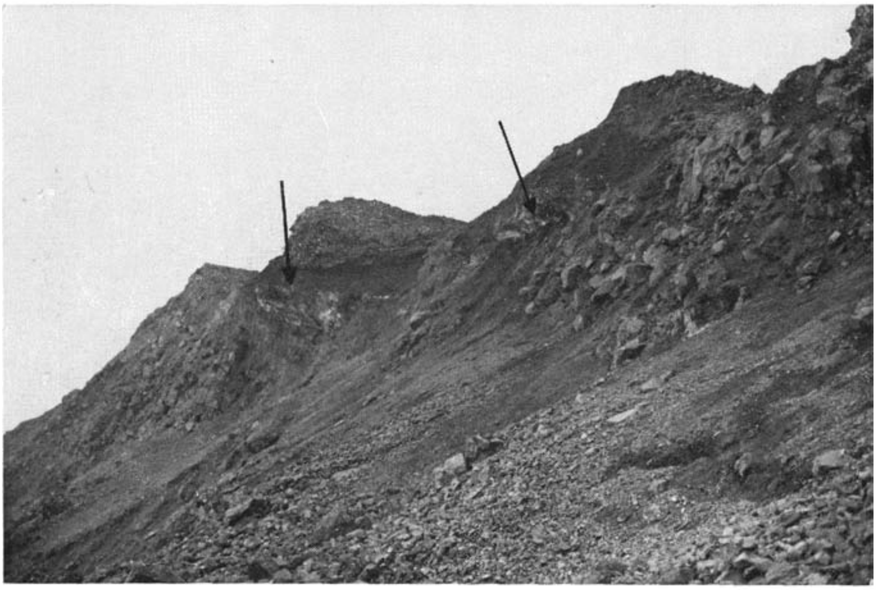

Fig. 6. *The seaward slope of Nyrøysa. Arrows point to buried ice.*

icelandite (benmoreite) and a few erratic boulders of other rock types which all together form a hummocky surface. To the north and south, where the recess in the cliffs ends, this hummocky platform is bordered by a smooth beach deposit where well-rounded material of various rock types occurs. The beach in front of Nyrøysa (Westwindstranda) is much more heterogenous because the well-rounded shore material is mixed up with lava blocks and debris sliding down the steep frontal slope of Nyrøysa. The whole platform is suffering continuous abrasion from the action of waves. In the steep slopes toward the sea, ice is buried in the upper part of the platform deposit (Fig. 6). Pictures from 1966 and 1979, taken from the same location, show a pronounced abrasion (50 — 100 m wide) during this time span, and also a settlement and sinking of the surface (Fig. 7). In many places on the platform there are good records in the form of kettle holes, showing that ice or glacier remnants occurred buried there previously.

The surface structures of the lava blocks at Nyrøysa have been discussed by several authors (Baker and Tomblin 1964; Lunde 1965; Winsnes 1966; Baker 1967; Verwoerd et al. 1976; Furnes and Løvlie 1978). The distribution of rock types on the surface reported by Baker and Tomblin (1964) could not be verified during the 1978/79 expedition. In fact, Furnes and Løvlie (1978) made their observations of what was supposed to be a recent lava flow partly within the area where Baker and Tomblin reported "uplifted older lavas and pyroclastics". Baker and Tomblin (1964) reported that tumuli occur most frequently in the north-central and most elevated parts of the platform. Common all over the platform are lava flows or domes with structures varying from chilled, glassy contacts (or outer parts) via vesicular parts to jointed, massive lava, similar to those described by Furnes and Løvlie (1978).

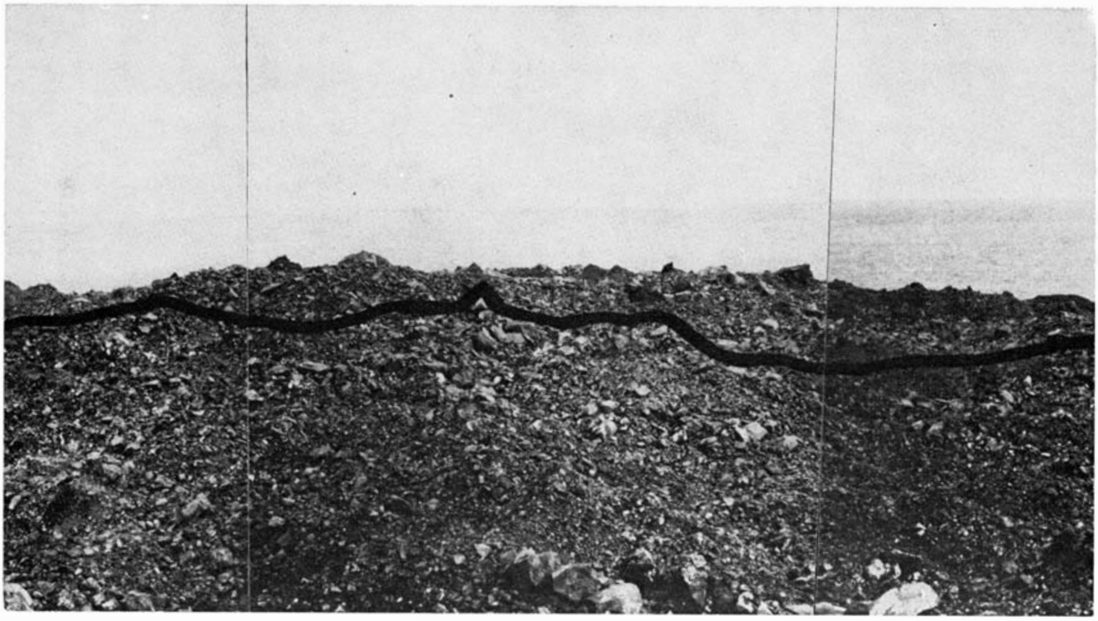

Fig. 7. *Abrasion of Nyrøysa from 1966 to 1979.*

These features are usually observed in «domes» or huge blocks (Fig. 8) and even in blocks along Westwindstranda. Between these huge blocks the surface is covered mainly by flaggy, jointed, or massive lava and a mixture of sand and gravel. This gravel is probably the mechanical breakdown product of the vesicular lava surfaces. The climate close to the sea at this rather high southern latitude is such that the temperature fluctuates around the freezing point one or more times every day during most of the year, giving very good conditions for frost-weathering of a porous rock.

In some places lava surfaces of a aa-type are seen, revealing subaerial conditions during cooling. Furthermore, sedimentary structures of unsorted and sometimes sorted material (Fig. 9) are observed to be in contact with vesicular or massive lava. The dip of these layers is sometimes very steep (more than 60°). The rocks can be described as volcanic breccias, but their origin is not fully understood. Some of the observed features are similar to what is found in rocks described as pillow block breccias (Furnes and Fridleifsson 1979), but other features indicate that the material is reworked, at least to some degree.

The steep cliffs south and north of Nyrøysa are made up of lava flows and pyroclastic material of transitional basalts which in some places are dissected by both basic and silicic dikes. In the recess behind Nyrøysa, pyroclastic rocks or volcanic breccia are the predominant rock types. These are highly altered by hydrothermal processes, resulting in celadonite and chlorite formation to give the typical green colours of these rocks. The alteration is sometimes clearly connected to dikes around which pyrite and clay minerals are concentrated. These altered rocks also have abundant secondary calcite.

Fig. 8. *Dome of trachytic icelandite, Nyrøysa. Flaggy, massive lava to the left. The vesicular central part part grades into a glassy surface towards the right side of the photograph.*

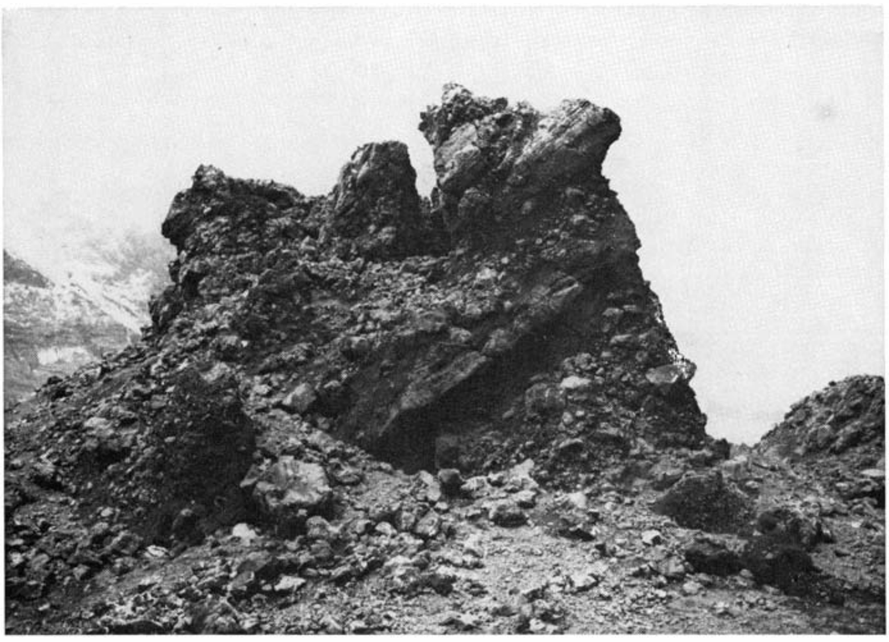

Fig. 9. *Steeply dipping volcanic breccia with relatively well sorted layers of tuffaceous material. Close to tumuli of the highest point of Nyrøysa.*

Fig. 10. *Hydrothermally altered volcaniclastic breccia cut by rhyolitic dikes in the steep slope of Nyrøysa towards Westwindstranda.*

At higher elevation this sequence of mainly fragmental volcanic rocks is overlain by massive lavas (sampled at a ridge north of Nyrøysa, Location 13 in Fig. 1). These lavas have suffered much less alteration than have those of the underlying sequence. The reasons for this may for instance be: a) the lavas are more dense and massive such that there is much less percolation of hydrothermal solutions than in the underlying fragmental deposit, or b) there is a depositional break at the contact (a hiatus).

In the steep slope of Nyrøysa towards Westwindstranda a stratified section is found in some places. The lowermost part of the section consists of highly-altered pyroclastic or breccia type rocks, sometimes cut by dikes of both silicic and basic composition (Fig. 10). Above this is a blocky lava which in turn is overlain by flaggy trachytic icelandite. At the pyroclastic rock/blocky lava contact a layer of clay, 5 — 20 cm in thickness, is developed.

Petrographic descriptions of the intermediate rocks of Nyrøysa have been given by Baker (1967), Verwoerd et al. (1976) and Imsland et al. (1977). Baker (1967) interpreted the calcite found in some samples to be of deuteric origin and Verwoerd et al. (1976) mentioned that reddish alteration zones were observed along curved joints. This latter feature was confirmed during the 1978/79 expedition and in addition, it was observed that the trachytic icelandite contains abundant secondary minerals, mainly calcite and aragonite. The layer of clay mentioned above consists of smectite, quartz, calcite, and pyrite whereas the secondary minerals of the pyroclastic rocks behind Nyrøysa are celadonite, chlorite, quartz, and pyrite. Alteration minerals in massive basaltic lavas include secondary minerals after olivine and matrix glass, matrix calcite, and calcite/quartz filling in veins and along fractures.

Fig. 11. *Flow lamination in rhyolite, Larsøya. The flow is vesicular in most places, but has a massive central part (around hammer) made up of obsidian.*

Location 2. Norvegiaodden

The outermost part of Norvegiaodden consists of a dense, black, aphyric basic lava. Difficult topographic relations prevented detailed investigations, but the steep cliffs behind this point are made up of tuffaceous rocks dissected by a few dikes. The dike frequency is clearly lower than behind Nyrøysa. The pyroclastic layers dip about 15° towards the south.

Location 3. Small ridge between Norvegiaodden and Larsøya

A difficult helicopter landing made observations and sampling possible at this location. The cliff is composed of a basic hyaloclastite breccia cut by a few dikes. The matrix glass of the hyaloclastite fragments is almost completely altered to clay and/or chlorite type minerals, and some calcite is also observed.

Location 4. Larsøya

A landing at Larsøya permitted mapping of the southwestern parts of this islet. The rock is a flow-laminated rhyolite of black to slightly greenish colour. In some places parts of the flow are developed as massive obsidian, whereas in other places a scoriaceous rock type has resulted from very high vesicularity. Large-scale laminar flow structures are shown in Fig. 11.

A big colony of brooding penguins (which are protected under Norwegian law) prevented investigations on the eastern parts of the island. However, Verwoerd et al. (1976) report rhyolite and "veins" of obsidian from this part of Larsøya. The highest parts to the northeast of the islet consist of a stratified deposit, some of which is thought to be tuffaceous material (Verwoerd et al. 1976).

Fig. 12. *Lava flows (or flow units) with scoriaceous partings. Cliffs above Cato-odden (Location 5 above).*

The samples of rhyolite from Larsøya are extremely fresh. Microphenocrysts of anorthoclase occur in a glassy or partly devitrified matrix. Chemically these rhyolites are characterized as *comendites* (Bailey and MacDonald 1970; Imsland et al. 1977). Dikes were not seen to cut the rhyolite flow at any place.

Location 5. Deglaciated ridge above the cliffs at Cato-odden. (Elevation 200 m)

At this location there is a variety of basaltic lava flows or flow units (Fig. 12). The thickness of the flows is invaryably less than 10 m (commonly only 1 — 2 m) and oxidized scoria occurs between most flows. The uppermost flows are characteristically highly plagioclase-porphyritic, whereas the lowermost ones have somewhat less plagioclase. On the eastern side of the ridge a 2 — 3 m thick, brown palagonitized hyaloclasite sequence was observed. Cavities in the hyaloclastite are partly filled in by aragonite/calcite lumps with a concentric growth pattern. The relationship between this hyaloclastite and other flows could not be observed in detail. The presence of hyaloclastite, however, shows that the area was probably overlain by a thin ice cover at the time of eruption. On the other hand, the lava flows/flow units are typical features of subaerial eruptions.

Location 6. Rustadkollen

Rustadkollen was visited later in the season. The exposures observed stretch from 320 m to almost 400 m a.s.l. and consist of several lava flows of porphyritic transitional basalts dipping gently to the SE. The vesicular top of several

Fig. 13. *Curved columnar jointing in silicic dome of Kapp Valdivia. Height of visible section: 30 m.*

flows indicates a subaerial deposition. The lower part of the sequence seems to reappear in Moseryggen further east. Glacial striae, both on higher and lower levels, indicate the previous existence of an ice cover moving towards the south. The lower surface is partly covered with gravel and soil with a rich lichen vegetation, indicating that it is a considerable time since it was covered by ice.

Location 7. "Moseryggen" on the western side of Christensenbreen. (Elevation about 200 m)

This ridge, which is about 150 m in a north-south direction and about 50 m wide, is made up of a massive, slightly porphyritic (plag + ol), grey coloured, evolved transitional basalt. The flow is rather thick (> 20 m) and no lower contact was found. In some places glacial striae were found on the lava surface showing that the glacier previously covered the ridge. No scoriaceous material or other features typical of a vent were observed. This flow, then, probably originated at higher levels of the volcano, possibly from the main crater/caldera rather than from a flank eruption. The distance from the caldera rim is only about 1.5 km.

Location 8. Ridge between Randibreen and Kapp Fie. (Elevation about 75 m)

This ridge is about 50 m long in a north-south direction and is made up of black, porphyritic (plag + ol + cpx) basalt which varies from highly vesicular to massive types. This basalt is the only one recorded at Bouvetøya in which olivine phenocrysts are abundantly present. The ridge is partly

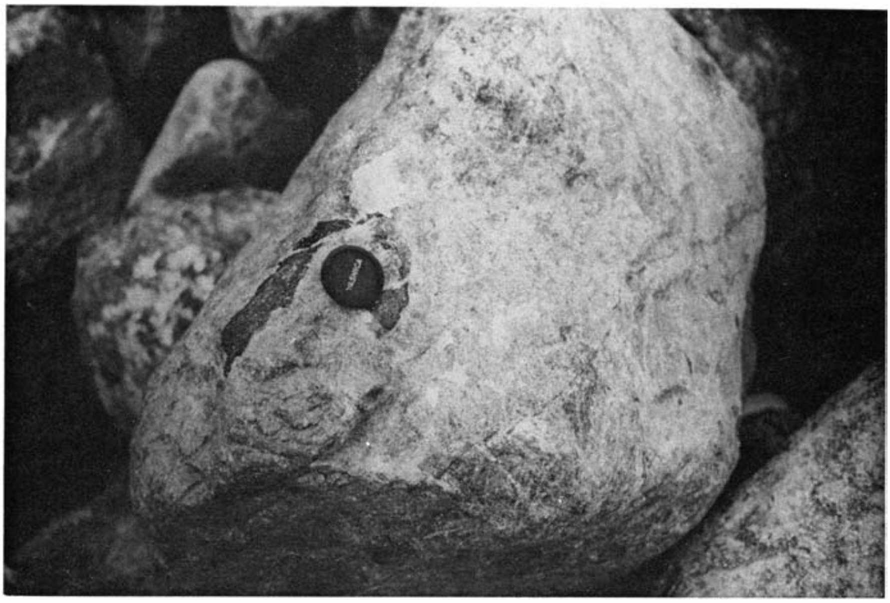

Fig. 14. *Basaltic xenoliths in well-crystallized silicic lava. Kapp Valdivia.*

covered by till, and among the transported boulders palagonitized hyaloclastites and fragments of dense, aphyric basalts are quite common, indicating that subglacial eruptions have taken place at higher elevations.

Loation 9. Kapp Valdivia

This promontory in the northern part of Bouvetøya consists of a massive comendite lava flow or dome. In the steep cliffs slightly curved, well developed columnar jointing (Fig. 13) can be observed whereas the crest of the ridge shows somewhat vesicular lava with flow lamination. The rock is grey coloured except for some red-to-brownish stained spots on the uppermost flowbanded parts of the flow. Both towards the east and west it can be seen that the lava overlies a sequence of interbedded hyaloclastites and basic lava flows.

Megascopically the rock looks like a fine-grained granite, but all thin sections show a porphyritic texture with anorthoclase phenocrysts and microphenocrysts of clinopyroxene and minor amphibole in a well crystallized matrix. A few xenoliths of both vesicular basalt and some rhyolitic material were observed in the massive parts of the rock (Fig. 14).

Location 10. Beach west of Kapp Valdivia

A 400 — 500 m long beach west of Kapp Valdivia gave access to a cliff surface here. It consists of pyroclastic rocks cut by several dikes, varying in form and texture from porphyritic to aphanitic. One dike showed columnar jointing. The rocks at this location are generally similar to those north and south of Westwindstranda.

Fig. 15. *Isolated pillowy bodies in brecciated transitional basalt. Kapp Circoncision.*

Location 11. The fumarole area

This location lies at about 250 m elevation east of Posadowskybreen (Fig. 2) on the northern side of Bouvetøya. The steep walls of exposed rocks apparently are located within the area supposed to represent a caldera. Approximately 100 m east of the fumaroles is a steep cliff 30 — 40 m high which is composed of different rock types. The lowermost section is stratified (tuffaceous rocks) whereas the uppermost part seems to be represented by rather massive lava flows. Dikes crosscut the wall in several directions. A lava close by is a vesicular subaerial basalt with phenocrysts of plagioclase, clinopyroxene, and olivine (now partly altered). The rocks exposed at the site of the fumaroles are brecciated or similar to the lowermost section of the previously mentioned steep wall. An almost vertical dike (0.5 m wide) was sampled, and the matrix of this basalt is heavily altered to clay minerals. The plagioclase phenocrysts are, however, rather fresh. Calcite was observed in the matrix, but only in small amounts.

Only *weak* secondary mineralization of calcite due to the fumarolic activity was observed on the rock surfaces. The reason for this may simply be that the slope of the area is so steep that small slides of gravel and boulders, which take place intermittenly, keep the rock surface almost clean. Furthermore, the action of meltwater contributes to the same process.

It is impossible from the observations made at this location to state whether the exposed rocks represent a section of the pre-caldera structure of Bouvetøya or a post-caldera infilling.

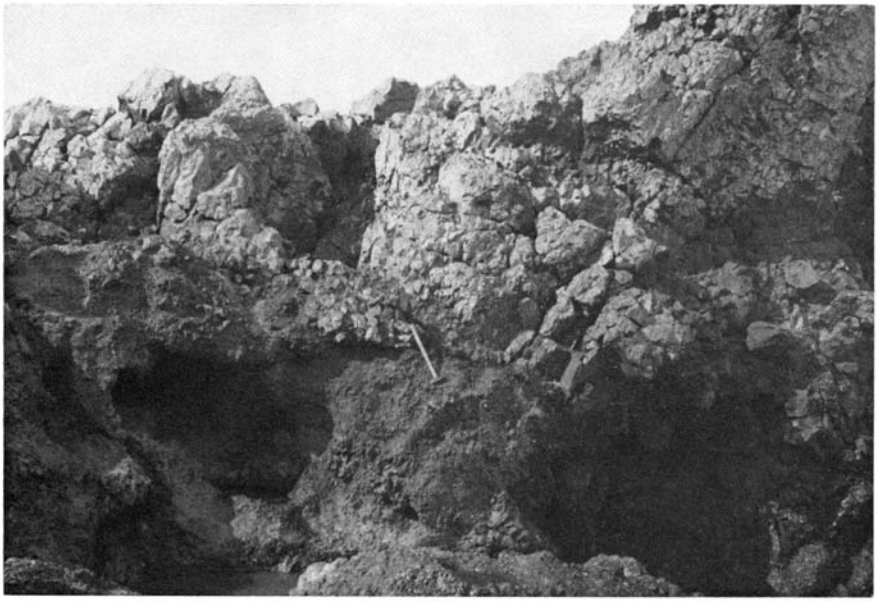

Fig. 16. *Transition from fragmented (below hammer) to massive transitional basalt. Kapp Circoncision.*

Location 12. Kapp Circoncision

This is another promontory in the north/northwestern part of the island. It is divided by the action of waves into a high ridge made up of pyroclastic rocks connected with the mainland, and a rather flat 100 — 150 m long and up to 100 m wide outer part made up of a black, very fine-grained and aphyric basalt. This rock is characteristically irregularly jointed on a small scale (~ 5 cm), and in some places the rock grades into a breccialike type where the fragments may have glassy rims. In a few lowlying places, isolated pillows were found (Fig. 15). A transition from such fragmental or jointed rocks (believed to represent subaquatic eruption) to subaerially cooled lava (Fig. 16) was observed at an elevation of about 5 m. An almost vertical basaltic dike with red-stained large phenocrysts of plagioclase (analysed by Verwoerd et al. 1976) crosscut the whole sequence.

Locations visited only by earlier expeditions

The 1978/79 expedition visited most places that had been described earlier. Important exceptions are: a) *Kapp Meteor* on the eastern coast where a section of hyaloclastites and thin lava flows defines a former sea level (Løvlie and Furnes 1978) about 15 m above the present shoreline. All rocks collected here are of hawaiite type (Furnes unpublished). b) *Kapp Fie* on the southeastern coast where a greenish-brown aphyric lava of mugearite composition was found by Verwoerd et al. (1976). This is the only rock intermediate between transitional basalts (hawaiites) and trachytic icelandites reported from Bouvetøya prior to the 1978/79 expedition. c) *Sjøelefantstranda* west of Catoodden. Broch (1946) and Imsland et al. (1977) reported both basalt and rhyolite from this locality. Because no sampling reports exist from the "Norvegia" expeditions, it is not known whether these samples represent in situ rocks. Some highly plagioclase porphyritic basalts from this locality appear to be very similar to some of the lava flows observed during the 1978/79 expedition at the top of cliffs above this shore (Location 5 above).

Sjøelefantstranda, reported as a beach in reports from the "Norvegia" expeditions, has now completely disappeared. This observation is in agreement with what was observed by the second "Norvegia" expedition, that the shoreline in some places changed very much from one year to the other.

d) *Store Kari.* Verwoerd et al. (1976) sampled material from this pinnacle 1.5 km east of Kapp Valdivia and several hundred metres from the present shoreline. The composition is hawaiitic.

Observations made from helicopter

As on previous expeditions (Baker 1967; Verwoerd et al. 1976), it was possible to make observations from the helicopter along the cliffs in areas where we could not land to make detailed observations and sampling. From these studies we conclude that the coast between Kapp Valdivia and Kapp Meteor consists of interbedded lava flows and hyaloclastites, probably of similar type as those described from Kapp Meteor by Løvlie and Furnes (1978). In some places brown colours (similar to what is found in palagonitized rocks) occur, indicating that some of the eruptions were at least partly subglacial, or that we are observing reworked tuffaceous material.

From the coast between Larsøya and Norvegiaodden it is clearly seen that the lowermost section consists of mainly tuffaceous material (hyaloclastites as in Location 3 above) dissected by dikes, whereas the uppermost section is dominated by flows of lava. This relationship is somewhat similar to what is seen in the recess behind Nyrøysa except that at Nyrøysa the hydrothermal alteration seems to have been much more extensive.

Fumarolic activity on Bouvetøya

Fumarolic activity has been reported by most expeditions visiting Bouvetøya. All observations come from the western, northwestern, and northern parts of the island (between Norvegiaodden and Posadowskybreen). Most of this activity could be confirmed on this expedition. A number of both active and extinct fumaroles were observed, particularly in the cliffs between Kapp Circoncision and Posadowskybreen, and a single steam vent was observed high up in the cliff east of the front of Posadowskybreen. None of the active fumaroles seemed to be producing any large amounts of steam. The fumarole between Nyrøysa and Norvegiaodden observed by the South African expedition in 1966 is still active, but the fumarole reported from the northern part of Westwindstranda (Baker and Tombin 1964) is obviously now extinct.

An occurrence of low-temperature vapour activity was found close to the talus fans behind the platform on the southern part of Nyrøysa. The activity here is probably waning, but a temperature as high as 27.2° C was measured

Fig. 17. *The fumarole area (Location 11 above).*

Fig. 18. *Close up photograph of steam vent in the fumarole area (Location 11).*

in the soil at a depth of 0.5 m. An area of several tens of m^2 characterized by a thick cover of green moss, represents the influence area of this "high" temperature activity. This is close to the place where Furnes and Løvlie (1978) reported an extinct fumarole.

