Temperatures, steam emission and moss cover in thermal areas of Surtsey

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INTRODUCTION

In August 1972, four days were spent on Surtsey, 12-15/8. In the years after 1968, colonization by mosses on the island has been followed in detail (cf. Bjarnason and Fridriksson, 1972; Fridriksson, Bjarnason and Sveinbjörnsson, 1972; Fridriksson, Sveinbjörnsson and Magnússon, 1972a). The largest patches of danse moss cover are found in the thermal area of the island (cf. Magnússon, Sveinbjörnsson and Fridriksson, 1972). This does not mean, however, that the largest number of recorded localities with primary colonization by bryophytes are to be found within the thermal area.

At the beginning of 1972, I received the generous invitation of the Surtsey Research Society to come to Surtsey. My intention put forward at that time was to study microclimatic conditions in the thermal area in places where moss cover was present. The main question to be studied were the influence of heat, steam and windtransported material (accumulation and erosion) on colonization by mosses.

A "Grant multipoint temperature recorder, model D, was used for the temperature recordings. With this instrument, it is possible to record temperatures from 28 thermistor probes within 3 minutes, i.e., almost simultanously. The recordings are made automatically at intervals of one hour. Reading the recorded values, and calibration of the instrument, including the necessary use of a conversion chart, allows the measurement of temperatures to ± 0.2°.

The probes used during the measuring series were equipped with radiation shelters of aluminium foil. The full capacity of the instrument could not be used, as there were difficult problems with short circuit because of the permanent steam in the measuring areas.

Meteorological measurments in August on Surtsey (cf. Sigtryggsson, 1970) indicate a mean temperature of 10.7°, wind velocity at 2 m above ground level of 3.9 m/sec. (13 days) and precipitation of 25.4 mm (13 days).

MEASURING AREAS

A. A total of 13 probes were scattered within and in the vicinity of the so-called "Bell", which is a cave formed by tephra and accumulated sand. It has a W-facing entrance and a hole in the roof. The "Bell" is situated in the section J 13 (110 m above mean sea level) to the NE of the so-called Surtur I crater (cf. below). It is situated on a S-facing slope with an inclination of about 30%. In the area are numerous steam-emitting holes. Steam comes out continuously from places in and close to the cave. Moss cover is concentrated in the vicinity of the steam holes, in the interior of the cave and at the top of the cave where the sand is permanently moist. In this locality, sand covers 90-100% of the new lava (cf. Fridriksson, Sveinbjörnsson and Magnússon, 1972b).

B. A total of 21 probes were placed in the northern part of the crater "Surtur I" (local names cf. Thórarinsson, 1968) in the section L 12. This part of the crater has very many steam fissures and holes. There is continuous condensation of water in the area, and the accumulation of sands is considerable. 17 probes were placed within the crater; 2 probes on the northern rim; and 2 in a place with no steam emission, E of the rim. Moss cover is frequently present close to places of steam emission. The degree of cover

within sample plots of the size ¼ m² exceeds 50% in several places.

RECORDINGS

A. Locality: "The Bell".

Time period: 12/8 14.00-14/8 13.00 (1972).

Weather: 12/8 14.00, 100% cloud cover, winds from SE about 10 m/sec. In the night 12-13/8, strong winds and scattered rain showers. 13/8 12.00, generally 100% cloud cover, winds from W-SW, about 15 m/sec., scattered rain showers. 14/8 after 07.00, about 75% cloud cover, winds from S-W, 5-10 m/sec.

All measuring points (fig. 1: 1-5): Temperatures measured at intervals of one hour have been connected in the diagrams. Values from 13 probes will be discussed below. Mean, maximum and minimum temperatures refer to the whole measuring period of 48 hours. Probe numbers followed by (a) indicate that the position was below the soil surface, if followed by (b) the position was at the soil surface.

Probes 1a and 2b (fig. 1:1).

Position: Inside "the Bell". (1a ——) at the base of the northern wall, 1 cm below the soil surface in moist loose sand; (2b . . . . . .) same locality, at the surface.

1a. max. 19.0° min. 8.7° mean temp. 13.8°
2b. „ 14.8° „ 5.6° „ 10.5°

At short intervals steam is blown into the cave from the steam hole to the W and it is also emitted from the bottom of the cave. The steam keeps the sand permanently warmer than the air at the sand surface where steam is frequently removed by the winds blowing through "the Bell". Condensation of water is especially abundant on the N vertical wall in the cave, where the moss cover has the highest degreee of cover. — Bryophytes: *Atrichum undulatum, Leptobryum pyriforme.*

Probes 3a and 4b (fig. 1:2).

Position: Inside "the Bell". (3a ——) at the S wall, 1 m above the bottom of the cave, 1 cm below the surface in densely packed moist sand; (4b . . . . . .) same locality, sand surface.

3a. max. 26.0° min. 14.5° mean temp. 20.9°
4b. „ 22.5° „ 4.2° „ 12.9°

The sand is kept permanently warm by the penetrating steam. Air temperatures are much less, because of the rapid air circulation in the cave.

Probes 5b, 6b and 7b (fig. 1:3).

Position: 1 m to the W of the entrance to "the Bell". (5b — . . — . . —) 5 dm S of a stem hole: (6b . . . .) 8 dm S of the steam hole, (7b —.—.—) 10 dm S of the same steam hole. All the probes at the surface, hard surface with very