However, by far the most active fumaroles (previously not reported) occur at about 250 m elevation between Posadowskybreen and Kapp Valdivia (Figs.

17 and 18). This activity is concentrated in two centers separated from each other by ice. The uppermost center (about 100 — 150 m from the lower one) is the most active. It was possible, however, to visit and observe in detail only the lowermost center. Because the fumaroles have melted the ice here, the surface rocks are exposed to some degree (see Location 11 above). Steam escapes from cracks or holes in the rock, and the activity seems to fluctuate slightly. Meltwater flowing through the steam vents is heated to the boiling point. The smell of the steam indicates that there is a certain amount of H_2S present.

Sampling of the steam from this locality resulted in a condensate, but unfortunately we got no sample of the gas itself. The condensate is now being analysed at the Nordic Volcanological Institute in Reykjavik and the results will be published elsewhere.

Pictures from 1966, taken at a distance, show no steam clouds in this area. This might indicate that the fumarolic activity was much lower or not present at that time.

Rock temperature

In a rock face on the north side of Nyrøysa, close to the lagoon, a horizontal 1.55 m deep hole was drilled to measure the temperature gradient of the rock. Thermistors were placed at 5 cm, 55 cm, 105 cm, and 155 cm depths. Detailed calibrations of resistance/temperature were conducted using a resistor bridge and a digital multimeter. An accuracy of $\pm$ 0.1° C was achieved.

The results are presented in Fig. 19. The highly variable readings at 5 cm depth is interpreted as due to air temperature variations. Direct sunshine on the rock surface is also thought to have influenced these temperatures. At 55 cm, 105 cm, and 155 cm depths the temperatures were much more stable, but the means were slightly higher at the end of the season than in the beginning. This feature may reflect the local weather conditions, but it could also result from a higher heat flow within the rock.

The gradients from 55 cm to 105 cm, and from 105 cm to 155 cm were 6.4° C/m and 3.4° C/m, respectively. These high values probably depend on the rather cold air and rock surface temperature, and it is not relevant to make any extrapolations. In this area of Bouvetøya, where fumarolic activity is generally located, the rock temperature is more probably depending on circulating vapour or water heated at deeper levels than on residual heat of lava flows or conductive heat from rocks at deeper levels. The maximum rock temperature of the cone at sea level is therefore thought to be around 100° C. Thus, if this temperature is reached about 100 m inwards from the surface, the *average gradient* (ranging from 6.4° C/m to 0.0° C/m) will be about 1° C/m. Based on the fact that only one drillhole was made, it is very difficult to make generalizations about the temperature distribution in the volcanic cone of Bouvetøya. The results obtained from drilling in the young pyroclastic deposits of Surtsey (Jacobsson and Moore 1980) further substantiate how difficult it is to predict temperature variations even in a very young volcanic structure.

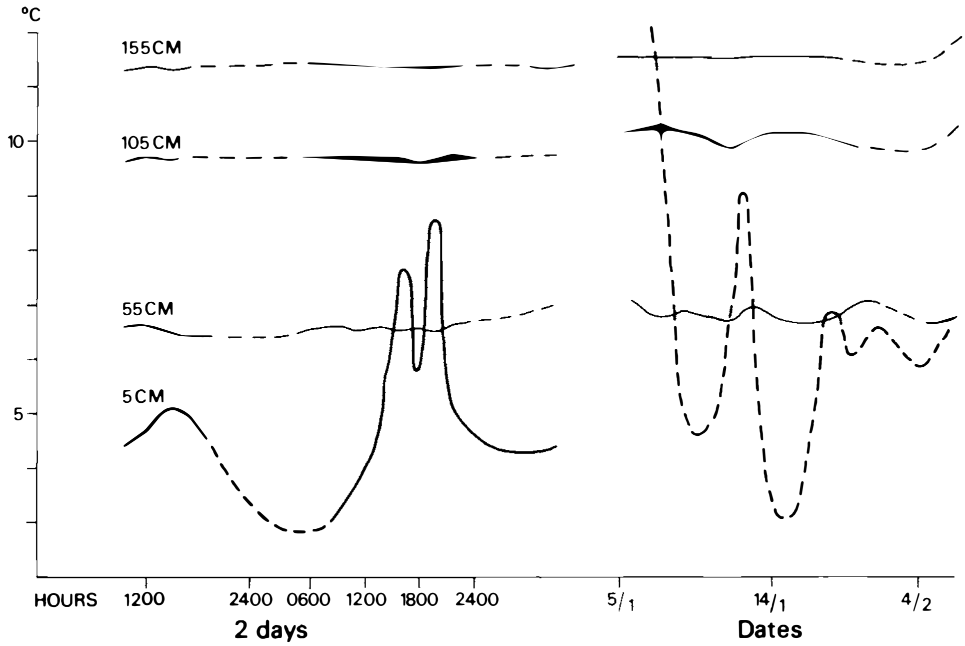

Fig. 19. *Rock temperatures at four levels in a vertical cliff, during two days and during one month.*

Formation of Nyrøysa

Since the discovery of this platform in 1958, its origin has been a subject of discussion. There are two main theories:

a) there was an eruption in the area between 1955 and 1958 (Baker and Tomblin 1964; Lunde 1965; Baker 1967; Furnes and Løvlie 1978).
b) the platform was formed as a result of landslide or avalanche type activity (Winsnes 1966; Verwoerd et al. 1976).

The areal distribution of "young" and "old" rocks referred to by Baker and Tomblin (1964) could not be verified during the 1978/79 expedition because trachytic icelandite is found on the surface over the entire platform. Nevertheless, the platform deposit appears to be stratified (as seen in the steep slopes towards Westwindstranda), and lava structures such as those described by Furnes and Løvlie (1978) indicating both subaquatic and subaerial cooling of the lava were observed in many places. As mentioned above, the surface of Nyrøysa is very hummocky, and there is little that reminds us of a recent lava flow. This fact was, however, mentioned and explained by Furnes and Løvlie (1978) as the results of lava-water and/or lava-air interaction during eruption.

The most important features favouring the landslide or avalanche hypothesis were summarized by Verwoerd et al. (1976) and include the following: The platform has a form typical for avalanche deposits and it is situated symmetrically in front of a recess in the otherwise steep cliffs. The presence of kettle holes and other surface structures indicates that the putative avalanche was a mixture of rock debris and blocks of ice. Photographs of the north-western coast of Bouvetøya, show that a promontory existing above the area where Nyrøysa is situated has now disappeared. Futhermore, secondary minerals (mainly calcite and aragonite) are found in vesicles and cavities of the lava, and iron is oxidized along cracks and fractures in the flaggy trachytic icelandite. Such features are usually found in "old" rocks and do not indicate a recent eruption. Secondary minerals may, however, form soon after eruption in some cases (Jakobsson and Moore 1980). Thus, these arguments do not seem to be conclusive, so other lines of evidence were looked for in order to resolve this question.

The rocks of Nyrøysa are of a special composition compared to most rocks found elsewhere on Bouvetøya. If the landslide or avalanche hypotheses are correct, the same rock type should be found in the uppermost cliffs behind the platform. Unfortunately, weather conditions did not permit in situ sampling of the cliffs. However, two boulders of trachytic icelandite almost identical to the flaggy lava on Nyrøysa, were found in the uppermost part of a scree fan (elevation c. 75 m) behind Nyrøysa. These screes are continuously active with a downwards motion, so the rocks certainly came from the lavas higher up.

Six samples of rocks from or closely connected to Nyrøysa have been analysed and dated by the K-Ar method. The analytical data are presented in Table 1. The results obtained must be considered in light of the fact that low amounts of radiogenic argon and a high degree of atmospheric contamination makes dating of such young rocks difficult. These data can, of course, be interpreted in several ways, but because four of the samples (B49, B28A, B49A, B16) show rather consistent results, averaging 0.43 Ma, it is tempting to suggest that this value approximates the real age of the rocks of the Nyrøysa surface. The higher age of B28 (which is taken at the same locality as B28A) may thus be due to the presence of extraneous ^{40}Ar of some kind. As mentioned by Imsland et al. (1977), the trachytic icelandites sometimes have inclusions or xenoliths of basalt and glomerocrystic aggregates of dioritic composition. There is thus, at least theoretically, a possibility that the B28 sample has inherited some ^{40}Ar from such sources. The much younger age of the scree boulder (B67), which is compositionally and petrographically identical to the trachytic icelandite from the platform itself, may be due to loss of radiogenic argon rather than to a real difference in age. This sample is considerably more altered than are the other rocks chosen for dating.

Despite the wide range of ages obtained for these rocks, the results strongly indicate that the lava of Nyrøysa represents material 0.4 — 0.5 Ma old, that was transported to its present location by a landslide or avalanche between 1955 and 1958.

The observations made by Furnes and Løvlie (1978) and those from the 1978/79 expedition show that the intermediate lava formed as the result of both subglacial and subaerial eruption(s). Of course, the mechanism given

Table 1

K-Ar analyses of rocks from Nyrøysa, Bouvetøya

	K %	^{40}Ar *ppm*	*Apparent age, Ma*	Rock type, etc.
B28[1]	2.364	$1.16 \cdot 10^{-4}$	0.71 ± 0.10	Trachytic icelandite, crystalline. Fresh.
B49[1]	2.108	$5.8 \cdot 10^{-5}$	0.40 ± 0.16	Trachytic icelandite, hyaline crust of lava flow. Fresh.
B28A[2]	2.150	$6.94 \cdot 10^{-5}$	0.47 ± 0.12	Trachytic icelandite, crystalline lava. Fresh.
B49A[2]	2.490	$6.81 \cdot 10^{-5}$	0.39 ± 0.10	Trachytic icelandite, hyaline crust of lava flow. Fresh.
B16[1]	3.730	$1.17 \cdot 10^{-4}$	0.45 ± 0.10	Comendite, crystalline jointed dome. Fresh.
B67[3]	2.490	$1.17 \cdot 10^{-5}$	0.068 ± 0.01	Trachytic icelandite, crystalline boulder from scree fan in the recess behind Nyrøysa. Somewhat altered.

Constants used: $\lambda_\beta = 4.962 \cdot 10^{-10}$ year^{-1}
$\lambda_\varepsilon = 0.581 \cdot 10^{-10}$ year^{-1}
$^{40}K/K = 1.193 \cdot 10^{-4}$ g/g (0.01167 atom %)

Reference to constants: Steiger and Jäger (1977).
Analysts:
[1] Kreuger Enterprises, Inc. Geochron Laboratories Division. Cambridge, Massachusetts, USA.
[2] FM CONSULTANTS LTD. Herne Bay, Kent, England.
[3] Graduate School of Oceanography, Oregon State University, Corvallis, Oregon, USA.

for the eruption by Furnes and Løvlie (1978) also would be consistent with a location at higher elevation of the island where the presence of an icecap is more easily accounted for.

The internal structure of Nyrøysa, with hydrothermally altered rock underlying the hummocky lava in the scarps towards Westwindstranda, and the existence of lavas in a restricted area which consistently show normal polarity (Furnes and Løvlie 1978) reveal that 1) the platform deposit has retained much of its original stratigraphy, and 2) the individual parts did not rotate or tilt significantly. The process responsible for a deposit with these characteristics is probably best designated as a landslide or landslip rather than an avalanche.

The irregular shape of Bouvetøya with steep cliffs along the west coast is the result of strong marine erosion. Whatever the triggering mechanism for the landslide forming Nyrøysa was, its formation in the 1950's and later abrasion mainly by wave action show how this marine erosion works.

The volcanic activity and age of Bouvetøya

It was shown above that the *maximum* age of the Bouvetøya volcanic structure (including the submarine parts) is about 4.5 — 5.0 Ma. On the other hand, Verwoerd et al. (1976) on the basis of the normal magnetic polarity of two rhyolites from Larsøya and one hawaiite from Westwindstranda concluded that the age of Bouvetøya (subaerial parts) was less than 1 Ma. Normal magnetic polarity was also found in a sequence of basic lavas at Kapp Meteor (Løvlie and Furnes 1978).

Because Nyrøysa was formed by a landslide, there is no direct evidence for a recent eruption on Bouvetøya. Fumarolic activity is still taking place at several locations on the island, and at Nyrøysa such activities has previously been connected to the theories of a recent eruption on the platform. However, this activity is now more easily explained as a general location of fumaroles of the island within or close to the caldera area.

Vertical tectonic activity of this area of the South Atlantic or of the island is not well known. However, Løvlie and Furnes (1978) presented evidence that uplift has taken place on the eastern coast. Other evidences of uplift (or, equally well, of universal lowering of the sea level (Wilson 1963)) are the exposed contact between fragmental and massive lava at Kapp Circoncision described above and the occurrence of some very poorly consolidated beach sediments (Fig. 20) occurring at the southern end of Westwindstranda. Even though subsidence is generally found among oceanic islands (Wilson 1963), some examples of uplifted oceanic islands have also been reported.

In addition to the samples from Nyrøysa, seven other samples from Bouvetøya were subjected to K-Ar analysis. The results are presented in Table 2.

Fig. 20. *Poorly consolidated, uplifted beach sediments. Southern end of Westwindstranda.*

Table 2

K-Ar analyses of rocks from Bouvetøya

	$K\%$	^{40}Ar, ppm	Apparent age, Ma.	Rock type, locality, etc.
B18[3]	1.046	$1.31 \cdot 10^{-5}$	0.23 ± 0.26	Transitional basalt. Aphyric lava flow with veins of quartz and calcite at southern end of Westwindstranda, south of Nyrøysa. Altered.
B32[3]	1.228	$4.16 \cdot 10^{-5}$	0.49 ± 0.09	Transitional basalt. Dense, aphyric lava from Norvegiaodden. Slightly altered.
B43[3]		–		Transitional basalt. Aphyric fragment in hyaloclastite from ridge between Norvegiaodden and Catoodden. Low stratigraphic position. Altered.
B31[1]	1.335	$1.29 \cdot 10^{-4}$	1.39 ± 0.2	Transitional basalt. Fine-grained, aphyric lava flow above the altered hyaloclastite sequence behind Nyrøysa. Slightly altered.
B62[1]	0.937	$6.9 \cdot 10^{-5}$	1.06 ± 0.3	Transitional basalt. Porphyritic, somewhat vesicular lava flow from the sequence of subaerial flows at the ridge above Catoodden. Fresh.
B44[1]	4.019	$3.1 \cdot 10^{-5}$	0.11 ± 0.10	Comendite. Porphyritic, well-crystallized rock from dome at Kapp Valdivia. Fresh.
B39[3]		–		Comendite. Slightly microporphyritic obsidian from lava flow at Larsøya. Fresh.

– = radiogenic argon not detected
Constants and data sources as in Table 1

Samples B18, B32, and B43 were all taken at sea level on the western coast of the island. In the hyaloclastite fragment (B43) radiogenic argon was not observed at all. This result shows that the hydrothermal solutions percolating through this lower section of the volcanic pile were able to open the system for argon degassing. B18 and B32, which also yielded low ages, represent lavas from the same section. Even though these rocks are rather massive, they are somewhat altered. This observation indicates that the apparent ages could be too low also for these rocks. The massive nature of these rocks, compared to the otherwise fragmental appearance of the lower section, indicates that these rocks may have been formed later, either as small intrusions in the pyroclastic rocks, or as lava overflows from later eruptions at higher levels on the volcano. The existing field data are not, however, conclusive on this point.

Much higher apparent ages were obtained from two subaerial flows, both from about 200 m above sea level. Sample B31, which is a slightly altered, fine-grained aphyric transitional basalt, overlies the predominantly pyroclastic and highly altered sequence on the north side of the recess behind Nyrøysa (Location 13, Fig. 1). Sample B62 represents a fresh, slightly vesicular, plagioclase-porphyritic lava flow or flow unit at the deglaciated ridge above Cato-odden (Location 5, Fig. 1). The age difference between these samples (1.39 and 1.06 Ma) and the Nyrøysa rocks (~ 0.4 — 0.5 Ma) is surprisingly high compared to their relative stratigraphic positions. However, especially sample B62 is very fresh and the apparent age (1.06 ± 0.3 Ma) should be considered to represent the time of eruption unless a significant amount of extraneous argon is present. One small xenolith (~ 2 mm) of intermediate to silicic composition is seen in a thin section of this sample. The effect of such a contamination on the apparent age of the sample can be estimated by using the formula $t_1 = t_3 + ft_2\frac{K_2}{K_1}$ (Dalrymple and Lanphere, 1969) where t_1 = apparent age of the sample, t_2 = apparent age of the contaminant, t_3 = true age of the sample, f = fraction of contaminant in the sample, K_2 = K% in the contaminant and K_1 = K% in the uncontaminated sample. In this case, where f is small (< 0.02) and the maximum age of the contaminant is 5 Ma (probably < 2 Ma), even a high-K contaminant would not be able to increase the age by more than 0.36 Ma and more likely less than 0.12 Ma. This calculation indicates that the two subaerial transitional basalts really represent eruptions that took place some 1 Ma ago. Thus, the volcanic activity of the island seems to have been very low between these eruptions and the time when the Nyrøysa rocks were formed.

It was mentioned above that the transition from hydrothermally-altered fragmental rocks to massive lavas in the recess behind Nyrøysa and elsewhere along the western coastline (Fig. 3) might represent a depositional break. The presence of a layer of almost pure clay at the corresponding contact in the scarps of Nyrøysa was, in fact, mentioned as evidence for this. On the other hand, it is hard to imagine how a predominantly pyroclastic cone could survive the intense marine abrasion for any long time. Thus, the age difference between the massive lava flows and the underlying fragmental sequence is most likely not very high. Percolating hydrothermal solutions in the fragmental sequence were probably not able to penetrate the overlying massive lavas to any great amount and were trapped so that the clay layer could be formed at the contact.

The low age (0.11 ± 0.10 Ma) of the comenditic dome of Kapp Valdivia is in good agreement with the field evidence, which shows an intrusive relationship to the somewhat altered basic rocks. The comendite itself is, however, extremely fresh. Furthermore, the relationship between the comenditic lava flow at Larsøya and the pyroclastic rocks of the mainland could not be observed, but the very fresh nature of the Larsøya rocks indicates that they also represent a rather late, parasitic eruption. The lack of ^{40}Ar in the analysed sample (B39) fortifies this suggestion.

The size and shape of a rather flat topographic feature surrounded by a few peaks in the summit area indicate that the island has evolved beyond the stage of caldera collapse (Imsland et al. 1977). Even though very little is known about the continuity of the magmatic activity of Bouvetøya, several features such as a general trend from basic to intermediate and silicic rocks with time and the scarcity of apparently very young rocks indicate that the volcanic activity, or a cycle of activity, is now in a declining phase.

However, before the geological history of Bouvetøya can be fully evaluated, more detailed data are needed. The radiometric ages presented above indicate that rocks with reversed magnetic polarity are present (and probably abundant) on the island. Future investigations should therefore include a detailed study of the magnetic polarity of stratigraphically-known sections. These studies should be combined with more radiometric dating.

Conclusion

1. Bouvetøya is built up of two geological formations. The older formation is dominated by various kinds of volcaniclastic rock types. This formation probably formed as hyaloclastites under submarine (Surtsey type eruption) conditions. The youngest formation mainly consists of lava flows with only subordinate clastic sequences. This feature indicates that the island had only a thin ice cap that gave rise to small amounts of hyaloclastites during the initial phases of the eruptions before it melted locally so that subaerial flows could be formed. The transition between the two formations most likely represents the time when the volcanic structure of the island was rigid and compact enough to prevent seawater from entering conduits or vents.
2. K-Ar ages indicate that some subaerial rocks were formed as early as 1.39 $\pm$ 0.2 Ma. Comenditic lavas appear to represent young (0.1 Ma or less) parasitic vents. The present volcanic activity seems to be restricted to abundant fumarolic activity along the north-western and northern coasts. These features together with the presence of a caldera in the summit region and the general trend from basic to silicic rocks with time indicate that the volcanic activity of Bouvetøya is now in a declining phase.
3. Topographic features as well as radiometric ages show that the platform Nyrøysa formed as a result of a landslide rather than from a recent eruption.

Acknowledgements

We are grateful to Dr. Harald Furnes for giving us information on some unpublished analyses of rocks from Bouvetøya. The K-Ar dating was funded by The Norwegian Research Council for Science and the Humanities (NAVF, grant D.42.31-19), Norsk Polarinstitutt, and Geologisk Institutt, University of Trondheim, NTH. One of us (T.P.) also thanks Norsk Polarinstitutt for the opportunity to participate in the Norwegian Antarctic Research Expedition 1978/79. Drs. Gordon G. Goles and Brian H. Baker read the manuscript and suggested several improvements.

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The seismicity of the Bouvetøya region*

By H. Bungum[1], Y. Kristoffersen and A.K. Nilsen[1]

Abstract

During the Norwegian Antarctic Research Expedition in 1978/79 three seismographs were in operation on Bouvetøya for six days and a three-component digital event recorder for a subsequent period of two months. The ambient noise level was very high and in addition a large number of events interpreted as ice and/or rock bursts were recorded. Shortly after the first seismograph came in operation, a magnitude (ML) 3.0 earthquake occurred in the north-eastern part of the Bouvet Fracture Zone. This earthquake was followed by a number of aftershocks during the next 20 hours, and a few earthquakes from the same area were also recorded later. Only a few weak events were recorded from the vicinity of the island ($\triangle \sim 20$ km), and none from other more distant parts of the plate boundaries in the Bouvetøya region.

Introduction

Bouvetøya, located at 54°25'S and 03°21'E in the South Atlantic, is the top of a volcano which measures 9.5×6 km^2 at sea level and reaches a height of 780 metres. The island is 95% covered by ice and steep precipitous cliffs form its perimeter. Bouvetøya is situated on the Antarctic plate (Fig. 1) on a submarine rise formed by the southwestern flank of a spreading ridge segment which is offset by the Bouvet Fracture Zone about 70 km northwest of the island and by a minor fracture zone named Moshesh by Sclater et al. (1977) about 70 km to the east of Bouvetøya. The boundaries between the South American, the African and the Antarctic plates intersect about 260 km west of the island at the Bouvet Triple Junction (Sclater et al. 1976; Johnson et al. 1973). The outline of the evolution of the triple junction given by Sclater et al. (1976) suggests that the Bouvet Fracture Zone has existed for about 20 million years. Assuming no significant asymmetric seafloor spreading took place before anomaly 2 (1.8 M.y), the age of the sea floor in the vicinity of Bouvetøya can be estimated to be 4 — 5 million years. The oldest unit of the transitional oceanic basalts of the island itself is dated to one million years (Prestvik and Winsnes 1981). Recent volcanic eruptions have not been ob-

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served and the glacier front exposed on the eastern side of the island showed no ash layers within the glacier. The gently undulating field of volcanic boulders (Nyrøysa, on the western side of the island) was formed by a massive rock slide (Prestvik and Winsnes 1981) between 1955 and 1957 rather than by an eruption (Lunde 1965; Baker and Tomblin 1964).

While most mid-ocean spreading centers can only be investigated microseismically by sonobuoy arrays or ocean bottom seismographs, the presence of Bouvetøya provides a possibility for an initial effort using more conventional instrumentation. This paper reports on a microearthquake survey carried out on the island in December/January 1978/79 during the Norwegian Antarctic Research Expedition. Three portable, vertical component, analog seismographs were operated for six days and a three-component digital event recorder for a period of two months.

Teleseismic events

Teleseismically recorded earthquakes for the period 1940—77 from the Bouvetøya area are plotted in Fig. 1 with available focal mechanisms (Forsyth 1975) and plate boundaries inferred from bathymetric data (Sclater et al. 1977). Although the location errors for some events may be several tens of kilometers, it is evident that the seismic activity is mostly confined to the fracture zones. There is a notable lack of earthquakes associated with the spreading centers in the vicinity of both Bouvetøya and the triple junction, and in this respect, the area is typical for what is commonly observed at mid-ocean ridges.

The available focal mechanisms show strike-slip motion for events 1 — 4 (Fig. 1), with a sense of motion that complies well with what is expected at each of the associated transform faults. For event 5, the faulting is oblique normal, but with a direction of the tensional axis which fits poorly with what should be expected for a ridge crest earthquake in that area.

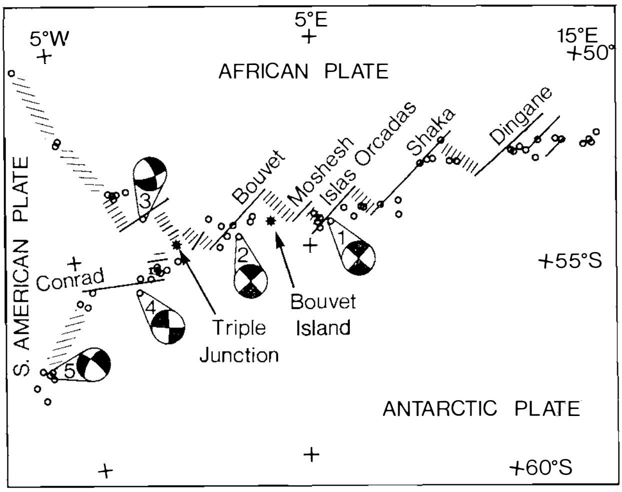

Fig. 1. *The Bouvetøya region, with epicenters for the period 1940—1977, focal mechanisms (Forsyth* 1975) *and plate boundaries inferred from the bathymetry (Sclater et al. 1977). The epicenters are predominantly those reported by the International Seismological Centre (ISC) based on teleseismic recordings with a few from other reporting agencies (USCGS, BCIS).*

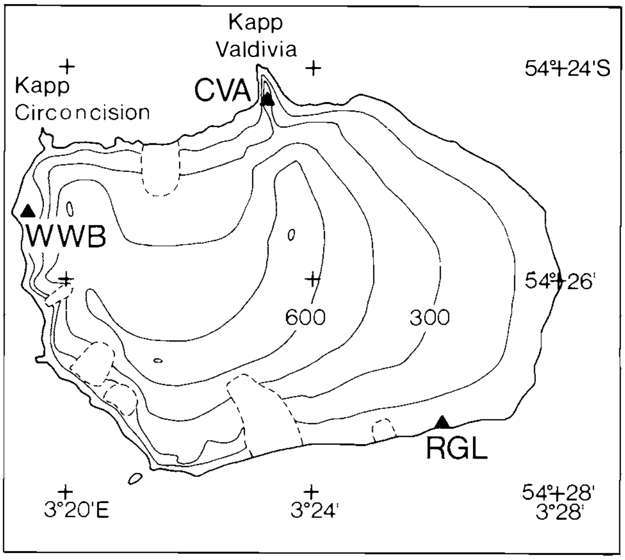

Fig. 2. *Bouvetøya with locations of seismic stations. The main camp was at WWB; other stations could only be reached by helicopter. Elevation in metres and major glacier tongues indicated by dashed lines.*

The microearthquake survey

The location of the microearthquake network is shown in Fig. 2 and the geographical coordinates of the seismic stations and their recording intervals are given in Table 1. The extremely rugged topography and the ice cover gave no other alternatives for siting of the instruments if a reasonable array geometry were to be maintained. Station WWB was located close to the main camp, while the other stations could only be reached by helicopter. Three vertical component Sprengnether MEQ-800 seismographs recording on smoked paper were in operation from 24 December 1978 to 4 January 1979. A three-component Sprengnether digital event recorder was subsequently installed at WWB and operated until 5 March 1979.

A major problem with operation of seismographs at Bouvetøya was the ambient noise level. Noise generated by impact of sea waves on the shores were dominant with considerable additional disturbances from movements in the glaciers and from rock and ice bursts along the near vertical cliffs sur-

Table 1

Names, geographical coordinates and times of operation for the Bouvetøya seismic stations used in this paper.

Station Name	*Code*	*Lat. (°S)*	*Long. (°E)*	*Time of Operation*
Westwind Beach	(WWB)	54.152	3.116	78.12.24–79.01.04
Westwind Beach*	(WWB)	54.152	3.116	78.12.31–79.03.05
Kapp Valdivia	(CVA)	54.146	3.139	78.12.27–79.01.02
Randi Glacier	(RGL)	54.164	3.157	78.12.26–79.01.02

* Digital event recorder

rounding the island. Therefore, the seismographs had to be operated with a maximum magnification as low as 11,000 at 1 Hz with 6 dB below this as a more typical value. The high frequency cut-off of the low pass filters was set at 5 or 10 Hz depending on the site and weather conditions.

Results

The network recorded a large number of events which most likely were generated by rock/ice bursts. Even though timing problems prevented us from obtaining accurate locations for these events, the data from the largest one (Fig. 3) were good enough to determine that the epicentral area had to be in the northwestern part of the island — east of Kapp Circoncision and west of Kapp Valdivia. The amplitude decay with distance leads to the same conclusion, also indicating that the events are surficial and consequently not earthquakes. As a matter of exclusion, we therefore conclude that they are generated by bursts of ice and/or rock along the steep cliffs around the island. It should be emphasized here that although only the largest of these events could be located as described above, a large number of similar but smaller events were also recorded. There is every reason to believe that these are scattered mainly around the perimeter of the island. Along the eastern side of Bouvetøya, ice bursts involving 100 metres or more of the 60 metres high glacier front were observed from the anchored vessel on several occasions.

The largest earthquake recorded during this experiment occurred only a few hours after the first seismograph came in operation on December 24,

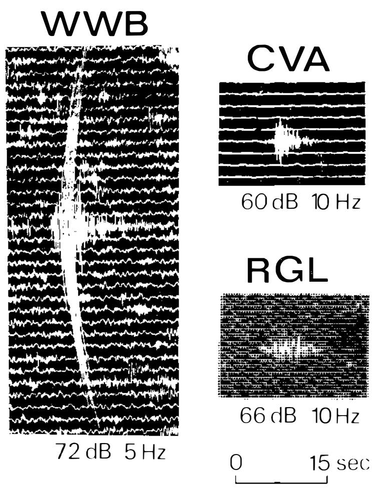

Fig. 3. *Recordings at all three stations of the largest of the surficial events at Bouvetøya, on December 30 1978, 1645 GMT. The gain (in dB) and high frequency cutoff (in Hz) are given for each station.*

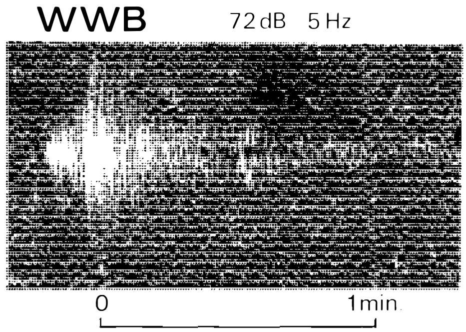

Fig. 4. *WWB recording of the largest of the recorded earthquakes, on December 24 1978, 1959 GMT. The epicenter has been estimated to be near the northeastern part of Bouvet Fracture Zone, at a distance of 60—80 km 3.0. Gain and filter settings are as in Fig. 3.*

Table 2

Recorded events, with arrival time (nearest minute only), number of recording stations (NST), estimated epicentral distance (△) in km, local magnitude (ML) and direction of approach (when possible).

Date	Hours	NST	△ (km)	ML	Direction
78.12.24	19.59	1	70	3.0	
	20.08	1	60	1.9	
	20.16	1	60	1.0	
	22.09	1	70	1.3	
	23.26	1	60	1.3	
78.12.25	04.10	1	60	1.6	
	06.16	1	80	1.7	
	09.10	1	60	1.2	
	15.51	1	30	1.6	
78.12.29	14.25	1	40	1.4	
	18.02	2	40	1.5	
78.12.31	01.40	3	20	1.5	Southwest
	05.12	3	60	2.0	Northwest
	21.35	2	80	1.7	
79.01.13	12.35	1	50	1.4	NW or SE
79.02.25	18.00	1	20	1.7	
79.03.03	17.25	1	20	1.2	

1978 (Fig. 4). The magnitude is estimated to be 3.0 using a local magnitude (ML) scale. Based on the S minus P travel time difference, we estimate the epicentral distance to be around 70 km assuming a standard oceanic crustal model. Following this earthquake, a number of aftershocks were recorded during the next 20 hours with arrival times, epicentral distances and magnitudes as given in Table 2. The magnitudes of the aftershocks range from 1.9 to 1.0, indicating a slope of the frequency-magnitude distribution (b-value) slightly below 1.0, i.e., a typical value.

Since this earthquake sequence was recorded at only one station, no direction of approach could be obtained. However, by looking at the tectonic setting of Bouvetøya (Fig. 1), we find the most probable source area for the earthquakes to be the northeastern part of the Bouvet Fracture Zone about 60—80 km to the northwest of the island. This interpretation is supported by the occurrence of two similar events seven days later, on December 31, 1978. At that time three stations were in operation, and although we still had some problems with absolute timing, a general northwesterly direction of approach could be derived from the data. The largest of the two events on December 31 is shown in Fig. 5. Note that for this figure as well as for Fig. 3, the gain is different for all three stations.

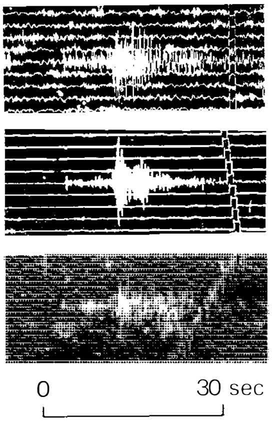

Fig. 5. *Recordings at all three stations of an earthquake on December 31, 1978, 0512 GMT. The epicenter for this event is the same as for the one reproduced in Fig. 4, and the magnitude (ML) is 2.0.Gain and filter settings are as in Fig. 3.*

In addition to the Bouvet Fracture Zone activity, there are a few events which have epicentral distances in the range 20—40 km (Table 2). However, at such short distances the S-wave identification is sometimes difficult, and when data from only one station are available there is a risk of mistakingly identifying two separate rock/ice bursts as P and S waves from an earthquake. The most certain identification of an earthquake with a source nearer than the Bouvet Fracture Zone is therefore the one on December 31 at 0140 GMT, recorded by three stations. Its epicenter was located to about 20 km southwest of the island.

The three-component digital event recorder was operated for 59 days after withdrawal of the analog instruments. The recorder has an automatic triggering system, and a total of 540 events were recorded during 46 days of continuous surveillance. The data set is dominated completely by ice/rock bursts and other transients in the ambient noise, and only three events can be assigned an epicenter distance with some confidence (Table 2).

Discussion and conclusion

Bouvetøya presents extreme conditions for seismic recording both because of difficult accessibility to sites away from the main camp and because of very high ambient noise level. The modest data base obtained from this study indicates that the seismicity associated with the Bouvet volcano is minor. The recording interval may fortuitously have covered a period of low activity, but an observational period of two months is of sufficient duration to reveal the general seismicity level. The few events actually recorded are probably of tectonic origin, i.e., fracturing and displacement of fault blocks, which is what typically is observed also in volcanic areas. Seismic events generated by draining and filling of magma chambers at depth are usually found in association with volcanic activity and eruptions, and such activity has not been observed during this study.

On a geologic time scale various factors indicate that the activity of the Bouvetøya volcano is in a waning phase:

1) the volcano has probably evolved beyond the stage of caldera collapse as indicated by the glacier-filled circular depression on the western half of the island (Imsland et al. 1977),
2) the upper unit of predominantly lava flows is at least 1 M.y., although small parasitic vents are younger (0.1 M.y. or less). There is no evidence of eruptions in historic times (Prestvik and Winsnes 1981),
3) present volcanic activity seems to be restricted to minor fumarolic activity along the northern and northwestern coast.

The seismic data, albeit on a much shorter time scale, are consistent with the assumption that the Bouvet volcano is in a declining phase. No recorded earthquakes could with certainty be located to the volcano or its deeper structure and reveal any significant magmatic or tectonic activity. A few events were recorded within a range of 20 km of the island, while most of the seismic activity appeared to be associated with the northeastern part of the Bouvet Fracture Zone. We also note that during the two months of continuous recording no events were detected which originated from a source area farther away than the nearest part of the Bouvet Fracture Zone. If we use a frequency-magnitude relation derived from the teleseismic data in Fig. 1 with proper scaling, the number of expected earthquakes per month within a 500 km radius of Bouvetøya would be one event above magnitude (m_b) 4 and six events above magnitude 3. This indicates that our recording interval covers a period of relative seismic quiescence along the plate boundaries in the Bouvetøya region.

Bouvetøya is a strategically located platform for geophysical monitoring of one of the more poorly investigated triple junctions and surrounding plate boundaries. Future expansion of automatic data acquisition capability beyond the weather station presently in operation, should therefore include seismic data.

Acknowledgements

We thank the crew aboard M/S Polarsirkel, the helicopter pilots and the participating scientist for logistical support which made this experiment possible. In particular we thank Dr. T. Engelskjøn for maintaining the instrument between January 4 and March 5, 1979. This work was completed while one of us (H.B.) was a visiting scientist at Saint Louis University. The Norwegian Antarctic Research Expedition was organized by the Norwegian Polar Research Institute under a special grant from the Norwegian Government.

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The glaciers of Bouvetøya*

By Olav Orheim

Abstract

Bouvetøya has an area of 50.0 km² of which 93% is glacier covered. It has polar maritime climate, and the accumulation areas of the glaciers are in the soaked facies. The equilibrium line has an elevation of 200—350 m, and is highest on the north- and west-facing glaciers. There is considerable mass loss by calving from the steep ice fronts.

The frontal positions of the glaciers are mostly determined by the topography, and are not very sensitive to climate changes. Nevertheless, a climatic trend is suggested for the past fifty years. Glacier retreat is observed at seven localities, whereas only one glacier has advanced during this interval.

Introduction

Bouvetøya is a sub-Antarctic island located at 54°25′S, 3°21′E, about 500 km south of the Antarctic Convergence. It is of volcanic origin, rising to 780 m, and with steep slopes on all but the eastern side. The island has an area of 50.0 km², of which 46.2 km² is glacier covered (see enclosed map 1:20,000 of Bouvetøya).

Bouvetøya experiences a polar maritime climate, characterized by small daily and seasonal temperature variations, and potential snowfall on all days of the year. Data on the weather and climate of Bouvetøya have mostly been obtained in recent years. The Norwegian Antarctic Research Expedition (NARE) 1976/77 established an automatic weather station on the island which transmitted data during most of 1977 and 1978. A manned meteorological station was operated from December 1978 to March 1979 as part of NARE 1978/1979. At this time two new automatic weather stations were established on the island, one of which is still in operation. Results from these meteorological studies are described by Vinje (1978, 1981). Vinje (1981) finds that mean monthly temperatures near sea level vary from 1.3° C in January to —2.7° C in July. Cloud cover in summer is 80—90 percent. Daily short wave radiation was 238 cal cm^{-2} in February and 23 cal cm^{-2} in June. Total precipitation in January and February was just above 100 mm.

* Publication No. 45 of the Norwegian Antarctic Research Expeditions. (1976/77 and 1978/79).

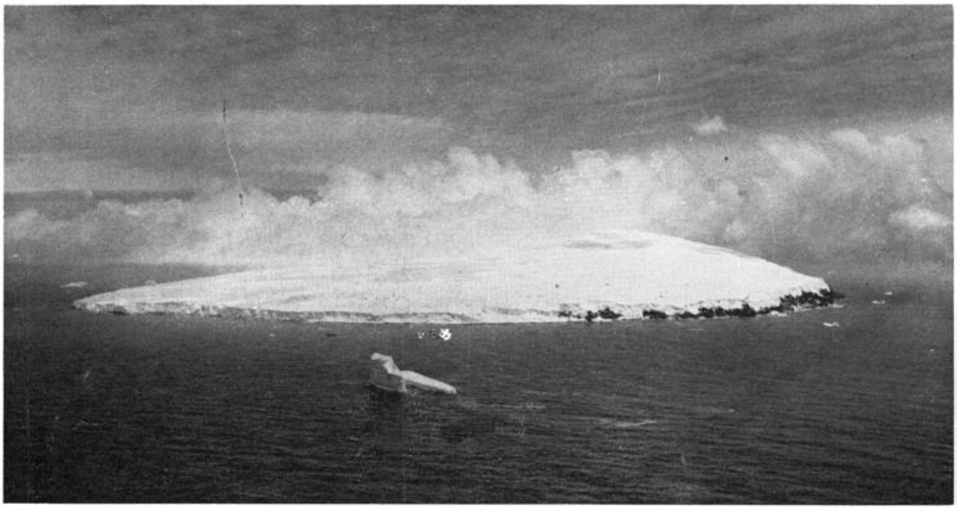

Fig. 1. *Bouvetøya seen from east-northeast (ENE), showing glaciers which mostly terminate above narrow beaches washed occasionally by the sea.*
Photo: Norsk Polarinstitutt B78—79 07.

Glacier morphology

The glaciers on Bouvetøya flow radially from the volcanic cone, and cover practically all parts of the island apart from steep cliffs and low-lying beaches. One-third of the total circumference of 30 km is in the form of glaciers terminating at sea level, including a 4.8 km long section of 50 m high icefronts above narrow beaches on the east coast (Fig. 1). Two large glaciers on the north side, one small in the north-east, and a small and a large glacier in the south also terminate in the sea. For the remaining two-thirds of the circumference, the glaciers terminate in calving ice fronts above steep rock cliffs (Fig. 2). Three regenerated glaciers that almost reach sea level are formed on the western side (Fig. 3). Together these cover an area of 0.47 km^2

Mass balance and facies conditions

It follows from the above that all glaciers on Bouvetøya have some mass loss by calving. Visual observations and inspection of photographs taken late in the summer season show relatively small areas of bare ice, and even within this ablation zone are areas where the winter snow is preserved in local hollows.

Inspection of photographs taken by T. Winsnes in early March 1966 shows the following elevations of the equilibrium line: 270—290 m on the south side, 350—360 m on the west side, and 300—340 m on the north. On the eastern side the elevation is less certain, but seems to be below 200 m.

Photographs by the author in late February 1977 show equilibrium line elevations corresponding to around 300 m on the south side, 320—350 m on the west

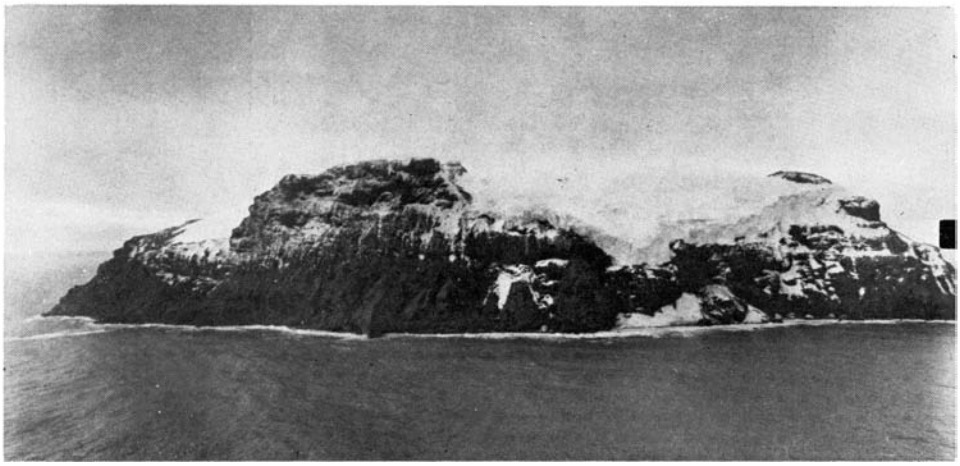

Fig. 2. *Bouvetøya seen from the south. Rustadkollen is left of centre.*
Photo: Norsk Polarinstitutt B78—79 010.

and around 350 m on the north. On the east side the equilibrium line was probably around 200 m. Thus these results indicate an equilibrium line elevation around 330—350 m on the north and western sides, about 50 m lower on the south, and probably more than 100 m lower on the east. We do not have data to judge whether these elevations are representative for the multi-year means.

No direct mass balance measurements have been carried out at Bouvetøya. Ten stakes were placed at 270—300 m elevation on the east side of the island by a South African Expedition in 1966 (CSIR 1967), but have not been remeasured. Winsnes (pers. comm.) observed one of these stakes from afar in 1979, indicating a multi-year mean net balance near zero at this locality. No other stakes were visible, and possibly these have been buried, indicating a more positive net balance than suggested by the single stake observation. A generally positive net balance at this elevation would accord with the above equilibrium line observation.

Observations of burial of sensors at the automatic station at 420 m elevation on the east side indicate a snowfall from February to July 1979 of about 0.5 m (Vinje 1981). Pits dug on the east side in 1966 showed many ice layers in the snow (Winsnes pers. comm.), and the observations at the automatic station show that rain and possibly snow melting occurred several times during the winter, raising the snow temperatures to 0° C. Thus the winter snow can be expected to have fairly high density, and the accumulation of 0.5 m snow for four winter months suggests a balance around 0.5 m water equivalent for the whole winter season.

The meteorological mesaurements show that it is likely that there will be sufficient rain and meltwater to raise the summer temperature of the snow and firn layers to melting point even at the highest part of Bouvetøya. The accumulation areas of the glaciers are in other words in the soaked facies.

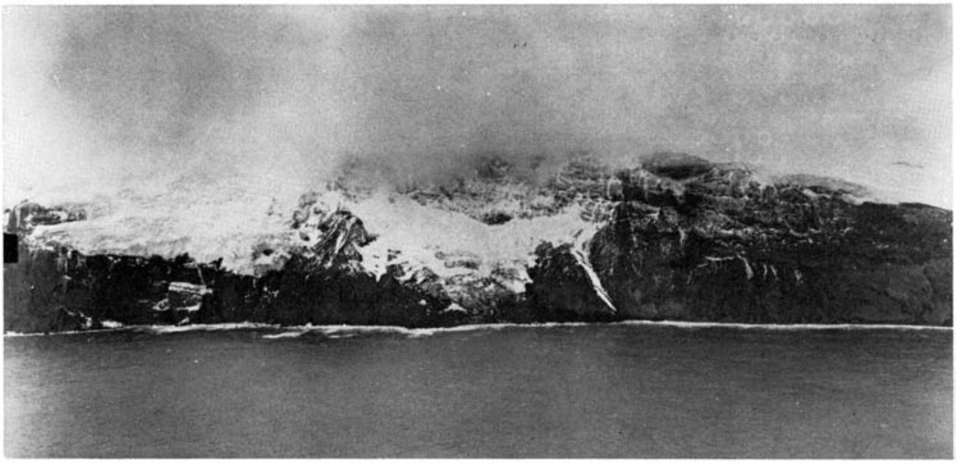

Fig. 3. *Bouvetøya from the west, with Engelbrechtbreen on the left and an unnamed regenerated glacier in the centre.*

Photo: Norsk Polarinstitutt B78—79 015.

Historic glacier variations

The frontal positions of most glaciers on Bouvetøya are at present related to the topography. The glaciers terminate in calving ice fronts where the slopes become too steep, or in the sea. Thus the variations in frontal position cannot be expected to be sensitive to climatic trends.

The Valdivia Expedition in 1898 (Aagaard 1930) observed that Horntvedtbreen and the glacier west of it reached the sea. Photographs from 1978 show these glaciers terminating 140—200 m above sea level, at distances of 150—200 m from the sea. This retreat over the past eighty years is large compared to the following observations of the retreat during the past 50 years.

The island was extensively photographed by the Norvegia expeditions from 1927 to 1930, including aerial photography in 1929/30. These photographs, published in Aagaard (1930), have been compared with photographs from NARE 1976/77 and 1978/79. The main changes are shown on Fig. 4, and can be summarized as follows: In the east and north-east there are no significant changes. There is a retreat of 10—40 m along a one kilometre section in the eastern part of the south coast. There are no other changes along the south coast, except that the glacier west of Rustadkollen has retreated about 80 m. On the west coast the regenerated glacier south of Engelbrechtbreen reached the sea in 1929, and has retreated 50—100 m. Part of the glacier north of Engelbrechtbreen has retreated 100 m and there is a very small retreat of Aagaardbreen. On the north coast, Posadowskybreen has retreated slightly, while the glacier to the east of it has advanced 150 m to reach the sea.

There is also a change in glacier extent caused by changes in topography related to the formation of Nyrøysa in the north-west in the 1950's. The slope above Nyrøysa became more gentle, and two new glaciers are now located here. Together these cover 0.25 km^2. Unfortunately the Norvegia Expedition

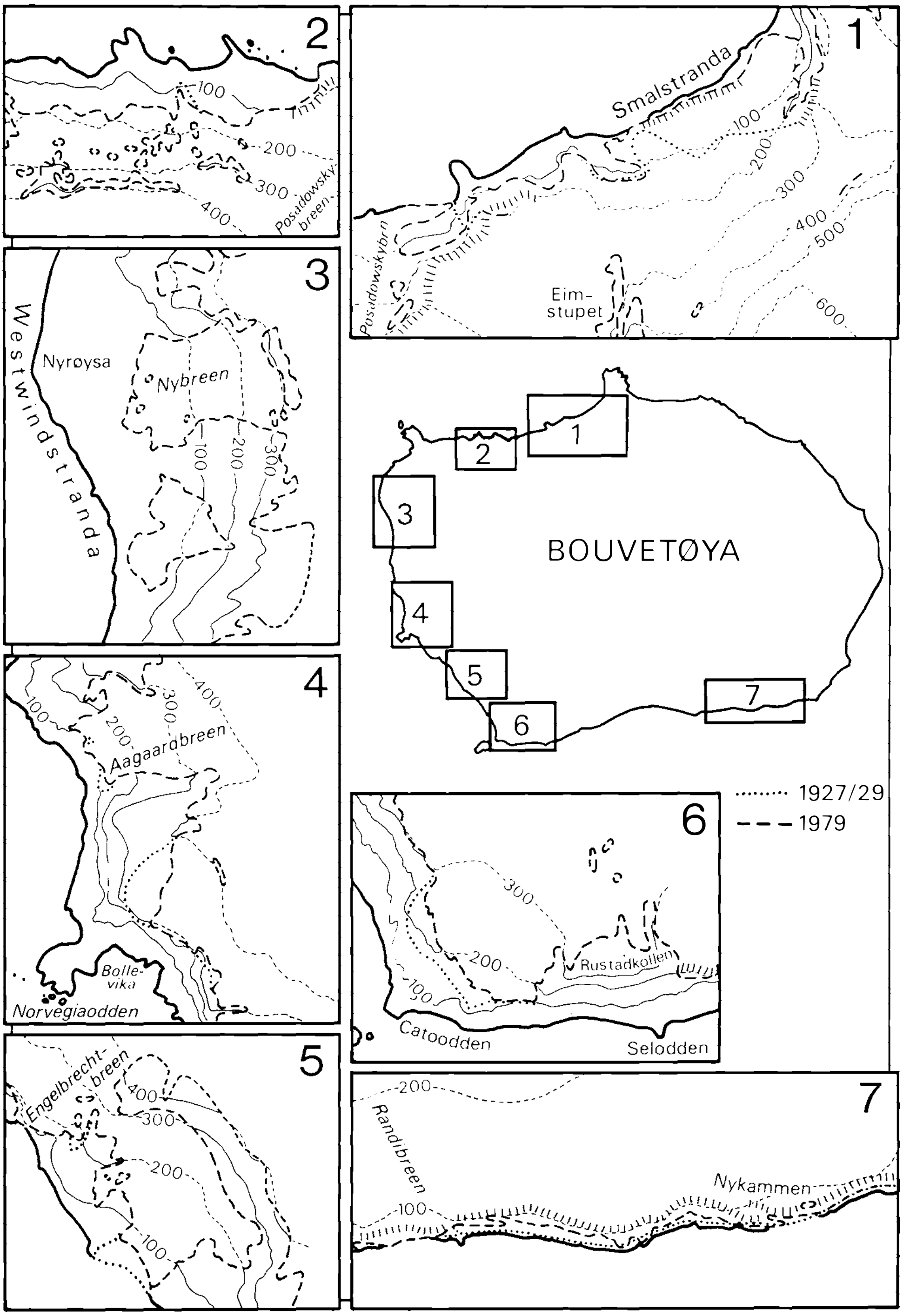

Fig. 4. *Changes in terminal positions of the glaciers at Bouvetøya during the past fifty years Hatched lines indicate ice cliffs in 1979.*

did not provide good photographic coverage of this area, but it is clear that if there were any glaciers here prior to the formation of Nyrøysa, then they must have been very small.

Disregarding the formation of new glaciers above Nyrøysa, we find that the total loss of glacier area is 0.12 km^2, and the total advance of the glacier east of Posadowskybreen also covers 0.12 km^2. However, although this suggests that there has been no changes in glacier area related to climate, the overall impression is one of slight retreat since 1927. Retreat is observed at seven localities spread around the island, whereas there is only one advance.

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Meteorological observations from Bouvetøya*

By Torgny E. Vinje

Abstract

Standard surface and upper air observations for January and February 1979 are discussed as well as observations from automatic stations mounted near the sea level and at 420 m on the glacier covering Bouvetøya.

The thermal stratification of the air masses in the surface layers is found to be close to adiabatic on an average. Short-lived strong gusts are observed on the lee side of the island; apart from this local effect, the surface wind at sea is seldom very high during the frequent passages of lows. Comparisons show that the present observations of the surface temperatures are 1—3° C lower than previous estimates for this area. The greatest difference is found during the summer months. The observed variation in the air pressure indicates a greater variability in the atmospheric circulation in the Bouvetøya region both during summer and winter compared with the corresponding northern latitude.

The automatic observations on the glacier indicate a snow accumulation of about half a metre between February and July 1979. The monthly mean temperature at this height is below freezing for the mentioned period, however, with maximum temperatures well above zero for all months except August. Sudden increase of the temperature towards zero at the depth of 1.5 m in the snow occurred several times in connection with advection of warm air. This indicates an effect of the liberation of heat by the freezing of percolating rain and melt-water.

Average values for the upper air observations show good accordance with available estimates for the area, both for heights, wind speed and temperatures. The highest air temperature observed in the air column was 7.3° C at the height of 800 m, i.e. just above the top of the island. Lee wave effects were clearly indicated by a systematic variation in the ascention rate for all the soundings. Wave lengths of 3—14 km, and vertical velocities of 1—4 m s-1 can be estimated.

Introduction

A manned station was operated on Bouvetøya in January and February 1979 to carry out a meteorological programme in connection with the Global Weather Experiment. The establishment and operation of an upper air station, together with the mounting of the automatic stations on the island, was one of the main tasks for the Norwegian Antarctic Research Expedition (NARE) 1978/79, planned and operated by Norsk Polarinstitutt.

* Publication No. 46 of the Norwegian Antarctic Research Expeditions. (1978/79).

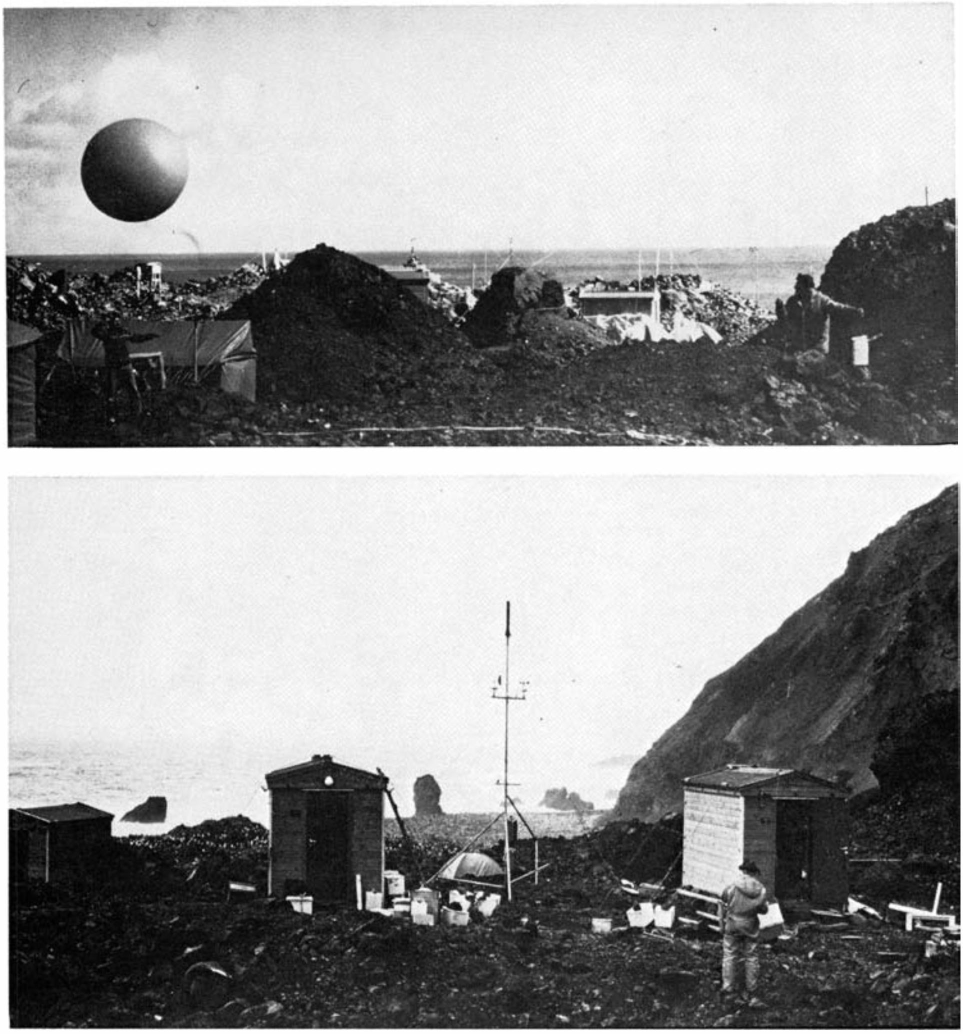

Fig. 1. *View towards the west (a) and the north (b), from the camp at Bouvetøya. The automatic station in the center of (b) and Kapp Circoncision to the right near the horizon.*
Photo: T. Vinje/Norsk Polarinstitutt.

The meteorological station was established with the aid of helicopters. Three huts, serving as operational facilities were built on a rock slide terrace, Nyrøysa, on the western side of the island (Fig. 1). The camp was planned in accordance with a series of observations from an automatic Nimbus-6 RAMS station mounted on Nyrøysa by NARE 1976/1977 (Vinje 1978). Two automatic stations, one near the camp at the elevation of 35 m, and another at 420 m above sea level on the ice cap, were mounted and equipped with batteries for two and one years, respectively.

The Omega positioning system was used for calculations of the upper wind. Direct sight between the transmitter attached to the meteorological balloon and the receiver in the camp, was necessary. Because it was assumed that westerly winds would frequently carry the balloon out of sight behind the island, a specially constructed relay station was mounted on Kapp Circoncision. This arrangement proved satisfactory, and it turned out that it was necessary to use the relay station for as much as 95 per cent of the time. Apart from a few periods with strong northerly winds carrying the balloon out of sight of the relay station, the observation programme had a high degree of regularity.

Surface observations

General features

The top of Bouvetøya is generally encompassed by clouds. In addition to the fact that a low cloud layer is frequent over the region, orographic lifting will generally form clouds in the passing moist air also under otherwise cloud-free conditions. The orographic effect is also reflected in a pronounced increase of turbulence observed when approaching the island. As should be expected, the most gusty and strong winds are generally observed on the lee side, while the calmest area is encountered on the windward side.

There were some occasions with winds of damaging strength during the establishment of the camp. This happened when there was a fairly strong easterly air current in connection with low pressure centers passing north of the island. The estimated speed of gusts would be about 30—40 m s^{-1} on Nyrøysa, while the expedition vessel, M/V "Polarsirkel", anchored on the windward side, reported 10—15 m s^{-1}. On the other hand, with westerly winds, nearly calm conditions were observed on Nyrøysa, while the expedition vessel on the lee side reported 25—35 m s^{-1}. When circumnavigating the island under such wind conditions, the barograph would indicate a very pronounced drop of 3—4 mb when entering the turbulent area on the lee side. Spectacular downdrafts were sometimes shown by clouds moving or rolling at very high speed down the steep hills of the island. Conditions with lee wave formation were relatively frequent. Stationary areas of clear sky would then develop in an otherwise thick, very dark layer of clouds. Because of these effects, the helicopters generally flew along the windward side between the expedition vessel and the camp on Nyrøysa.

Standard observations

Meteorological surface observations were taken every six hours at Nyrøysa in January and February. The free sight section was between 180° and 360° because of a steep hillside east of the camp (see enclosed map). The wind observed at Nyrøysa was of course not representative for the area, and wind speed and direction were therefore estimated from the state of the sea. Fig. 2 summarizes some of the observations. The most predominant wind direction was westerly. Relatively few occasions with easterly winds are registered, indicating that most of the low pressure centers passed south of the island during the observation period. The most frequent speed (10 min. average) was between 5 and 10 m s^{-1}. Speeds above 10 m s^{-1} were observed during 19 per cent of the period.

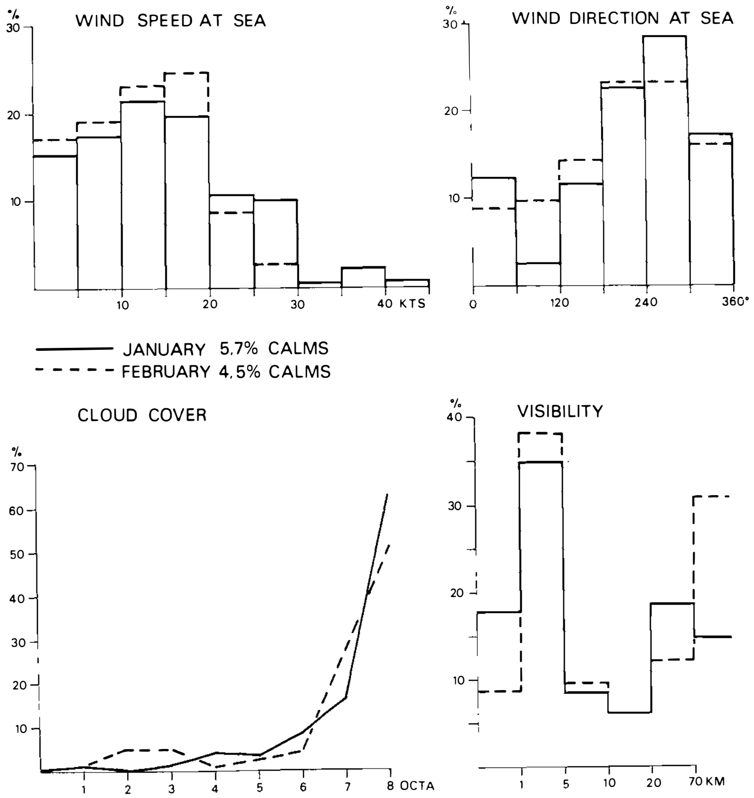

Fig. 2. *Frequency distribution (%) of wind speed, direction, cloud cover, and visibility as observed at Bouvetøya in January and February 1979.*

Wind speeds (at sea) above 20 m s^{-1} were observed only twice during our stay. This agrees with the long-term observations of Ivanov et al. (1960) that the lows in the region of Bouvetøya are not distinguished by great wind speeds. We observed wind speeds above 15 m s^{-1} on eight days in January and only two days in February. The observed frequency of wind speeds above this limit based on reports from whaling and research ships is five days per month (Ivanov et al. 1960).

According to the Atlas of the Oceans (1977), the average speed of the wind in the Bouvetøya region is stipulated to 9.2 m s^{-1} for January and about 10 m s^{-1} for February. The monthly averages we observed were considerably lower: 6.1 and 6.4 m s^{-1}, respectively.

The weather was generally better in February compared with January. This is expressed by smaller average cloud cover (6.7 versus 7.3 octas in January). Fog (visibility less than one kilometre) was also less frequent in February.

Our observations of the average cloud cover, 91 per cent for January and 84 per cent for February, are somewhat greater than the average value of 80 per cent given by van Loon (1972). His figure is based on several climatological atlases. The Atlas of the Oceans (1977) gives above 90 per cent cloud cover for both months. The frequency of fog is quoted to 10—12 per cent for

January and February, while our observations gave 18 and 8 per cent for the two months, respectively.

The highest daily amount of precipitation was 13.2 mm observed as rain in a period with very strong NE winds in January. The highest daily value in February was 5.9 mm. The total precipitation amounted to 76.0 and 27.4 mm for January and February, respectively. Apart from the extremes, most of the precipitation at the camp occurred as snow which due to radiation, melted during the day.

The short-wave radiation was measured with an Eppley precision pyranometer. Because of the relatively high cloudiness, the daily radiation totals are generally small. The average daily sum for the period 24 January to 2 March was 238 cal $cm^{-2}day^{-1}$.

Automatic observations at Nyrøysa

An automatic station was mounted near the camp 35 m above sea level (Fig. 3) in the beginning of March 1979. The surface near the mast is covered with gravel and small rocks. The distance from the mast to the edge of the rock slide terrace was about 20 m and the distance to the 600 m high steep hillside was about 300 m. The observations were transmitted via the TIROS-N Argos system whenever the satellites were in sight. Observations were obtained about ten times a day when one satellite was in orbit. The number of daily observations increased to around fifteen after the second US satellite (NOAA-A) came into use from July 1979. There are no observations between

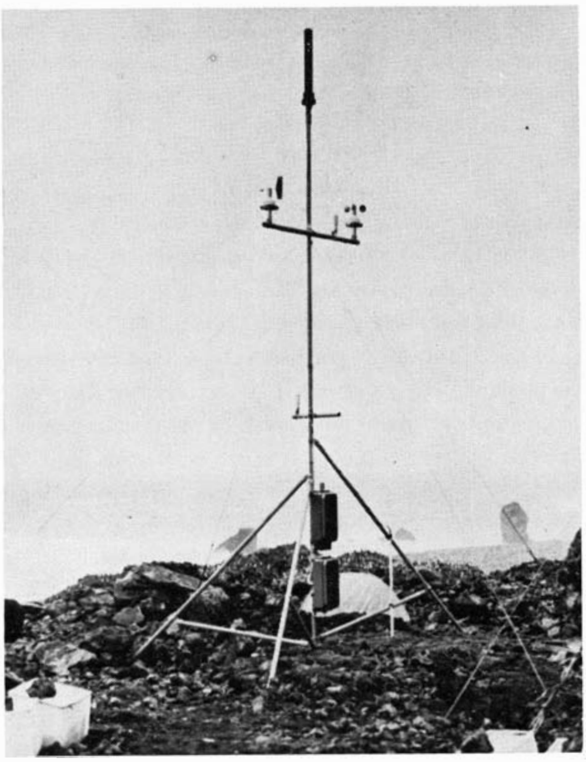

Fig. 3. *Automatic Argos station at Nyrøysa, Bouvetøya, 35 m above sea level, seen towards the NW. Batteries in lower, and electronics in upper box. Antenna at the top of the mast. The automatic stations mounted at Bouvetøya have been manufactured by Chr. Michelsens Institute, Bergen. Photo:* N. Nergaard/Chr. Michelsens Institute.

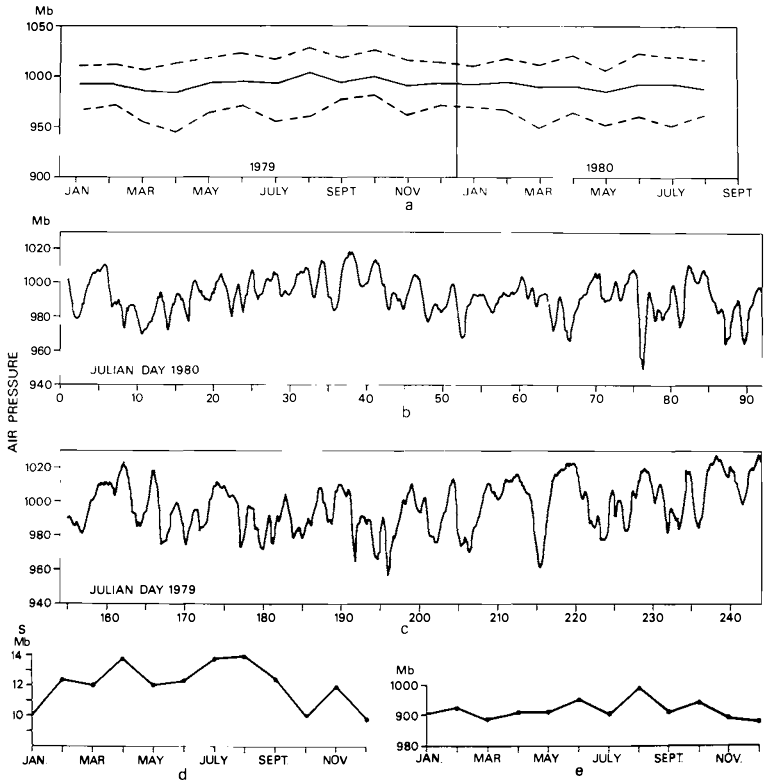

Fig. 4. *Sea surface air pressure observations at Bouvetøya: a: monthly means and extremes, b: observations for three summer months, and c: three winter months, d: the average annual course of the standard deviation, and e: of the sea surface air pressure based on the two 16-month periods referred to in Table 1. January and February values are based also on manual observations.*

approximately 1000 and 1400 GMT because of the orbit scheme. This must be remembered when maximum temperatures are considered. Two restrictions have been applied to the data to filter out faulty observations which amounted to 1 percent of the total. When incorrect figures occur in the registration, they generally occur in all the words given via the satellite. In addition, incorrect figures generally produce quite unrealistic observations.

The automatic platform was manufactured by Chr. Michelsens Institute, Bergen, to measure air pressure, wind speed and direction, and temperatures at seven different levels. The sensors were controlled with other instruments at Bouvetøya. The automatic air pressure reading showed a mean deviation of 1.1 mb which is within the FGGE specifications. The temperatures are correct within $\pm 0.1°$ C.

The frequency of the maximum and minimum of the air pressure seems to be roughly equal for summer and winter months (Fig. 4b and c). The pressure variations are, however, greater in the winter. This is also the case for the standard deviations (Fig. 4d) which are 10.8 and 13.7 for the summer and winter months, respectively, i.e. an annual range of about 3 mb. The corresponding values for the same latitude in the Northern Hemisphere (Shumann

Table 1

Monthly averages of sea surface air pressure (Po three last figures) and air temperature (T 0.5) 0.5 m above the surface of Nyrøysa with the corresponding standard deviation(s) for the two observation periods starting March 1977 and March 1979.

		MAR	*APR*	*MAY*	*JUN*	*JUL*	*AUG*	*SEP*	*OCT*	*NOV*	*DEC*	*JAN*	*FEB*	*MAR*	*APR*	*MAY*	*JUN*
1977	Po	92.7	96.7	97.8	96.2	90.1	96.1	90.8	91.1	90.7	85.7	91.4	93.0	90.6	99.9	93.1	00.1
	s		15.9	12.6	13.8	14.2	12.9	14.8	10.5	12.9	8.9	10.1	14.0	12.3	11.5	12.5	9.9
1979	Po	85.6	84.2	93.7	94.8	92.8	04.2	94.3	99.9	90.6	93.6	92.3	95.3	89.5	90.6	85.3	92.6
	s	11.5	15.2	11.8	12.5	13.4	15.1	9.9	9.3	10.9	10.6	10.2	10.8	11.6	12.8	11.1	12.8
1977	T O.5	2.8	1.2	0.2	–1.3	–2.4	–2.5	–2.0	–1.8	0.1	1.1	2.1	2.2	1.6	1.6	1.3	–1.7
	s		1.3	1.4	1.4	1.6	1.7	2.1	2.3	1.4	1.9	1.7	2.4	1.5	2.0	1.8	1.8
1979	T O.5	0.6	–0.1	–0.8	–2.3	–2.9	–2.5	–3.1	–1.5	–1.3	0.5	1.1	0.8	1.2	–0.3	–1.3	–2.3
	s	1.2	1.3	1.9	2.7	2.8	2.4	2.8	2.0	1.8	1.5	1.1	1.0	1.5	1.0	1.3	2.0

and van Roy 1951) are 7, 12.2, and 5.2 mb, respectively. Using the standard deviation as a measure for the variability of the atmospheric circulation, we might conclude that the circulation at Bouvetøya is more variable than at corresponding latitudes in the Northern Hemisphere. However, the observed annual range is smaller at Bouvetøya. The annual average of the standard deviation at Bouvetøya (12.0 mb) is similar to the corresponding figure based on long-term winter observations in the north (12.2 mb). Van Loon (1972b) concluded that the long-term average circulation is as variable in the Southern as in the Northern Hemisphere in the winter, and more variable in the summer.

The winter value of the standard deviation at Bouvetøya (13.7 mb) is somewhat higher than the zonal average value (12.1 mb) that can be estimated for this latitude from van Loon's (1967) figures based on IGY data.

According to van Loon (1972b) the amplitude of both the yearly and half-yearly air pressure wave should be relatively small around Bouvetøya and the observed annual course of the average monthly air pressure (Fig. 4e) seems to support this statement. However, because of the great variability in the atmospheric pressure in this area, the observation period is probably too short to give conclusive indications in this respect.

The temperatures given in Table 1 refer to a level of 0.5 m above the surface at Nyrøysa. The annual average air temperature at this level (March to March) is —0.3 and —1.0° C for 1977/78 and 1979/80, respectively. This difference in the annual average air temperature may well be due to differences in the positions of the two stations at Nyrøysa and do not necessarily express an actual change in the annual average for the area. The Argos station was mounted near the highest most exposed area at Nyrøysa and the temperature observed at this site is therefore probably the most representative of the two. The Nimbus-6/RAMS automatic station was mounted 28 m above sea level at a more narrow place at Nyrøysa (Vinje 1978).

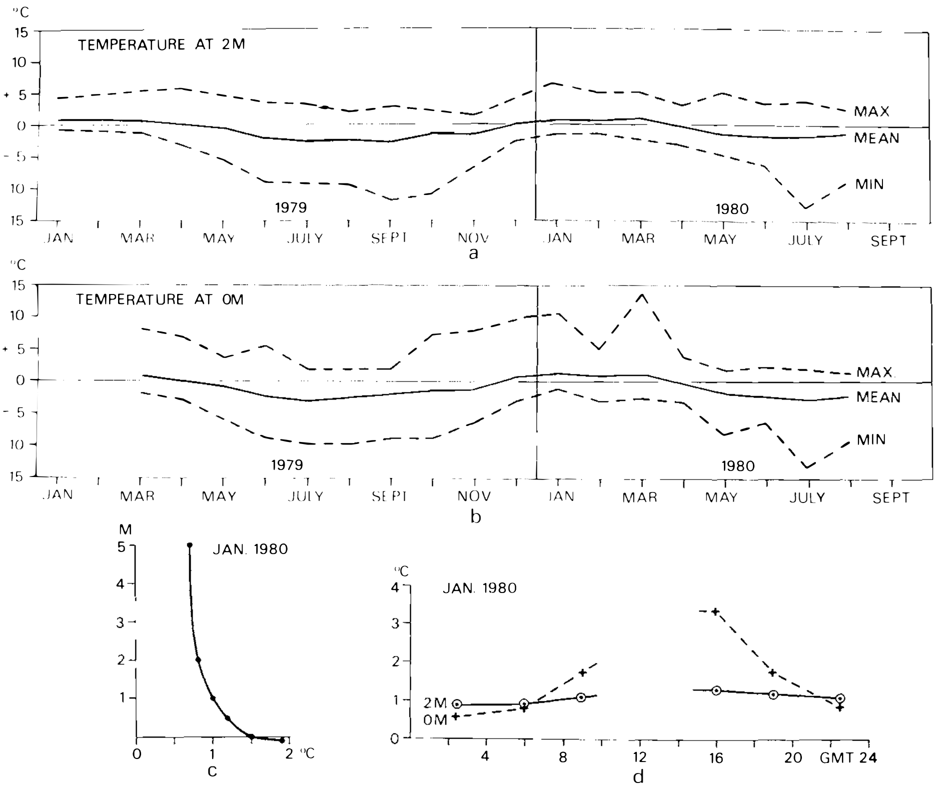

Fig. 5. *Temperature observations from Bouvetøya. a: monthly means and extremes 2 m above surface, and b: at the surface, c: the average vertical profile, and d: average daily variation for January 1980 at 2 m height and at the surface, based on automatic observations. January and February 1979 values are based on manual observations.*

The temperature sensors at the Argos stations are mounted at levels 5, 2, 1, 0.5, 0.0, and —0.05 m. Fig. 5a illustrates the annual variation of the monthly mean temperatures as well as the monthly extremes at the 2 m level and of the surface. Note the maximum surface value for March 1980 of about 14° C which is probably caused by intense sun radiation. The effect of this heating of the dark surface is pronounced at the 0.5 and 1 m levels (not reproduced here), but only faintly traceable at 2 m height. This indicates that the air temperature at the standard observation level is affected only to a small extent by the surface conditions. The monthly mean of the vertical temperature profile is reproduced in Fig. 5c for January 1980 when the wind speed was particularly low (Table 3). The average daily variation for the same month is given in Fig. 5d. Unfortunately, the lack of satellite passes between about 1000 and 1400 GMT means that the maximum values for levels less than 2 m are probably some tenths too low. (This, of course, also applies to the average temperatures for the lower heights.) The vertical profile clearly shows that the influence of surface effects on the temperatures at higher levels should be very small. The reduction with height of the average daily range and of the standard deviation (Table 2) also demonstrates this. The standard deviation as well as the daily amplitude of

Table 2

Standard deviation (s) of all temperature readings and monthly average for the daily range (A) at different levels for July 1979 and January 1980. Numbers of observations are 453 and 401, respectively.

Level in m:	*5*	*2*	*1*	*0.5*	*0.0*	*−0.05*
January 1980						
s	0.9	0.9	1.0	1.1	1.4	1.6
A	1.7	1.8	2.3	2.6	3.6	4.0
July 1979:						
s	2.7	2.7	2.8	2.8	2.8	2.6
A	3.9	4.0	4.0	4.0	3.7	2.6

the air temperatures increase markedly from summer towards winter. This increase probably reflects the increase of the meridional temperature gradients towards winter when the sea ice expands about 1500 km from the Antarctic continent (e.g. Taljaard et al. 1969). The fact that the standard deviation and the daily amplitude become nearly constant with height during the winter (Table 2) reflects the influence of the high albedo of the snow cover on the local surface heat budget as well as the small income radiation at that time.

A comparison with the Atlas of the Oceans (1977) shows that our observed monthly average surface temperature (2 m level) is systematically 1—3° C lower. The difference is smallest during the winter months when, on the other hand, the basis for the Russian figures is least good. Comparison with the long-term mean values given by Taljaard et al. (1969) shows that our January and July means are 1° C and 0.3° C lower, respectively. The systematic deviation from previous estimates could suggest that the period in question was colder than normal during the summer months.

The effect of the N-S running steep mountain wall east of the camp is sharply reflected in the distribution of the registered wind directions. A similar frequencies distribution as given in Fig. 6 is observed for the whole sixteen-month period considered here.

Higher wind speeds are relatively rare at Nyrøysa, apart from strong short-lived gusts during conditions with easterly winds (Table 3). The very strong gusts experienced for periods during the establishment of the camp, were of such short durations that the peak speeds are probably not represented in Table 3, even though we measured only over 50 sec.

Bouvetøya was revisited by the West-German Antarctic Expedition at the end of February 1980. A new anemometer with another type of grease was mounted. Although the old instrument was later in Norway found to operate normally it seems to have had a greater inertia as the frequency distribution for the lower wind speeds change after the new anemometer was mounted (Table 3).

Table 3 shows that wind speeds above 15 m s^{-1} occur in less than 6 per cent

Table 3

Frequency distribution (%) of observed 50 sec averages of wind speed (m s⁻¹) at Nyrøysa, Bouvetøya.

Month	*Wind speed interval, m s⁻¹*									*No. of observ.*
	0	*0–5*	*5–10*	*10–15*	*15–20*	*20–25*	*25–30*	*30–35*	*35–40*	
1979 Mar	10	59	22	5	2	0.66	0.10	0.05		1980
Apr	10	63	18	7	2					2519
May	4	54	30	10	1	0.04				2576
Jun	19	45	21	12	3			0.04		2357
Jul	13	53	22	9	2	0.02			0.02	4944
Aug	12	46	26	10	4	1.95	0.70	0.02		5020
Sep	14	56	22	7	1	0.31	0.04			4872
Oct	10	55	22	9	3	0.66	0.04			5024
Nov	13	62	18	5	1	0.05				4439
Dec	27	55	15	2						4959
1980 Jan	54	38	6	1	1	0.02				4096
Feb	27	38	28	6	1	0.11				3796
Mar	4	49	28	17	3	0.02				4929
Apr	3	42	39	13	2				0.02	4795
May	3	43	32	18	4	0.12				4998
Jun	4	46	33	15	2	0.17				4183

of the time. Wind speeds below 5 m s^{-1} are most frequent and calm conditions are generally registered for less than 20 per cent of the time. An exception is January 1980, when this percentage was as high as 54.

The battery capacity of the Argos station elapsed at the end of December 1980. At the end of January 1981 a South African expedition revised the camp and reactivated the station.

Automatic observations on the glacier 420 m above sea level

A second automatic station was mounted on the glacier 420 m above sea level on the eastern side of the island. This station was equipped with an air pressure sensor, as a reserve for the beach station during the Global Weather Experiment. The sensor gave unrealistic values for shorter periods, but otherwise the average difference from the camp observations were below 0.5 mb when reduced to surface. Temperature sensors were mounted at 2, 0.5, 0.0, and —1.5 m heights and were calibrated to the nearest ±0.1° C.

An Eppley pyranometer was also mounted on the mast two metres above the snow surface. The receiving surface faced downwards to avoid hoarfrost formation. The registered values were compared with simultaneous radiation registrations made with an Eppley pyranometer in February at the manned camp. This comparison showed that the values observed at the glacier had to be multiplied by a factor of 1.118 to give the global radiation at the sea surface. This factor takes account of the albedo which is supposed to be more or less constant throughout the year, as well as the effect of multiple reflection of

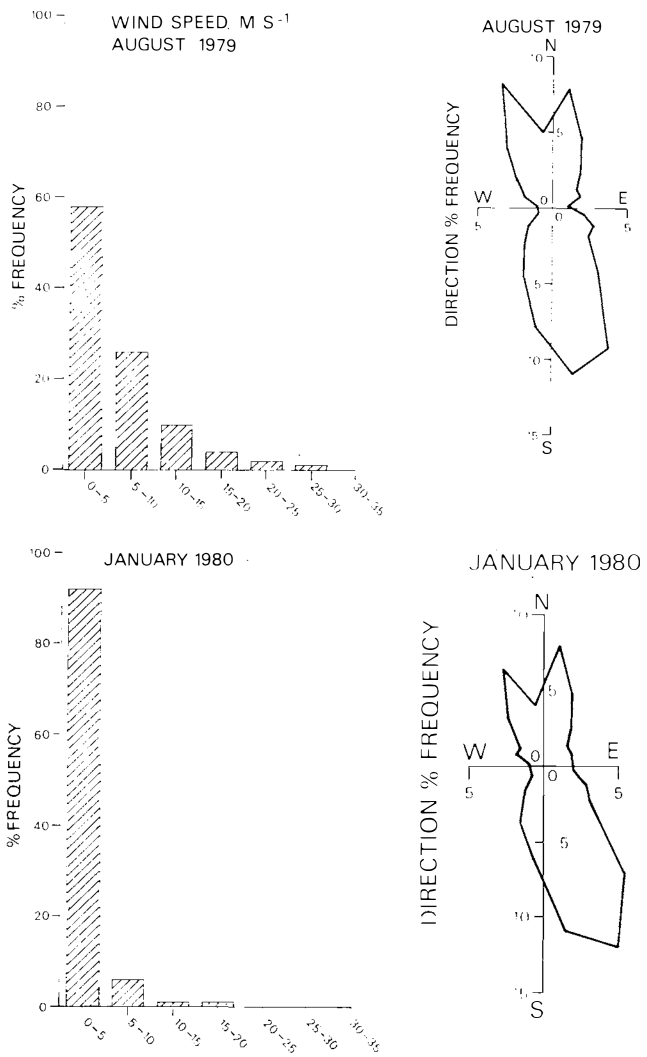

Fig. 6. *Frequency distribution (%) of wind speed and wind direction in summer and winter months observed at Nyrøysa.*

radiation between the bright snow surface and the nearly permanent cloud cover. Two radiation averages of fourteen minutes each were registered on each satellite pass. An average daily curve was calculated for each month to evaluate the monthly income of short-wave radiation (Table 4). Rime ice has probably accumulated on the instrument for periods, effecting the measurements. However, the annual variation in the monthly sums is reasonable and in fair accordance with indirect calculations made by Sasamori et al. (1972). The largest deviation occurs in February where interpolation from the indirect calculated values is 34 per cent higher than that observed at the camp.

The sensor mounted 0.5 m above the surface in Jaunary showed a marked reduction in July in the variability of the temperature indicating that snow had then accumulated to that height. Except for August, the maximum tempe-

Table 4

Daily average income short wave radiation in 1979 observed at Bouvetøya (R) compared with indirect calculated values (C) ly day^{-1} made by Sasamori et al. (1972). Figures in parentheses indicate interpolated values.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
R		238	177	117	45	23	32	60	136	
C	377	(320)	(180)	97	(45)	(30)	27	(80)	(150)	253

ratures at a depth of 1.5 m (nominal) were close to 0° C (Fig. 7d) indicating liberation of heat by the freezing of percolating rain and meltwater. Registrations of a temperature course like that in Fig. 7e indicate that advection of warm air with rain occurred on six occasions from May to September. The temperature rise in the snow was generally observed to start with a sudden increase 4—12 hours after a pronounced temperature increase in the air. The effect of liberation of heat by freezing of water is also indicated by the fact that the snow temperature at 1.5 m depth is 2—5° C higher than the air temperature, even in the summer (Fig. 7f). The upper air soundings (Table 6) show the occurrence of temperatures well above freezing, also at the top of the island, suggesting that rain and melting may occur at this level as well.

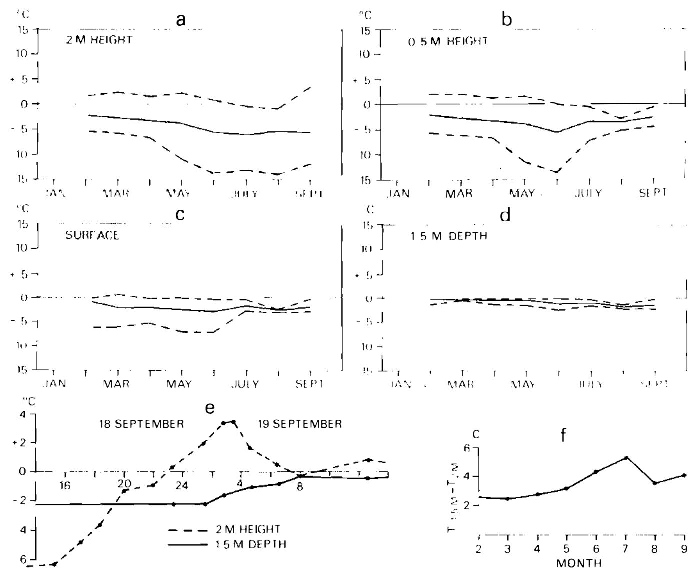

Fig. 7. *Temperature observations 420 m above sea level on the eastern slope of the Bouvetøya glacier. Monthly means and extremes, a: 2 m and b: 0.5 m above the surface, c: at the surface, and d: 1.5 m below the surface, e: temperature variations 2 m above, and 1.5 m below the surface during conditions with assumed rain percolation, f: mean monthly temperature differences between observations 1.5 m below the surface and 2 m above.*

Table 5

Monthly average, T, standard deviation, s, and average daily variation, A, for the temperature 2 m above the surface at 1: 420 m above sea level on the glacier, and 2: 35 m above sea level. G is the monthly average vertical temperature gradient, °C/100 m. Number of observations each month lies between 240 and 300 for March—June and between 440 and 480 for July—September.

Month:	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*
T1	−2.4	−3.2	−3.7	−5.5	−6.3	−5.4	−5.5
T2	0.5	−0.1	−0.7	−2.2	−2.7	−2.4	−2.7
G	0.75	0.81	0.78	0.86	0.94	0.78	0.73
A1	2.6	2.7	3.2	3.3	4.7	4.4	4.1
A2	1.4	1.9	2.2	2.4	4.0	3.2	2.7
s1	1.4	2.0	2.8	3.4	3.5	3.0	3.3
s2	0.8	1.2	1.8	2.6	2.7	2.3	2.6

The monthly average vertical temperature gradient between the two automatic stations is fairly constant, 0.7—0.9° C/100 m, throughout the year (Table 5). A relatively small annual variation of this parameter should be expected as long as the drift ice does not enclose the island, which it did not in 1979 (NAVY-NOAA Joint Ice Center Charts).

The monthly mean of the daily temperature range (A) shows a clear seasonal variation (Table 5). The standard deviation (s) also shows similar annual variation. This again reflects the annual variation in the meridional temperature gradient (Taljaard et al. 1969), which will cause greater temperature variations in the winter than in the summer when lows are passing.

There is a very small difference both in A and s in spite of a very different surface below the two automatic stations. This again reflects the dominating influence of the ocean on the thermal regime of the island.

Upper air observations

Introduction

The upper air programme was supposed to fill in an open and important space in the international observation net during the first Special Observing Period, 5 January—5 March, of the Global Weather Experiment. We made a total of 110 flights, of which 93 gave successful results (Table 6). We have considered January and February together, as a splitting-up in monthly periods gave very small and unsystematic differences.

Temperature

The standard deviation of the temperature which is 1.1° C at the surface, increases markedly with height, and shows two maxima, one near the 700 mb

Table 6

Mean, standard deviation (s), maximum, minimum and number of observations (n) of various parameters from the upper air observations 5 January —5 March 1979. H: height (gpm), T: air temperature (° C), D: dew point depression (° C), f: wind speed (ms^{-1}).

	H	*T*	*D*	*f*	*H*	*T*	*f*	*H*	*T*	*f*
		Surface				*250 mb*			*30 mb*	
Mean		1.3	2.0	7.7	9973	−48.3	26.6	24085	−42.5	8.2
s		1.1	1.5	5.7	155	4.2	16.1	67	2.1	4.0
Max.		4.2	8.0	22.6	10310	−40.3	76.0	24200	−40.5	13.9
Min.		−0.9	0.0	0	9380	−58.7	5.1	23960	−45.7	2.1
n		93	93	93	70	70	61	9	9	9
		850 mb				*200 mb*			*20 mb*	
	1246	−5.7	4.7	13.5	11457	−46.0	23.2	26910	−37.5	8.5
	80	3.8	7.8	6.9	119	4.0	12.5	67	1.5	4.2
	1393	6.4	30.0	33.9	11750	−40.7	58.0	26990	−35.5	11.8
	1048	−11.5	0.0	1.0	11270	−58.9	5.1	26850	−38.9	2.6
	93	93	92	79	67	67	58	5	5	4
		700 mb				*150 mb*				
	2753	−11.0	17.2	14.9	13372	−46.2	20.5			
	101	4.5	11.7	7.7	105	2.8	8.9			
	2971	3.4	38.0	38.6	13700	−40.3	53.4			
	2276	−20.9	0.0	2.1	13190	−54.1	7.2			
	93	93	89	79	67	67	57			
								mb	*T*	*f*
		500 mb				*100 mb*			*Tropopause*	
	5272	−25.2	18.9	20.5	16060	−47.6	15.6	290	−51.7	27.9
	111	4.0	11.1	10.8	84	2.7	5.5	39	4.2	16.6
	5500	−8.1	30.0	51.9	16300	−40.3	30.8	384	−42.7	75.0
	5100	−32.7	0.9	3.1	15880	−53.5	5.1	194	−61.5	3.1
	91	91	84	78	61	61	71	69	69	58
		400 mb				*70 mb*			*Max. wind level*	
	6850	−36.4	15.8	24.6	18450	−46.1	12.6	279		47.3
	125	3.6	12.3	14.2	81	2.1	4.3	66		15.0
	7110	−27.9	30.0	61.7	18630	−40.3	22.1	446		97.7
	6640	−44.9	0.0	4.1	18280	−49.3	8.2	114		32.4
	87	87	69	74	19	19	14	27		27
		300 mb				*50 mb*				
	8788	−47.9	19.5	28.8	20680	−45.1	9.9			
	143	4.0	11.5	17.7	72	2.2	4.2			
	9110	−38.9	30.0	92.0	20810	−40.1	19.0			
	8550	−53.9	4.3	2.1	20520	−48.3	4.1			
	77	77	17	64	17	17	12			

Table 7

Maximum range of the temperature variation (° C) as observed at the mandatory levels. B: Bouvetøya (January and February) and M: Maudheim (December and January).

	Surf.	*850*	*700*	*500*	*400*	*300*	*250*	*200*	*150*	100
B	5	18	24	25	17	15	18	8	14	13
M	8	14	12	12	13	13	18	17	13	8

level of 4.5° C and a second one near the 250 mb level of 4.2° C. This height variation indicates that the thermal influence of the vast ocean on advective warm and cold air masses may be observed up to the 700 mb level near Bouvetøya.

The absolute maximum temperature, 7.3° C, in the air column above the island, was observed at a height of 800 m. The temperature at the 850 mb level was on this occasion 6.4° C (Table 6). The maximum temperature variation observed at various levels shows great increase with height, with a maximum of 24—25° C at the 700—500 mb levels (Table 7). This variation is in contrast with the one observed at Maudheim (Schumacher 1958), where a maximum variation of 18° C is found at the lower levels of the stratosphere. It is supposed that the difference merely reflects the difference in distance to the waves on the polar front.

Wind

More than 70 per cent of the observed wind directions lie between 180° and 300° (Table 8), nearly equally distributed between the sectors 180°—240° and 240°—300°. It is only in the stratosphere that westerly winds (240°—300°) become most frequent (65—70%). In the lower troposphere and in the lower stratosphere, at 850, 700, 200, 150, and 100 mb levels, the most frequent wind speed is between 10 and 20 m s^{-1}, while in the upper troposphere, above 500 mb, wind speeds between 20 and 30 m s^{-1} are most frequent.

The standard deviation of the wind speed is at its maximum at 300 mb where we also observe the highest average wind speed (at the mandatory levels) (Table 6). The average level of maximum wind speed is at 280 mb with a mean speed of 47.3 m s^{-1}. The maximum wind speed observed was 98 m s^{-1} from 260°. The average maximum level indicates a jet current level of 9—10 km which can ble compared with 8—9 km given in the Atlas of the Oceans (1977).

Comparison with available estimates

The average figures obtained from the upper air programme at Bouvetøya are in close accordance with the available estimates from this area. Thus van Loon et al. (1971) give a zonally averaged geostrophic wind for January at the 500 mb level of 18 m s^{-1}; our observations show 17.6 m s^{-1}. Taljaard et al.

Table 8

Frequency (%) of wind speeds and of wind direction at various mandatory levels up to 100 mb for January and February 1979. Number of soundings, N.

		wind speed (ms^{-1})							
mb	*N*	*0–10*	*10–20*	*20–30*	*30–40*	*40–50*	*50–60*	*60–70*	*70–80*
850	77	33.8	50.6	14.3	1.2				
700	77	31.2	46.8	16.9	9.1				
500	76	19.7	31.6	32.9	10.5	3.9	1.3		
400	73	17.8	19.2	34.2	12.3	10.9	4.1	1.4	
300	63	12.7	20.6	28.5	14.3	11.1	6.3	3.2	1.6
250	60	16.7	20.0	28.8	13.3	10.0	3.3	1.7	3.3
200	57	12.3	42.1	19.3	12.3	8.8	5.3		
150	56	7.1	46.4	33.9	1.8	1.8	1.8		
100	50	12.0	64.0	22.0	2.2				

		wind direction (decadegrees)					
mb		*0–06*	*06–12*	*12–18*	*18–24*	*24–30*	*30–36*
850		3.9	5.2	5.2	35.1	37.7	13.0
700		2.6	2.6	9.1	39.0	36.4	10.4
500			1.3	6.6	38.2	46.1	7.9
400			1.4	6.8	41.1	35.6	15.1
300			4.8	3.2	39.9	42.8	14.3
250				3.3	41.7	41.7	13.3
200					42.2	49.1	1.6
150				1.8	23.2	69.6	3.6
100				2.0	30.0	64.0	4.0

(1969) give the mean height of 500 mb as 5280 m; we got 5270 m. For 200 mb the corresponding heights are 11,440 m and 11,460 m. Taljaard et al. (1969) give a long-term temperature of —46° C for January at the 100 mb level; we got —48° C. For greater heights Labitzke and van Loon (1972) used satellite radiation measurements together with monthly mean maps for January 1969. They give mean heights for 50 mb and 30 mb of 20,780 m and 24,200 m, which are within the range we observed for these heights at Bouvetøya. The corresponding temperatures are —46° C and —43° C, while we got —45.1° C and —42.5° C, respectively. According to the IGY data the standard deviation of the height of the 500 mb level shows a latitudinal maximum during the summer months near 55 S of 120 m (van Loon 1967). From the 91 flights to this level we get a standard deviation of 110 m. The above close accordance between the various parameters indicates a good internal consistency in the previous estimates and suggests that the average upper air conditions in the Bouvetøya area were fairly close to normal for the observation period.

Lee waves

Satellite imagery shows that atmospheric lee waves are often generated by isolated islands. This phenomenon has been studied by e.g. Fjellheim (1973),

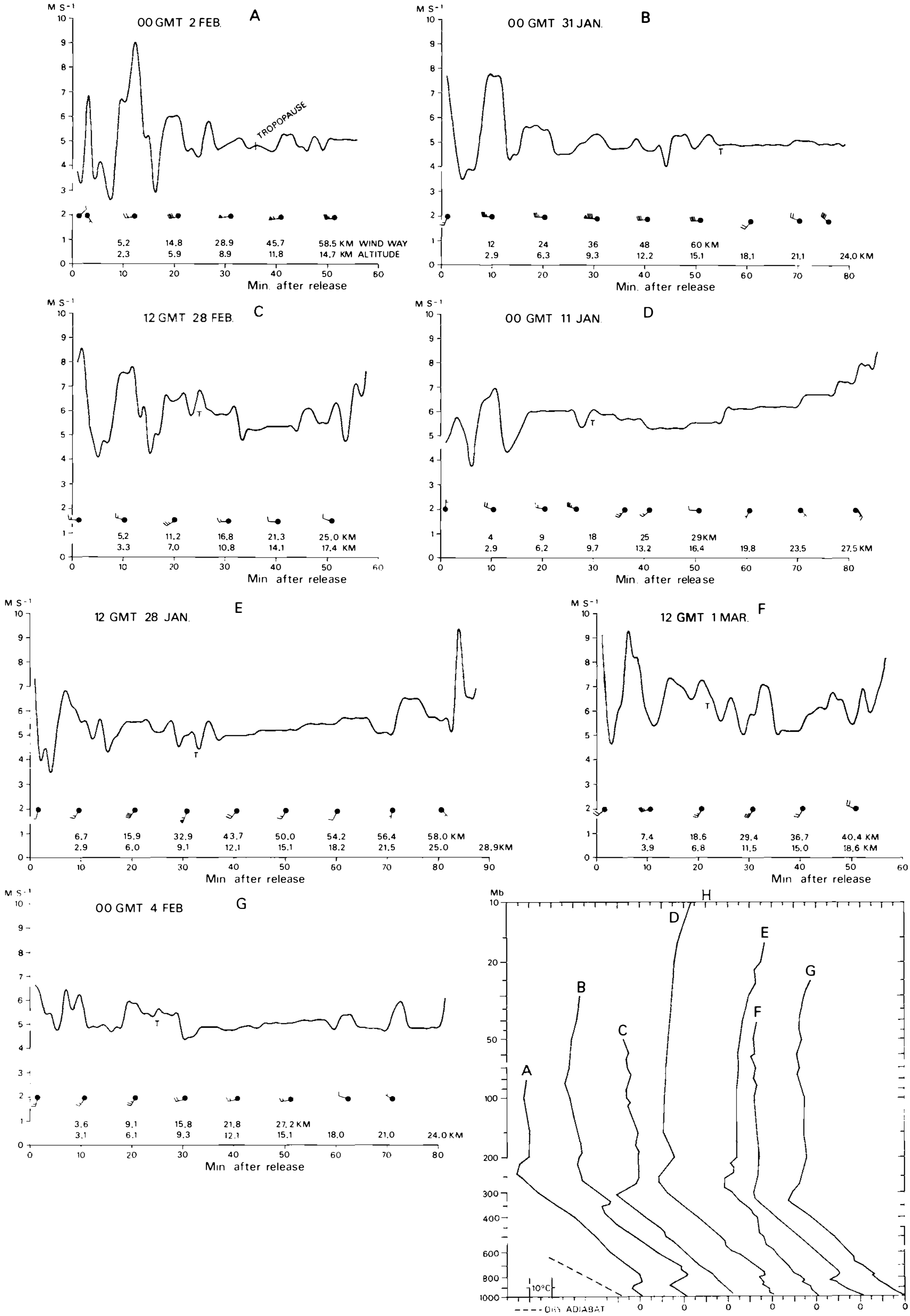

Fig. 8. *Characteristic examples of the variation with height of the ascension rate of the upper air balloons. Cubic spline smoothing has been applied on the minute-to-minute calculated ascension rate. Figure H gives the corresponding temperature observations. T. denotes the height of the tropopause.*

and Gjevik and Martinsen (1977) for some Arctic islands. Waves are found to be particularly frequent in the wake of Jan Mayen. Observations of meso-scale wake clouds in the Southern Hemisphere are reported by e.g. Fujita and Tescon (1977). Photographs taken from Skylab show that Bouvetøya may have an effect on the air masses over extensive distances (240 km). During our upper air programme it was soon realized that relatively great variations occurred in the ascension rate of the radiosonde balloons. Fig. 8 shows some characteristic examples. A cubic spline smoothing method has been used for the minute-to-minute calculated rate ascents. Similar variations were observed for all the 93 flights considered here, and Fig 8G represents conditions where the variations were at a minimum.

The observations of crests and troughs at various levels indicate wave lengths of the most pronounced lee motions of 3—14 km, and also that the wave length increases with wind speed. Wave lengths were estimated to 10—15 km from the Skylab photographs at Bouvetøya and from satellite imagery to 8—15 km behind the Arctic islands (Gjevik and Martinsen 1977).

Smaller irregularities may be observed near the crest and trough of the waves (e.g. Fig. 8B). This indicates that a complex wave pattern exists. The Skylab photographs show both transverse and diverging systems at the same time.

The reproduced examples in Fig. 8 give a general impression of a systematic reduction of the motions when approaching the tropopause. However, in some cases the vertical motions seem to increase again when moving into the stratosphere, and considerable vertical motion may be found at heights of between 15 and 30 km. During these conditions (Fig. 8 C, E, F, and G) the temperature soundings (Fig. 8 H) show a variable temperature stratification at these heights.

Apart from the flight shown in Fig 8 G, the maximum variation in the vertical ascension rate is observed to be 3—6 m s^{-1}. The departure from the average ascension rate for the individual flights is between 1 and 4 m s^{-1} which may indicate the magnitude of the vertical velocities affecting the balloon. We do not know if the balloon reached equilibrium with the accelerating (decelerating) forces when passing the crests and troughs. The actual vertical velocities may therefore be higher than stated above.

Acknowledgements

The meteorological programme was planned and funded in cooperation with the Norwegian National Committee for GARP. The data analysis was conducted by Ø. Finnekåsa, in cooperation with the Norwegian Meteorological Institute. Thanks are extended to all members of the expedition headed by O. Orheim, with special thanks to N. Nergaard, J. Snuggerud, Ø. Grothe, and T. Engelskjøn for cooperation at all stages of the expedition and particularly during the stay at Bouvetøya.

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Measurements of ocean current and bottom pressure near Bouvetøya, January—March 1979*

By A. Foldvik[1], T. Gammelsrød[1], and T. Tørresen[1]

Abstract

Registrations of current and bottom pressure for a period of six weeks are presented. The tidal periods dominate the records. The sea surface variations have a range of about 65 cm and the current 50 cm/s. A three-day period is also present, and it is suggested that the moving low pressure systems set up balanced, topographically steered currents of the same period. The mean current for the six-week period is 6.7 cm/s east-northeast (70°).

1. Introduction

This note presents the results from a sub-surface mooring launched south of Bouvetøya on 23 January 1979 and recovered on 8 March 1979 by the Norwegian Antarctic Research Expedition 1978/79. The water depth was 585 m and the position is indicated on the map (Fig. 1). The mooring consisted of an Aanderaa WLR-5 pressure recorder at the bottom, an Aanderaa RCM-4 current meter 250 m above the bottom, and a subsurface mooring buoy about 10 m above the current meter.

Bouvetøya is situated in the Antarctic Circumpolar Current south of the Antarctic Convergence Zone, e.g. Tchernia (1980). Hydrographical observations near Bouvetøya was first obtained by Mosby (1934) on the "Norvegia" Expedition 1927—28. His results agree well with a CTD station taken on the day of the recovery of the rig (Fig. 2). Mosby's observations show a colder surface layer, which is expected since his stations were obtained in December.

Fig. 2 shows that the stratification is weak below the seasonal pycnocline. The baroclinic pressure signal is therefore probably small, and the bottom pressure variations are expected to reveal the variations in the surface level plus atmospheric pressure. Wearn and Baker (1980) used similar bottom pressure observations to study variations in the Antarctic Circumpolar Current.

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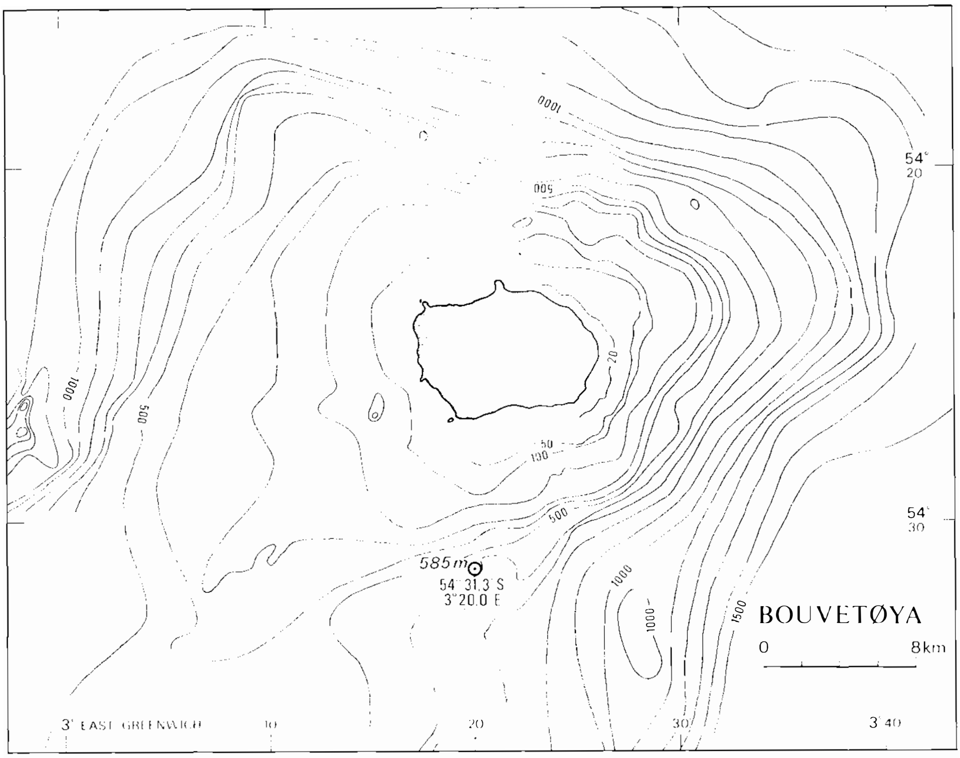

Fig. 1. *Bathymetry of the Bouvetøya region with position of instrumentation.*

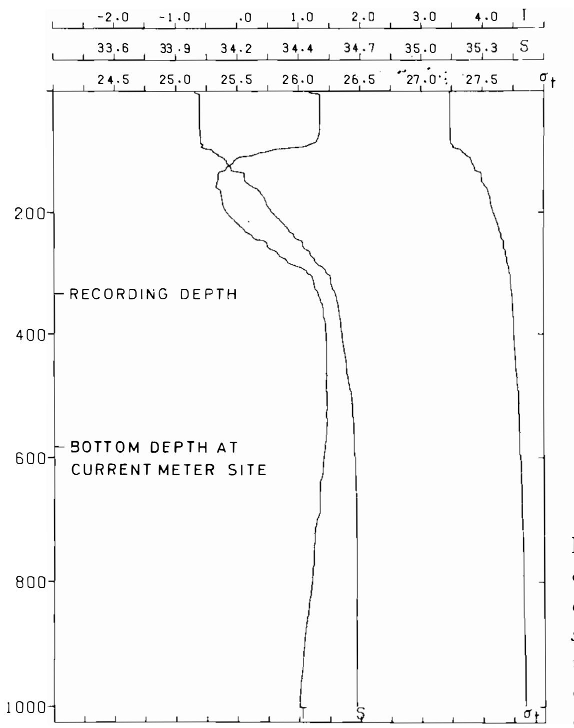

Fig. 2. *CTD-station near Bouvetøya, 8 March 1979. The curves show the distributions of temperature (T), salinity (S) and density (σ_t) in the upper 1000 m. Bottom depth and current meter depth at mooring site are indicated.*

2. Pressure Measurements

If changes in density are disregarded, the variations in the bottom pressure reflect variations in the sea level due to tides, varying atmospheric pressure and wind-driven currents, i.e. convergence or divergence in wind-driven Ekman transports. Theoretically, slow changes in atmospheric pressure cause the sea level to react as a reverse barometer. In the ideal case, with no other disturbing effects, changes in sea level will compensate completely for the varying atmospheric pressure and the bottom pressure will be unaffected. Therefore the variations in the observed bottom pressure are mainly caused by tides and wind-driven currents.

The registrations are presented in Fig. 3, and show a typical mixed tide with diurnal and semidiurnal periods dominating. The apparent two-week period is due to the interference of the semidiurnal periods M_2 and S_2. The maximum range during the observation period is 65 cm.

We have computed the power spectrum for the pressure record using the "Maximum Entropy Method" (see Fig. 4). As expected the tidal bands dominate. The subharmonic periods which show up near 8 hrs, 6 hrs, etc. are typical for shallow water tides. There is also a peak at approximately three days.

To study phenomena with periods longer than one day we have filtered out most of the short time variations using a 25 hrs running average. The

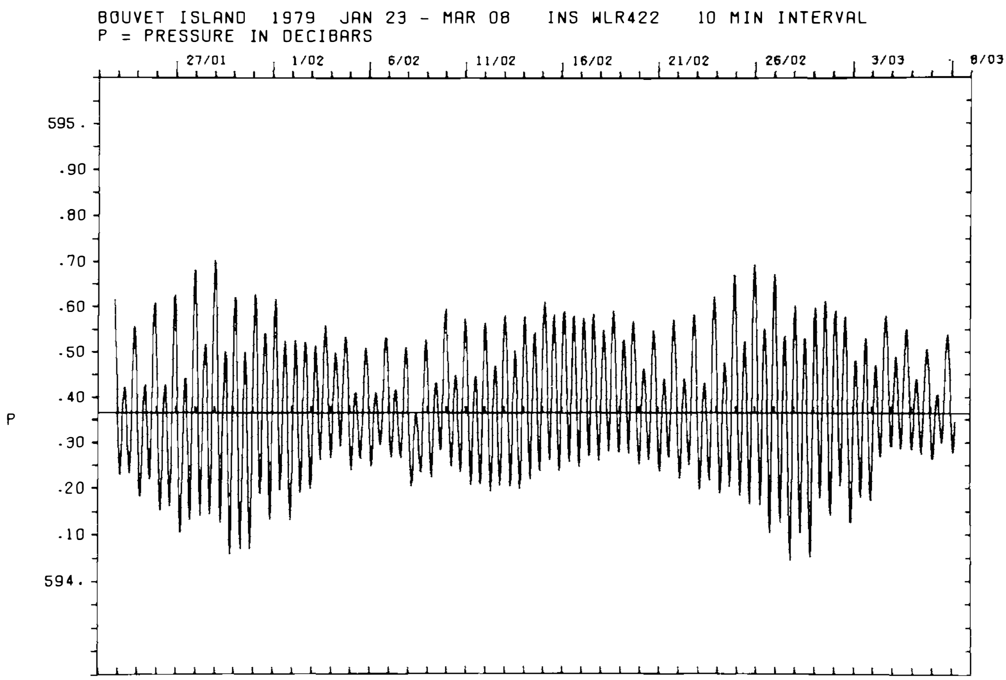

Fig. 3. *Bottom pressure record near Bouvetøya. One decibar corresponds approximately to one metre water column.*

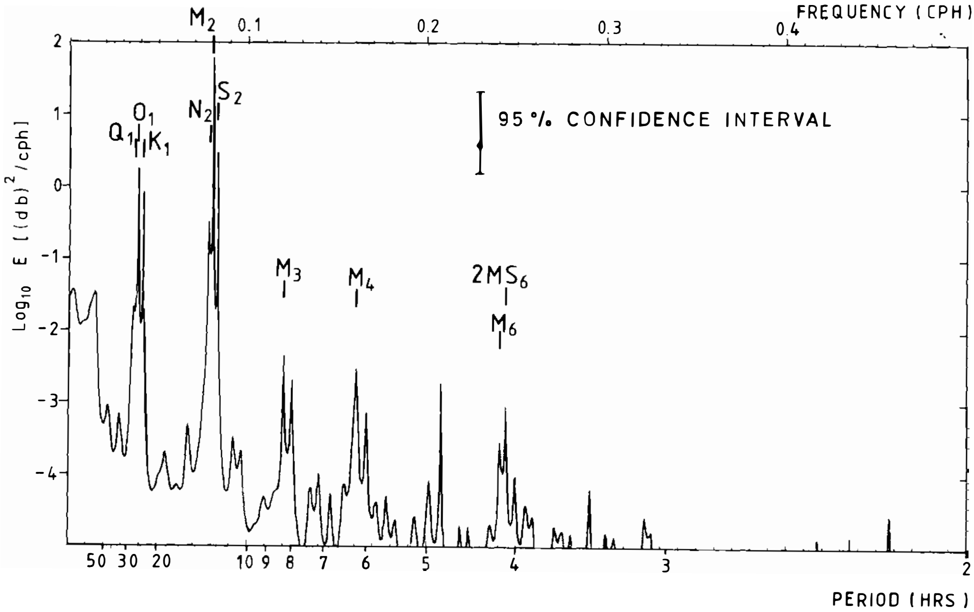

Fig. 4. *Spectrum of bottom pressure computed using the Maximum Entropy Method. The frequency of the prominent tidal constituents is indicated.*

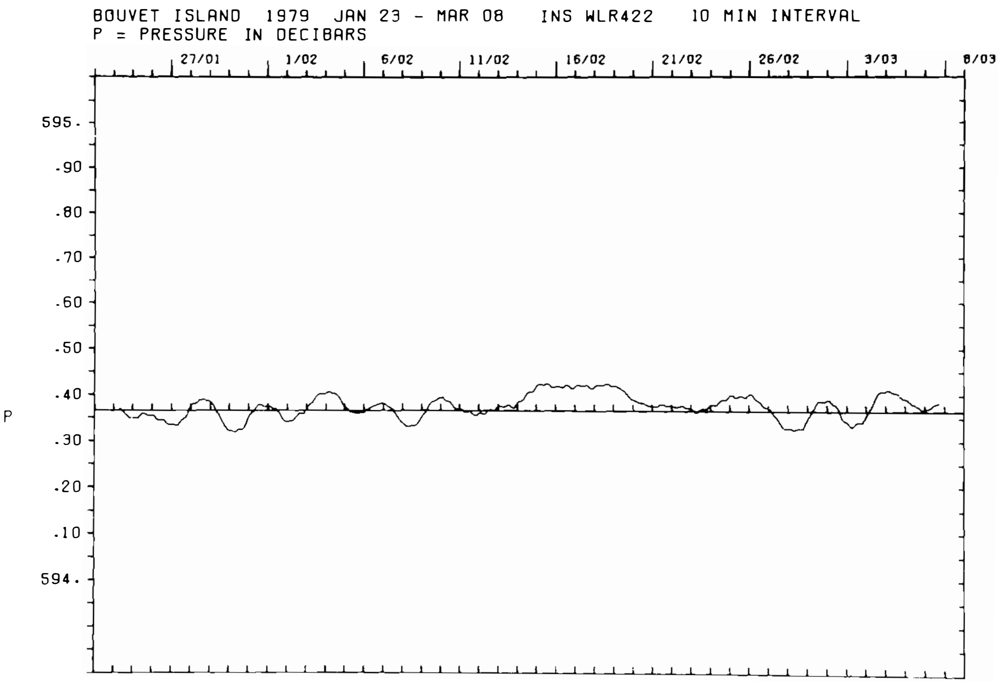

Fig. 5. *Bottom pressure record after applying a 25 hours running mean.*

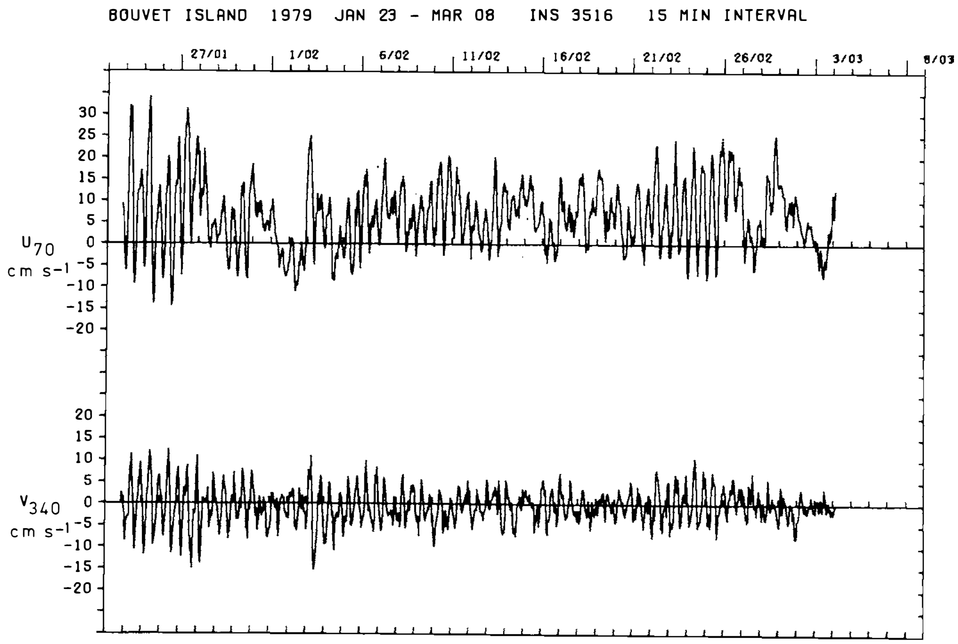

Fig. 6. *Components of current velocity along the isobaths (U_{70}) and normal to the isobaths (V_{340}).*

results are presented in Fig. 5 and show the sea level variations due to tides and wind-driven currents on a time scale longer than one day. The three-day period found in the power spectrum is clearly seen.

3. Current measurements

The current meter was situated 250 m above the bottom. The main direction of the isobaths at the mooring site is east-northeast (70°). The registrations are presented in Fig. 6 where the velocity vector has been decomposed in the direction of the isobaths (denoted by U_{70}) and in the direction normal to the isobaths (denoted by V_{340}). Obviously the mean current is directed along the

Table 1

Component	*long axis (cm/s)*	*short axis (cm/s)*	α
M_2	6.4	3.6	77°
S_2	3.6	1.6	64°
K_1	3.0	0.4	60°
O_1	1.7	0.5	57°

The Table gives the orientation and magnitude of the major and minor axes for the current ellipses shown in Fig. 7. α denotes the orientation of the major axis measured clockwise from north.

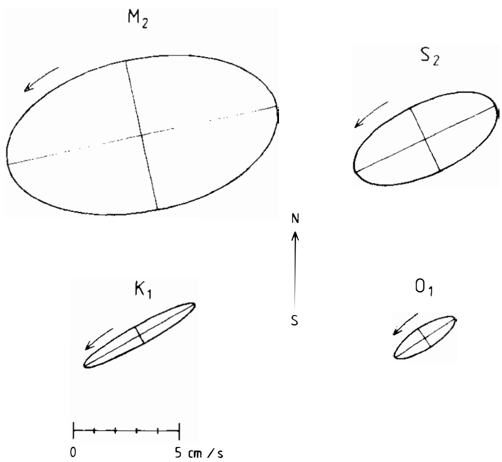

Fig. 7. *Current ellipses for M2, S2, K1 and O1.*

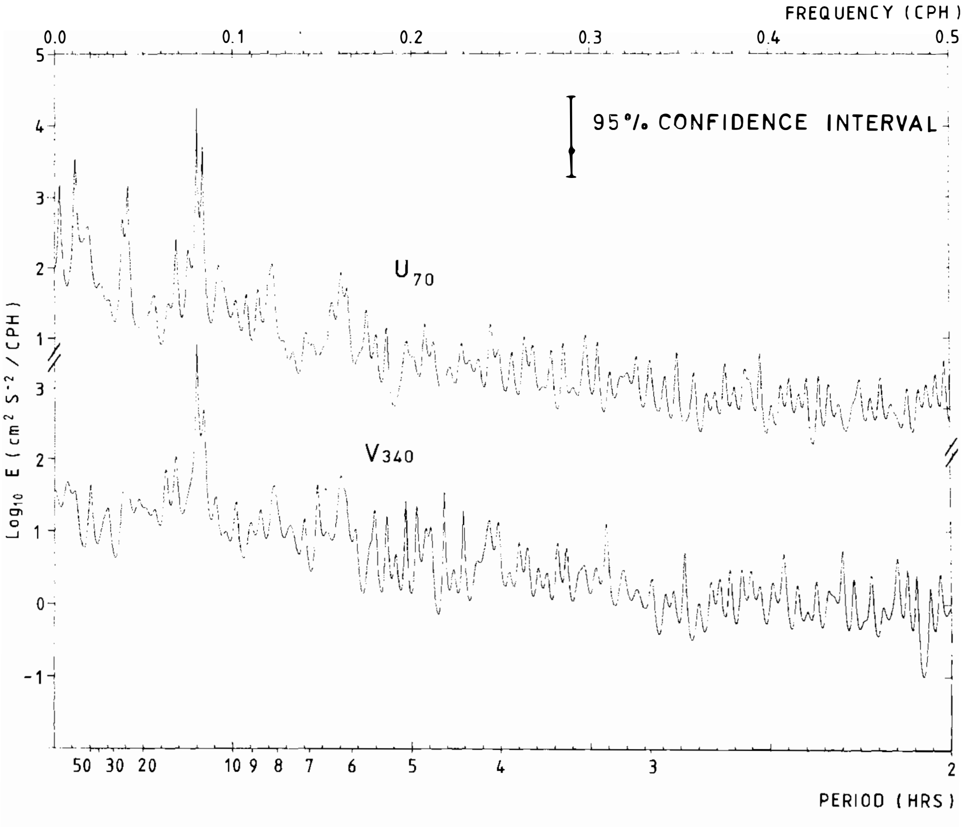

Fig. 8. *Spectra of current components computed using the Maximum Entropy Method.*

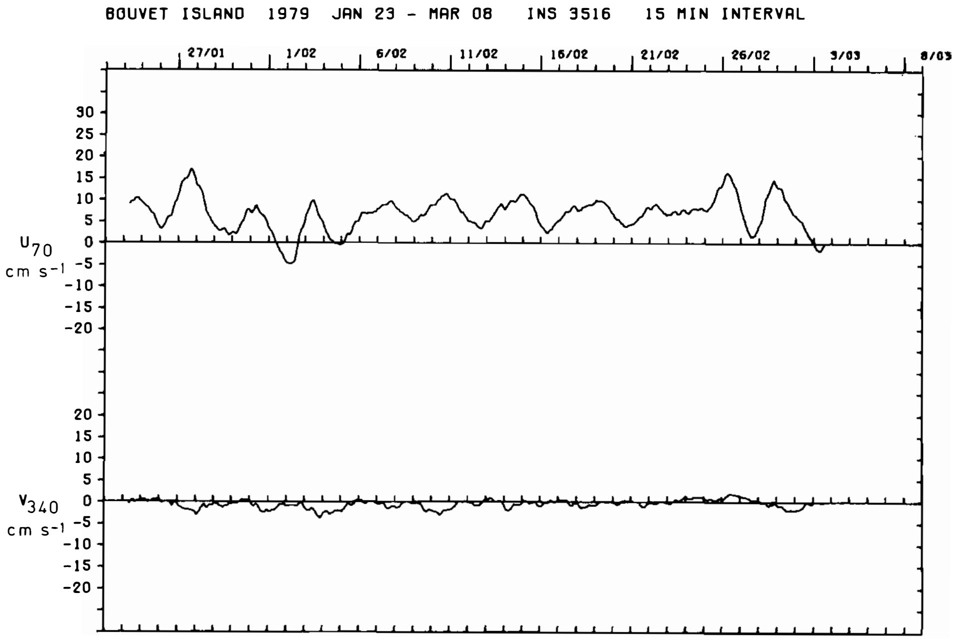

Fig. 9. *Records of current components after applying a 25 hour running mean.*

isobaths (see also Fig. 9). The current is dominated by the tides and the U_{70} amplitudes are larger (range up to 50 cm/s) than the V_{340} amplitudes.

The current ellipses for some tidal components are given in Fig. 7 and Table 1. The rotation is counter-clockwise for all ellipses and the M_2 component is the dominating one. Note that the major axes of the ellipses are oriented parallel to the isobaths and that the diurnal ellipses are very eccentric. Thus there are only weak cross-isobath currents with diurnal periods. This is also apparent in the power spectra for the current components (Fig. 8) which demonstrates how the diurnal period vanishes for the V_{340} component. For the U_{70} component a period of 3.5 days appears, and this period is also easily recognizable in the 25 hrs running averages (Fig. 9).

4. Discussion

As mentioned above, Bouvetøya is situated in the Antarctic Circumpolar Current. For the period of observation the mean current was 6.7 cm/s directed east-northeast along the isobaths. It should be noted that large fluctuations appear which, at intervals, may even cause westerly residual currents (see Fig. 9).

The power spectrum for the air pressure observations obtained at Bouvetøya during the mooring periods is shown in Fig. 10. The dominating periods are about 3 and 7 days with a longer 21-day period which is more uncertain due to the short period of observation. As mentioned earlier the three-day

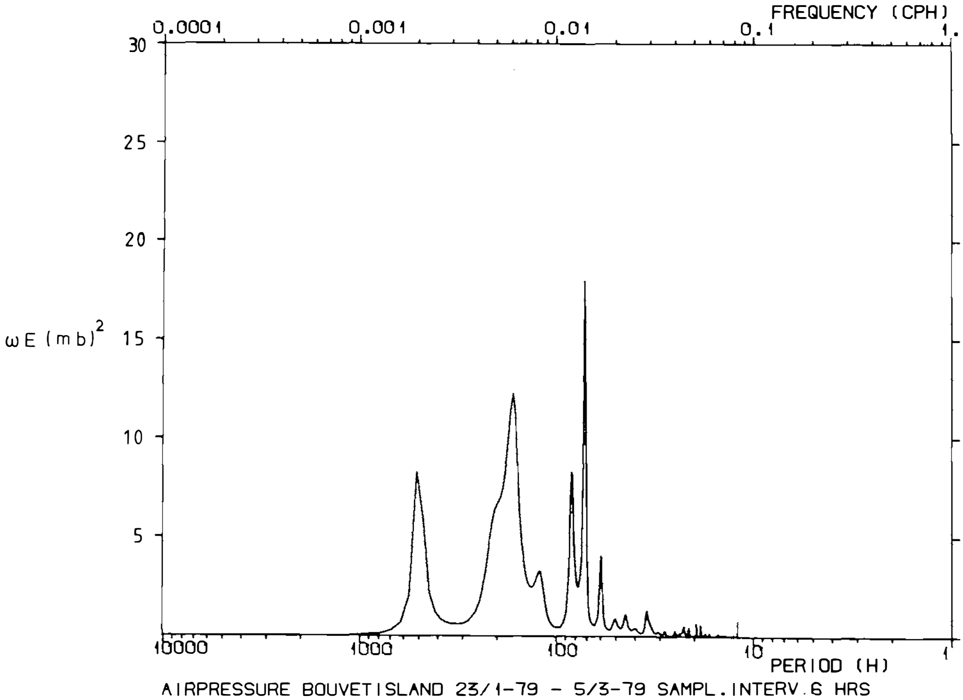

Fig. 10. *Spectrum of air pressure at Bouvetøya for the period of ocean measurements. ω is the frequency.*

period also appears in the records of bottom pressure and the U_{70} current component (see Figs. 5 and 9). A possible explanation is that the wind associated with the low pressure systems produce divergent water transports in the surface layer which yields a lowering of the surface level and is seen as low values in the bottom pressure record (Fig. 5). Variations in the sea surface level yield horizontal pressure gradients which give rise to acceleration of the water mass. Due to the relatively long forcing period the resulting motion will be near a geostrophic balance and controlled by the bottom topography. Thus the cross-isobath component is suppressed (Fig. 9) and the current along the isobaths varies with the same period as the air pressure.

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Analysis of wave measurements at Bouvetøya*

By Øivind Arntsen[1] and John Snuggerud[2]

Abstract

Waves were measured 5 km north of Bouvetøya during February 1979 (Antarctic summer). Period statistics, zero-up-cross and spectral analysis have been performed on the wave recordings. The sea state is described and occurrence and duration of storms are presented. Storm wave spectra are analysed and compared with common ocean wave spectra. Results show that the sea state during the Antarctic summer can be compared with the sea conditions on the Norwegian Continental Shelf in the winter.

Introduction

As part of the programme of the "Norwegian Antarctic Research Expedition 1978/79", waves were measured off Bouvetøya with equipment from the River and Harbour Laboratory (VHL) and carried out by Expedition personnel. Data processing and data analysis were undertaken by the VHL. This paper presents the measured data and the results of the data analysis.

The purpose of this investigation is to get a better knowledge and understanding of the ocean climate in the Antarctic areas, especially at Bouvetøya which is situated far away from other coastal areas. A survey of the sea and weather conditions in the area are given by Ivanov et al. (1960). Our measured data have been compared with main features presented in that paper, and no great discrepancy has been found between our registrations and that survey as far as waves are concerned.

The region off Bouvetøya distinguishes itself by great depths, up to 5000 m, and practically borderless fetches. Bouvetøya is situated in the westerlies and cyclones pass frequently; two to four storms per week are not unusual. The area is therefore one of the most exposed places in the World Ocean.

Periods with great stratification of the water may occur due to the melted ice and snow. Speculations have been furthered that the stratification may affect the surface waves in such a manner that they will not achieve the same heights as in the absence of stratification. This can be explained by energy transfer from surface waves to internal waves. Ivanov et al. (1960) claim

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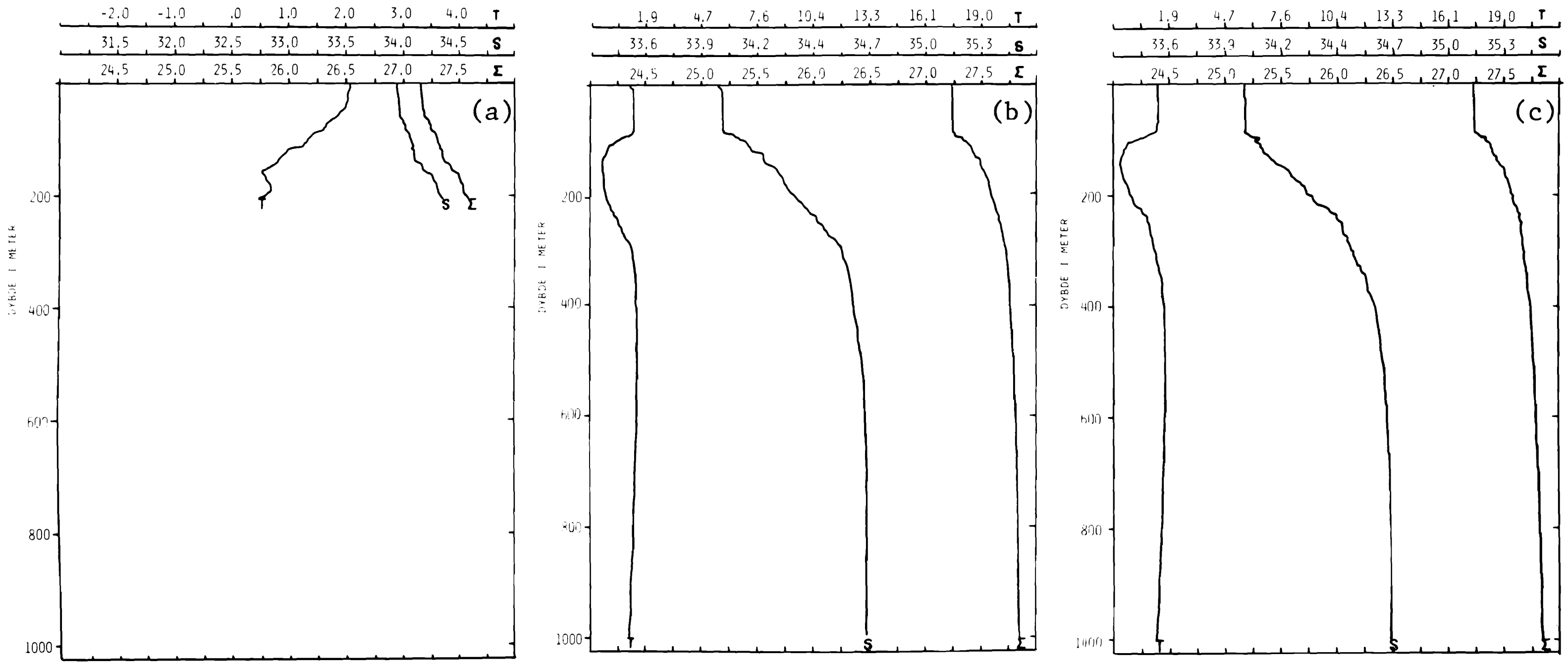


Fig. 1. *Hydrographic measurements off Bouvetøya. a) Near surroundings of the island. b) 70 km NNE off the island. c) 80 km NNE off the island. The figure shows values of temperature (T), salinity (S) and a density parameter (Σ) as a function of depth.* $[T] = °C$, $[S] = [‰]$ *and* $[\Sigma] = 1$. *Σ is given by* $\Sigma = (1-\varrho)x10^3$. $[\varrho] = kg\ dm^{-3}$, ϱ = *density of water. The scale of each parameter is given above the curves.*

that under the same wind conditions, wave heights may, in the absence of a pycnoclinic layer, become two to three times greater than in a situation with a strong pycnocline.

Figs. 1a, b, c show the result of hydrographic measurements at three locations off Bouvetøya. The measurements in deep water 70—80 km off the island show a very well mixed upper layer down to 80 m, and an intermediate shear layer down to 300 m. These measurements were taken just after a storm, while the results in Fig. 1a were achieved just before this storm and give perhaps a more reliable picture of the stratification in the area at the time when the wave measurements were conducted. It indicates that no pycnocline is present and that the stratification, therefore, has minor effect on the waves.

The instrumentation and data material

Description of the Waverider buoy

The waves were measured with a surface following waverider buoy (manufactured by Datawell, Holland) with a diameter of 0.7 m. Fig. 2 shows the mooring system. The wave buoy measured acceleration, and the double-integrated accelerometer signals were telemetered to a receiver placed at the Nyrøysa station.

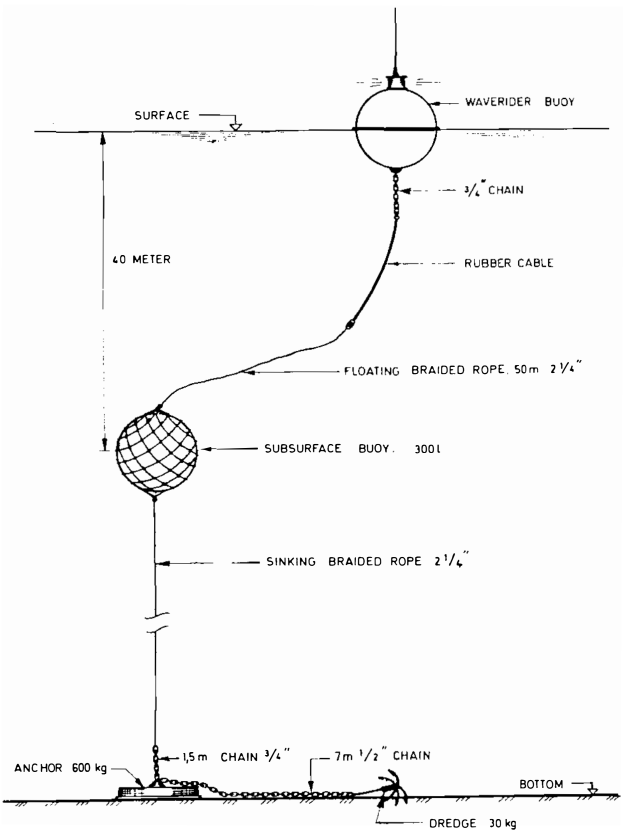


Fig. 2. *Waverider buoy mooring system for deep water.*

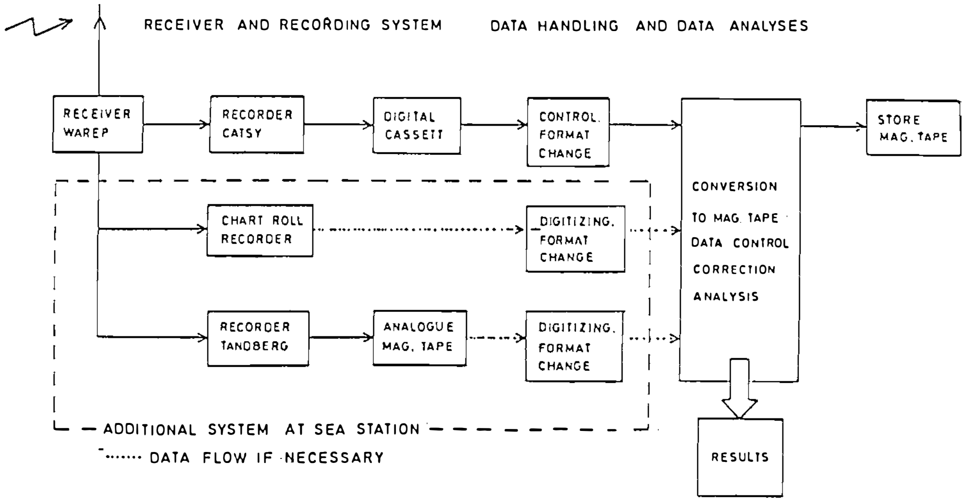


Fig. 3. *Data flows of the waverider recording and data handling system.*

The data were digitized every half second and stored on magnetic tapes. Normally one record of approximately 20 minutes was taken every third hour. The uncertainty in wave amplitude is less than 3% for waves with frequencies between 0.065 and 0.5 Hz, corresponding to wave periods from 2 to 15 s. Outside this interval, between the limits 0.035 Hz and 0.65 Hz, the deviation from the real amplitude may be up to 30%.

The waverider buoy was calibrated before shipment in a 4 m diameter wheel. The rotation of the wheel gives simulated wave periods from 4 to 20 seconds. The buoy was damaged (probably by freezing) in transport back from the Antarctic, and calibration after field service has therefore not been carried out. This has usually no effect on the results since the greatest deviation ever detected in calibration before and after field work is 5—10% in wave height and no deviation in wave period.

The wind data

The wind speed and direction used in this paper are visually estimated by watching the sea state from the meteorological station at Nyrøysa. The wind observations are therefore good estimates of the wind state at the buoy.

Wave data material

The buoy was moored north of Bouvetøya at 54°21.3'S, 3°18.8'E, where the water depth was 180 meter. The position is some 4.9 km from Kapp Circoncision and 4.4 km from Kapp Valdivia. Registrations started on 1 February 1979 at 0000 GMT and terminated on 1 March 1979 at 2100 GMT.

Wave data processing

The data handling and data processing routines are shown schematically in Fig. 3. This system is called NEPTUN and is built up for the following parts:

— Conversion to computer compatible tapes and mass-storage files.
— Data control and correction procedures.
— Data analysis with lists of spectral and zero-up-crossing parameters and period statistics.

Samples are rejected if there are too many spikes, successive equal parameters, unphysical accelerations, too long wave periods or too high values of H_s compared with H_{max}. The computer programme is written in FORTRAN for the UNIVAC (Torsethaugen and Krogstad 1979). Some of the computed parameters are shown in Fig. 4.

PARAMETER DEFINITIONS:

(UNIT METERS (HEIGHTS), SECONDS (PERIODS))

1. ZERO CROSSING PARAMETERS

H - Individual wave height.
H_s - Average of the one third highest waves.
H_{max} - Height of highest wave.
H_{mean} - Average of individual wave heights, H.
H_{S1max} - Height of steepest wave.

T - Individual wave periods.
T_s - Average period of the one third highest waves.
T_z - Average period of individual waves, T.
T_{Hmax} - Period of the highest wave.
T_c - Record length divided by number of crests.

S_1 - Steepness of an individual wave: $S_1=H/(1.56\ T^2)$.
S_{1mean} - Average wave steepness.
S_{1max} - Steepness of steepest wave, maximum of S_1.
S_{1Hmax} - Steepness of highest wave.

2. SPECTRUM PARAMETERS

H_{4RMS} - Estimate of H_s.

T_p - Period of spectral peak.
T_l - Lower wave period of significance.
5% of the energy have shorter periods.
T_u - Upper wave period of significance.
5% of the energy have longer periods.

Q_p - Spectrum width parameter.
R_b - Half value width of spectrum peak.

Fig. 4. *Parameter definitions.*

The programme is used for nearly all analyses of wave data gathered in Norway. As per 1 September 1979 approximately 30,000 time series had passed through the programme.

The spectral analysis

An estimate of the scalar frequency spectrum of the wave field is obtained by computing the periodogram of the record by means of Fast Fourier Transform (FFT). This is the usual way of obtaining power spectra, and is a fast, reliable, and thoroughly studied method.

The periodogram is computed from the time series

$$\{ X(j) \}_{j=0}^{N-1} \text{ as follows}$$

$$S(f) = \frac{1}{Nf_o} \left| X(j)e^{-ij\lambda} \right|^2 \quad ; \quad \lambda = 2\pi f/f_o$$
$$f = 0,\ f_o/N,\ 2f_o/N \ldots\ldots$$

where f is the frequency and f_o the sampling frequency. N is a power of 2 in order to gain maximum efficiency of the FFT. For presentation and computation of the derived parameters, a smoothed spectrum is computed by a moving average of the periodogram.

The zero-upcrossing analysis

The zero-upcrossings are the time when the record crosses the zero level from negative to positive values. When the zero upcrossings and heights are determined, we have also identified the waves, i.e. the pieces of the record between two subsequent zero upcrossings. The problem is not well defined since noise etc. greatly affects the results. The algorithm gives us an array of periods and heights of individual waves. Parameters computed from this array are described in Fig. 4.

Recovery and uncertainty of wave data

During the period, 196 samples containing a total amount of 28,307 single waves were recorded, which means a data recovery of 88%. The rest is rejected due to instrumentation failure and control criteria. The zero-upcrossing results indicate some systematic errors in the wave registrations which are not corrected by the NEPTUN programme.

There is a number of unphysical long waves in many samples which seems like a sort of drifting in the data. This is an instrumentation/calibration effect and can give rise to an error in parameters derived from the zero-upcrossing analysis. The drift leads to unphysically great values in the spectrum for very low frequencies. Parameters based on the spectrum where the integration limits are set beyond this error area will therefore be more reliable and the discussion and deductions are made mainly on the basis of these parameters.

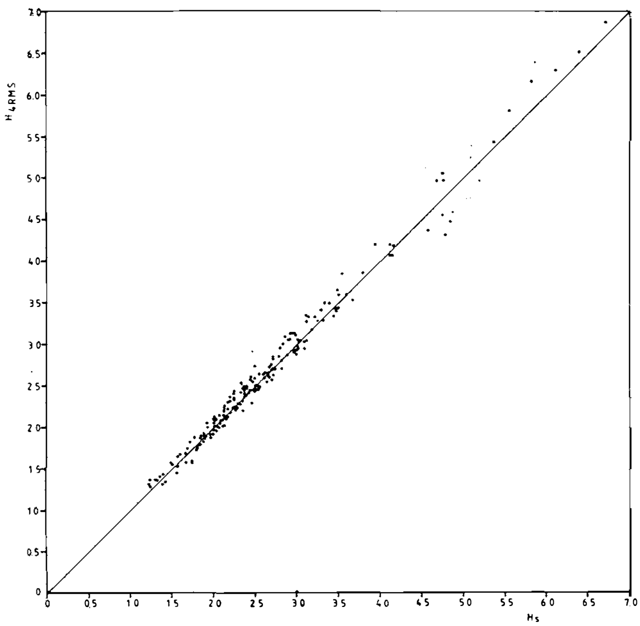


Fig. 5. *Comparison between H_s and H_{4RMS}.*

However, the comparison between H_s and H_{4RMS} shown in Fig. 5 shows that H_s is just as good an estimate of significant wave height as is H_{4RMS}. This agrees with common theory.

Results

General

The results of the wave data analysis are presented in tables and diagrams in Figs. 6 – 16. A logarithmic presentation of the spectrum for each 20-minute period is also calculated but these data are stored at VHL on data listings. However, some of the spectra in connection with storms are presented and an isoplet diagram of time development of energy density is given in Fig. 11.

Period variations of H_s, and H_{max} and H_{mean} are shown in Fig. 10. This figure shows that $H_s > 4.0$ m on five occasions and $H_s > 6.0$ m on only two occasions.

The maximum sea state, with wave height $H_{max} = 10.4$ m and period $T_{Hmax} = 11.7$ sec, was recorded during a storm 28 February – 1 March 1979. H_s reached its maximum with 6.7 m. The spectrum development of this storm is presented in Fig. 12, and a comparison with a parameterized spectrum known as the Pierson – Moskowitz spectrum is shown in Fig. 13. The parameters in the Pierson – Moskowitz spectrum are chosen by a best curve fit method.

The frequency distribution of H_s is given in Fig. 17. The table shows that 22 % of the registrations of H_s are below 2 m, 78 % below 3 m, and 93 % below 4 m, and that 56 % of the registered waves have $2\,m < H_s < 3\,m$.

H \ T	0 : 1	1 : 2	2 : 3	3 : 4	4 : 5	5 : 6	6 : 7	7 : 8	8 : 9	9 : 10	10 : 11	11 : 12	12 : 13	13 : 14	14 : 15	15 : 16	16 : 17	17 : 18	>18	SUM	%	AVERAGE
.0- .5		1028	1096	493	172	69	35	14	6	1										2914	10.3	2.6
.5- 1.0		107	766	1276	1159	779	562	379	169	93	57	36	14	3	2		2			5405	19.1	4.8
1.0- 1.5		17	76	533	1047	1194	1187	924	696	478	287	179	101	56	47	30	13	9	13	6887	24.3	6.9
1.5- 2.0			3	85	357	638	755	821	750	597	403	233	140	89	73	43	25	15	32	5059	17.9	8.2
2.0- 2.5				7	87	275	468	603	617	517	364	196	114	82	51	30	29	24	45	3509	12.4	8.9
2.5- 3.0					17	135	255	361	449	367	249	164	84	65	39	37	20	23	45	2310	8.2	9.4
3.0- 3.5						18	76	138	181	189	128	70	70	32	30	14	15	6	32	999	3.5	10.2
3.5- 4.0						6	33	62	79	84	65	37	38	24	16	11	2	7	18	482	1.7	10.4
4.0- 4.5						1	13	35	57	46	43	35	17	20	11	9	4	4	16	311	1.1	10.0
4.5- 5.0						1	6	12	30	19	26	15	11	11	16	4	3	3	12	169	.6	11.6
5.0- 5.5								6	5	13	16	14	15	8	8	3	2	1	3	94	.3	12.1
5.5- 6.0							1	2	8	5	5	6	5	8	6	3		1	1	51	.2	11.7
6.0- 6.5								1	2	5	8	4	4	5	4	3		1	1	38	.1	12.2
6.5- 7.0								1	1	5	5	10	9	6	1					38	.1	11.6
7.0- 7.5										3	2	2	2							9	.0	11.0
7.5- 8.0									1	1		2	3	1						8	.0	11.3
8.0- 8.5											2	2	2	2						8	.0	12.2
8.5- 9.0									1	2	1	1	2			1				8	.0	11.4
9.0- 9.5											1		1	3						5	.0	12.8
9.5-10.0												1			1					2	.0	13.2
10.0-10.5												1	1							2	.0	12.0
10.5-11.0																				0	.0	.0
11.0-11.5																				0	.0	.0
11.5-12.0																				0	.0	.0
SUM	0	1152	1941	2394	2839	3116	3391	3359	3052	2425	1662	1008	633	415	305	188	115	94	218	28307	100.0	
%	.0	4.1	6.9	8.5	10.0	11.0	12.0	11.9	10.8	8.6	5.9	3.6	2.2	1.5	1.1	.7	.4	.3	.8	100.0		
AVERAGE	.0	.3	.5	.8	1.1	1.4	1.6	1.8	2.1	2.2	2.3	2.4	2.6	2.7	2.7	2.6	2.4	2.7	2.9			
T	0: 1:	1: 2:	2: 3:	3: 4:	4: 5:	5: 6:	6: 7:	7: 8:	8: 9:	9: 10:	10: 11:	11: 12:	12: 13:	13: 14:	14: 15:	15: 16:	16: 17:	17: 18:	>18:			

Fig. 6. *Frequency table for H and T.*

HS \ TZ	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	> 15	SUM	%	AVERAGE	HS
.0– .5																	0	.0	.0	.0– .5
.5– 1.0																	0	.0	.0	.5– 1.0
1.0– 1.5						7	4	1									12	6.1	6.0	1.0– 1.5
1.5– 2.0						5	21	5	1								32	16.3	6.6	1.5– 2.0
2.0– 2.5						5	33	23	2								63	32.1	6.8	2.0– 2.5
2.5– 3.0							18	24	3	1							46	23.5	7.2	2.5– 3.0
3.0– 3.5						1	3	11	3	5							23	11.7	7.8	3.0– 3.5
3.5– 4.0								3	1	2		1					7	3.6	8.6	3.5– 4.0
4.0– 4.5										2		1					3	1.5	10.3	4.0– 4.5
4.5– 5.0									2		1	1					4	2.0	9.5	4.5– 5.0
5.0– 5.5									1								1	.5	8.5	5.0– 5.5
5.5– 6.0									1	1							2	1.0	8.9	5.5– 6.0
6.0– 6.5										2							2	1.0	9.4	6.0– 6.5
6.5– 7.0										1							1	.5	9.3	6.5– 7.0
7.0– 7.5																	0	.0	.0	7.0– 7.5
7.5– 8.0																	0	.0	.0	7.5– 8.0
SUM	0	0	0	0	0	18	79	67	14	14	1	3	0	0	0	0	196	100.0		SUM
%	.0	.0	.0	.0	.0	9.2	40.3	34.2	7.1	7.1	.5	1.5	.0	.0	.0	.0	100.			%
AVERAGE	.0	.0	.0	.0	.0	1.8	2.2	2.6	3.4	4.3	4.6	4.2	.0	.0	.0	.0				AVERAGE
TZ	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	>15				

Fig. 7. *Frequency table for H_s and T_z.*

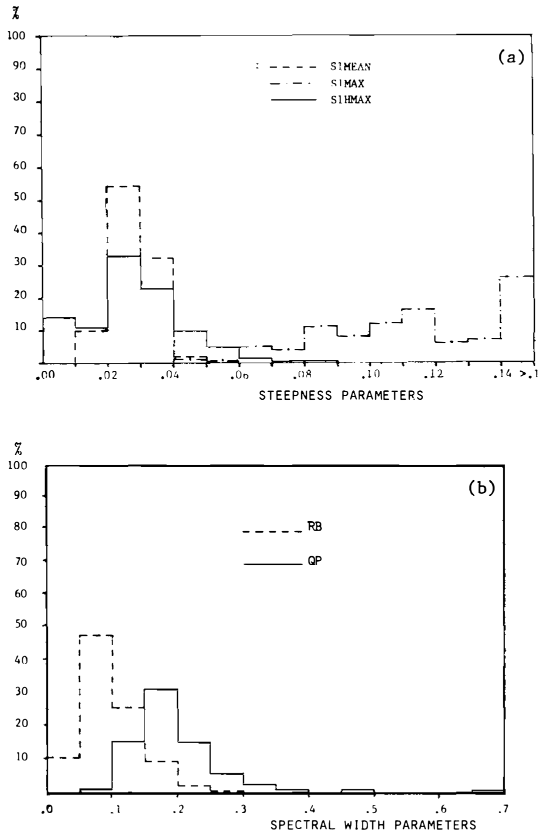


Fig. 8 *Histograms showing the distribution of: a) The average wave steepness* (S_{1mean}), *steepness of steepest wave* (S_{1max}) *and steepness of highest wave* (S_{1Hmax}). *b) The spectrum width parameter* (Q_p) *and the half value of spectrum peak* (R_b).

Duration of sea states

It is required for many kinds of operation at sea that the sea state is below a particular value for a certain duration of time. Although one month of measurements is too little to get reliable information on duration statistics, the data have been analysed with duration requirements of 3, 6, 12, 24, and 48 hours of sea state with $H_s < 2$, 3, and 4 m. The results are shown in the table in Fig. 14.

The analysis shows that the duration of $H_s < 4$ m for longer than 48 hours will occur 69% of the time, and that the duration of $H_s < 2$ m for 3 hours or more will occur 21% of the time in the observation period.

The results are compared with the same duration criteria at Tromsøflaket (71°30′N, 19°00′E) on the Norwegian Continental Shelf (Tryggestad 1980). Based on the Tromsøflaket data and an assumption of equivalence in change between summer and winter situations at the two places, winter sea-state distribution at Bouvetøya is calculated and presented in Fig. 14. This becomes a very rough estimate. The winter sea-state distribution is based on the assumption that the area considered is free from ice, which may not be the case in the area off Bouvetøya in the winter. The presence of icebergs and pack-ice will inhibit the development of waves. Therefore the sea-state during winters off Bouvetøya will be more quiet than indicated by the values in Fig. 14.

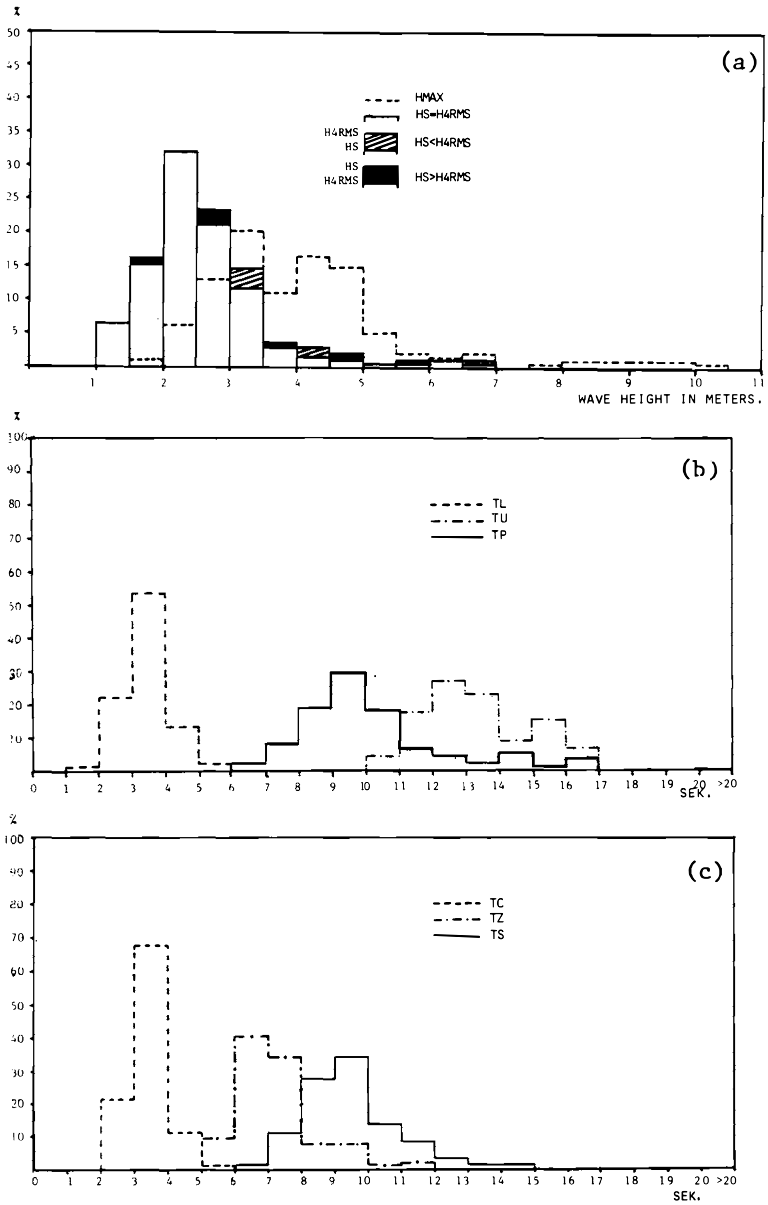
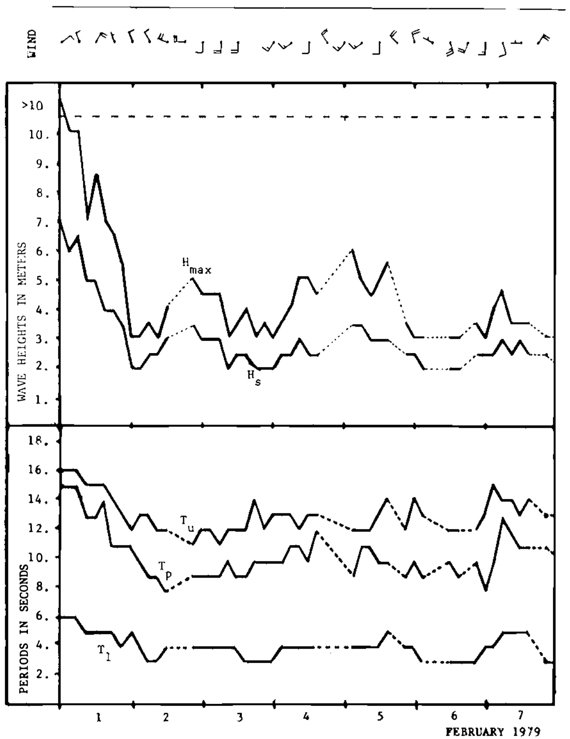


Fig. 9. *Histograms showing the distribution of: a) Height of highest wave* (H_{max}) *and significant wave height given by both* H_s *and* H_{4RMS}. *b) The lower wave period of significant* (T_l), *the period of spectral peak* (T_p) *and the upper wave period of significant* (T_u). *c) The period parameters* T_c *— the record length divided by number of crests.* T_z *— average period of individual waves, T.* T_s *— average period of the one-third highest waves.*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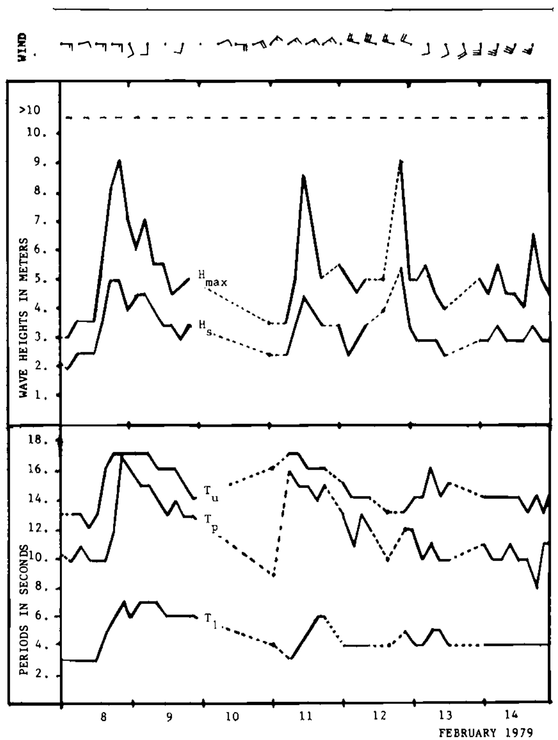
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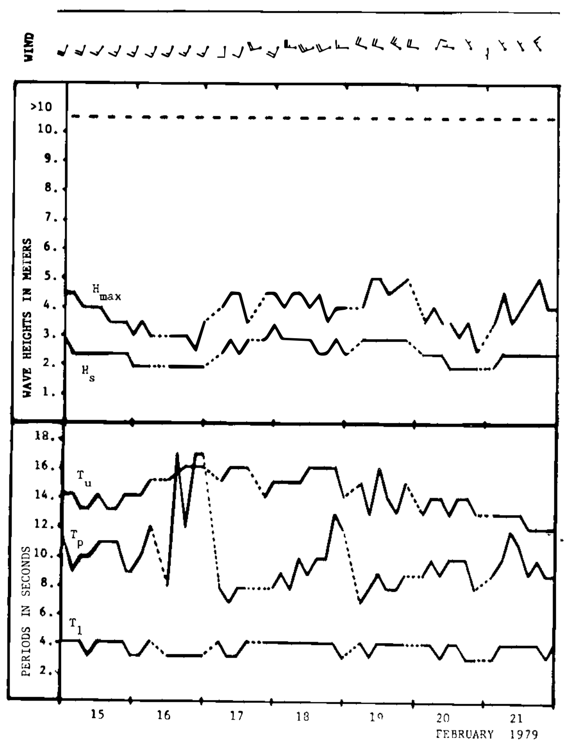
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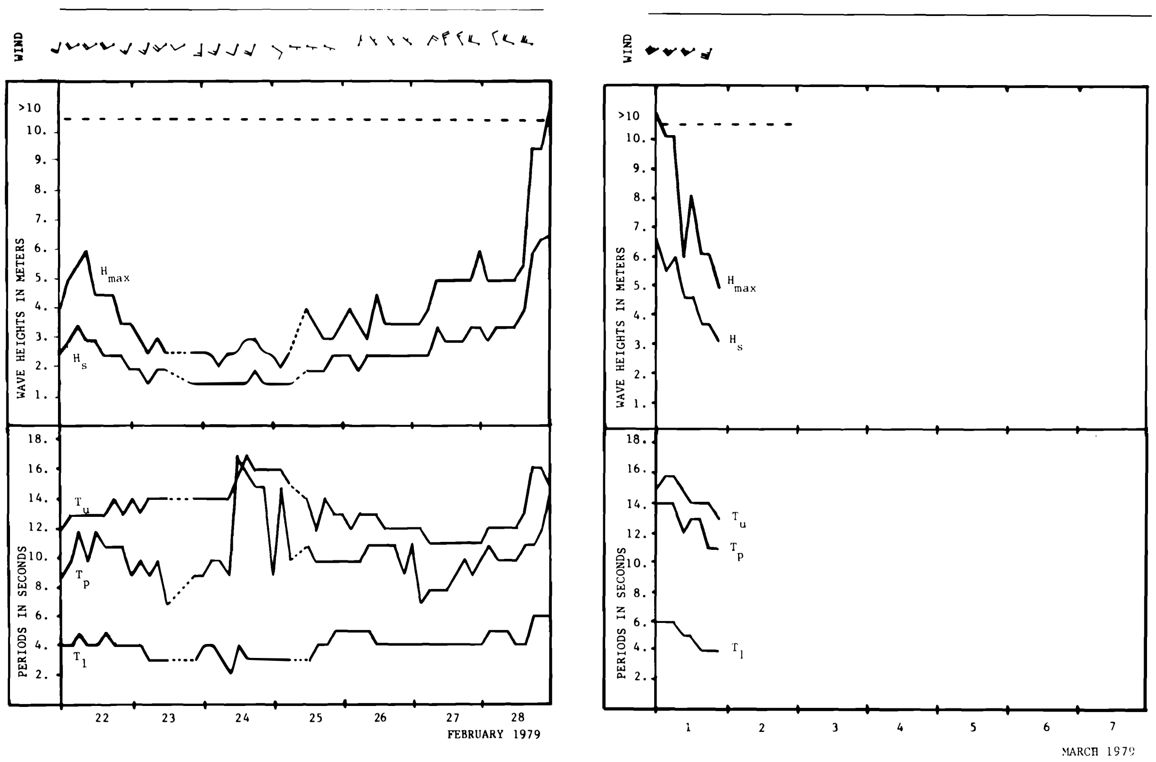

Fig. 10. *Time development of: Wind (speed and direction as wind-arrows); Wave heights: H_{max} and H_s. ; Spectrum width parameters: T_l, T_p and T_u. (Every 1/1 hook on the wind-arrows represents 5 m/s, and every 1/2 hook represents 2.5 m/s. The wind direction is given by the straight line ending at the dot.)*

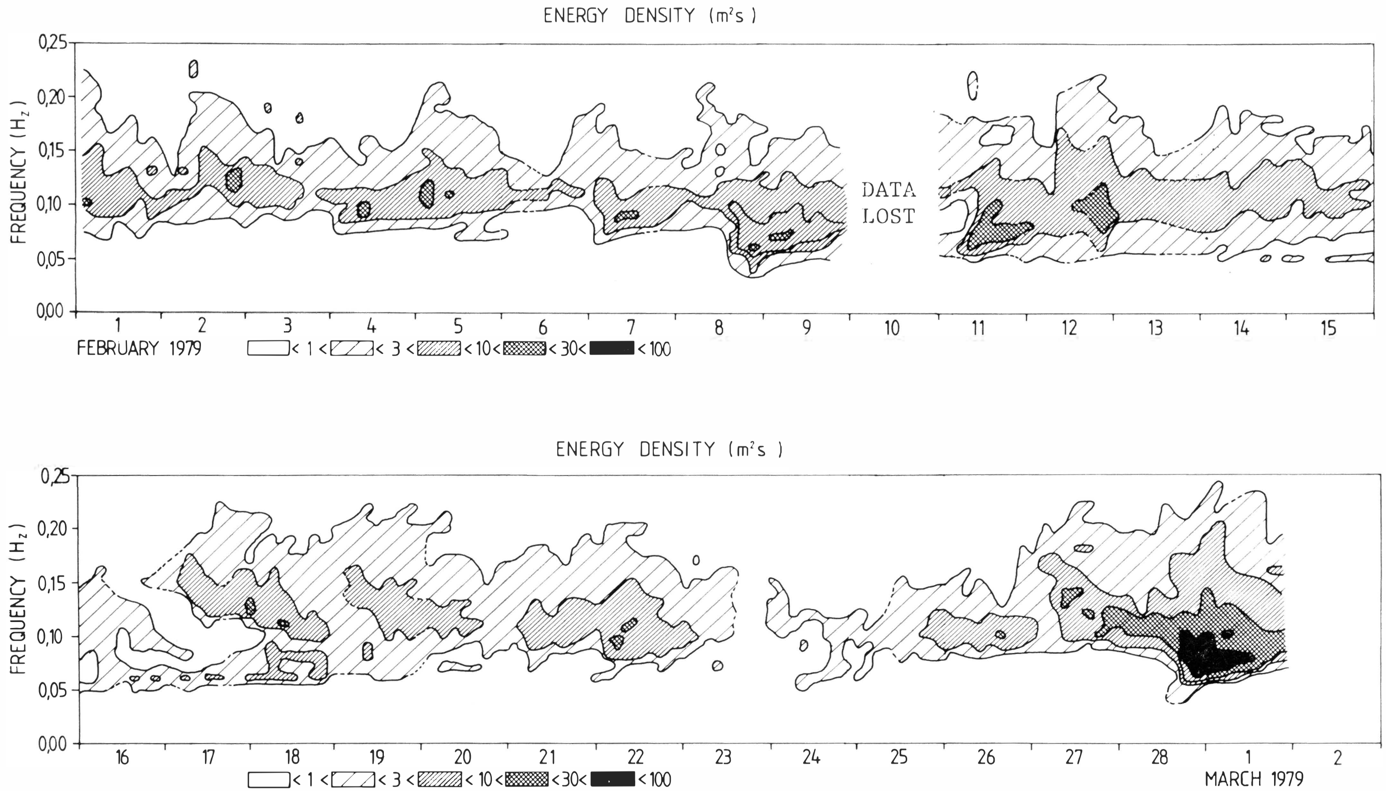

Fig. 11. *Isopleth diagram of the time development of spectral energy density. Values for frequencies less than 0.04 Hz are not included.*

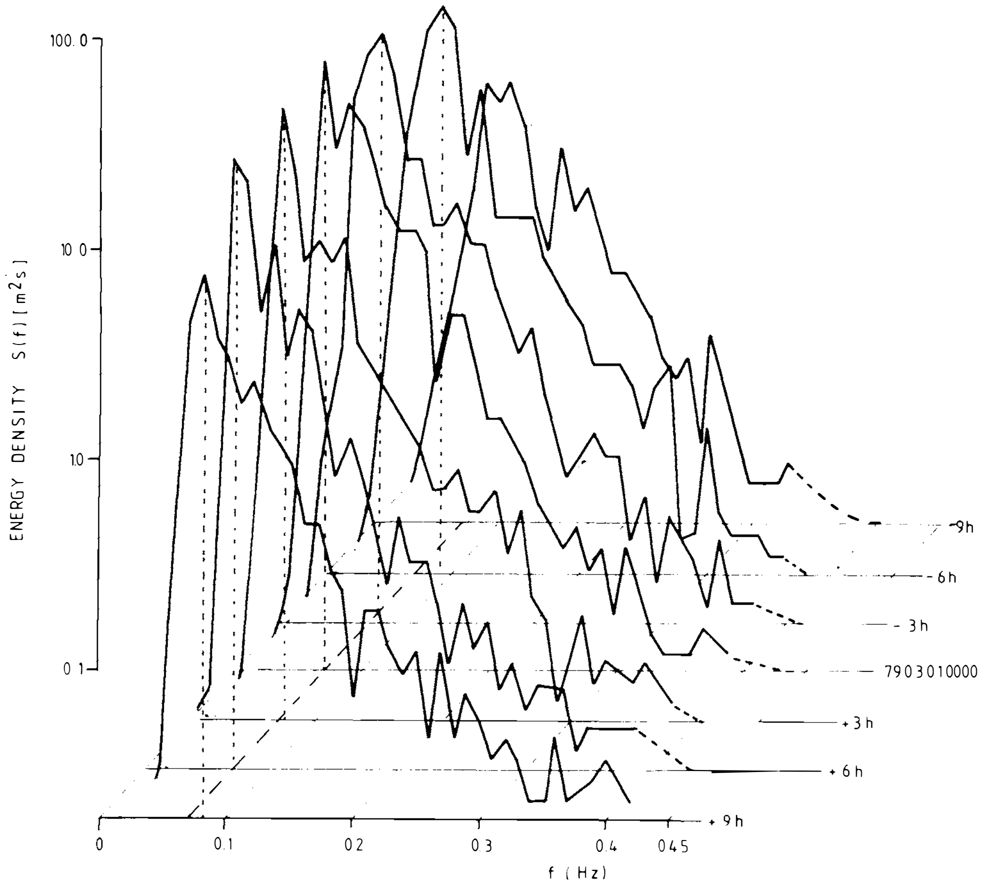

Fig. 12. *Wave spectra development in the storm on 28 February — 1 March 1979 at Bouvetøya.*

Storm conditions

There are two storm situations with wind speeds above 30 knots. Simultaneous values of wind speed and direction and significant wave height (H_{4RMS}) for these periods are shown in Fig. 15. From 11 to 12 February the wind speed was 20 – 30 knots, strong breeze to near gale. The significant wave height was between 2.5 and 5.5 m. From 28 February to 1 March the wind speed increased from 20 to 45 knots, strong breeze to strong gale. The significant wave height increased from 3 m to 6.7 m in 12 hours. The spectrum development of this storm is shown in Fig. 12.

Wave statistics

The joint distribution of H – T and $H_s - T_z$ is shown in Figs. 6 and 7. The amount of samples is too small to perform long-term statistics, but some distribution phenomena and characteristics can be deduced.

The highest measured wave, which had a height of 10.4 m and a period of 11.6 seconds, occurred during the storm on 28 February. The distribution of T

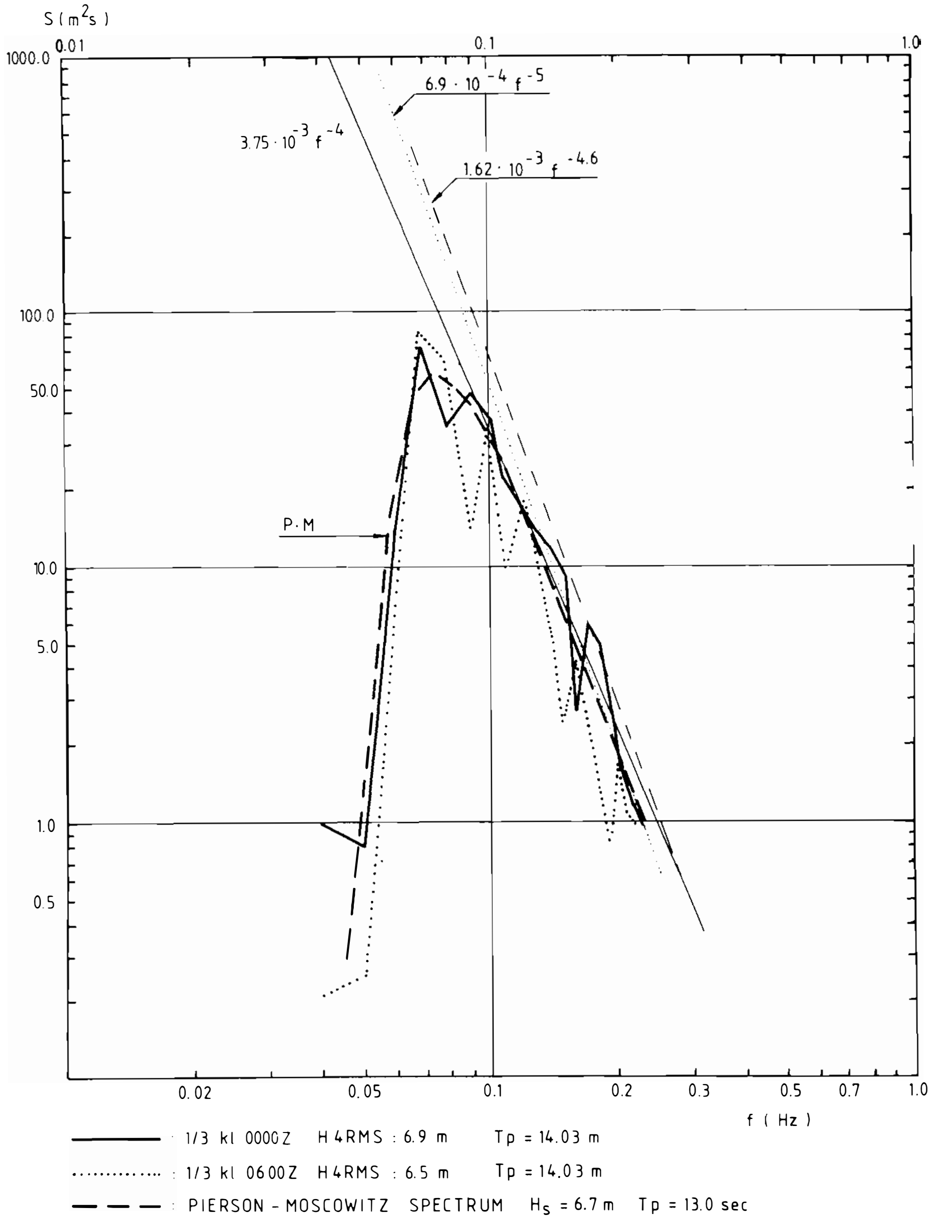

Fig. 13. *Comparison between registered storm wave spectrum on 1 March 1979 and the parameterized Pierson-Moscowitz spectrum which is chosen by a best curve fit method.*

is shown in Fig. 6. When we disregard waves with periods above 18 seconds, 1.4% of the waves have periods longer than 15 seconds and 35% greater than 8 seconds. The highest significant wave height, 6.7 m, was recorded at the same time as the highest measured wave. The corresponding periods were $T_s = 11.2$ sec, $T_z = 9.3$ sec, $T_p = 14.0$ sec. Values of T_s, T_z and T_p longer than 15, 12, and 17 seconds, respectively, have not been registered. 76% of the waves have

Frequency table of H_s in % as function of duration.

Wave height	$H_s \leq 2$ m					$H_s \leq 3$ m					$H_s \leq 4$ m				
Duration (hour) / Place & Period	3	6	12	24	48	3	6	12	24	48	3	6	12	24	48
Bouvetøya Feb 1979. Antarctic summer (from data)	21	20	16	15	10	77	75	73	73	43	90	90	87	85	69
Tromsø-flaket. Mean data summer 1977 and summer 1978	67	67	66	63	54	88	87	87	86	84	96	95	94	94	93
Tromsø-flaket. Mean data winter 77/78 and 78/79	21	21	18	12	4	60	59	57	53	44	80	79	78	76	70
Bouvetøya. Antarctic winter estimated on data from Tromsø-flaket.	7	6	4	3	1	53	51	48	45	23	75	75	72	69	52

Fig. 14. *Duration of sea state off Bouvetøya and comparison with results from Tromsøflaket (71°30'N, 19°00'E). The sea state off Bouvetøya during the Antarctic winter is estimated.*

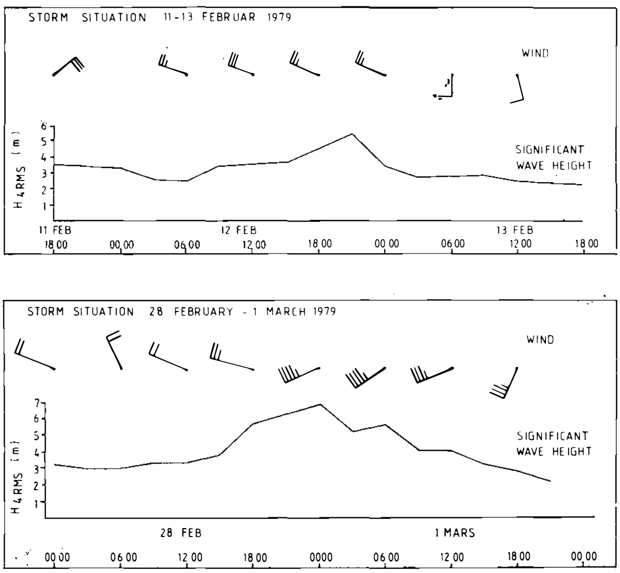

Fig. 15. *Simultaneous values of wind speed and direction and significant wave height during two storms.*

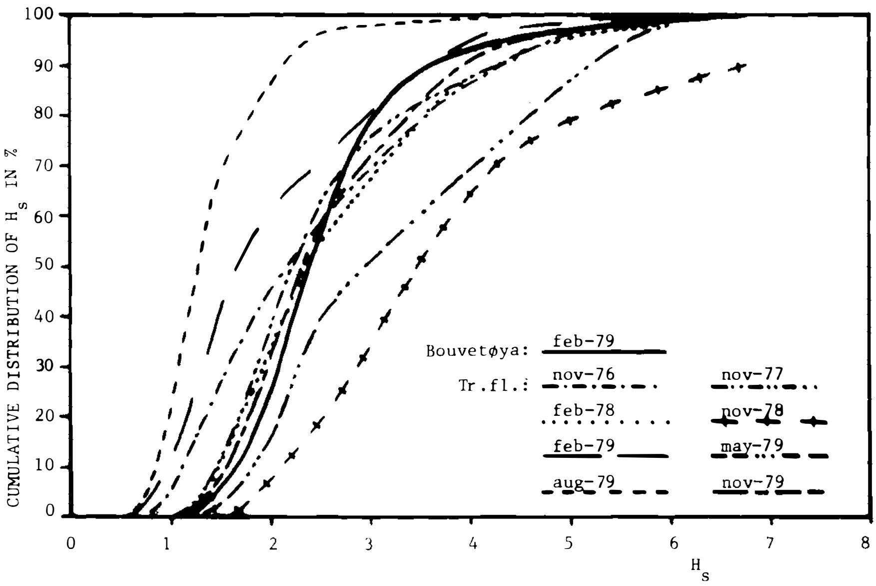

Fig. 16. *Comparison of distribution of H_s at Bouvetøya and at Tromsøflaket* (*Tr. fl.*).

8 sec < T_s < 11 sec, 74% have 6 sec < T_z < 8 sec, and 68% have 8 sec < T_p < 11 sec.

The spectral peakedness parameter Q_p seems to vary considerably (as shown in Fig. 8). 69% of the spectra has Q_p between 1.5 and 2.5, and this points towards the conclusion that the sea state can be described by a Pierson – Moskowitz spectrum in most cases.

The cumulative distribution of H_s at Bouvetøya is compared in Fig. 16 with the distribution of H_s at Tromsøflaket in different periods. It shows that the sea state at Tromsøflaket in November is similar to that registered at Bouvetøya.

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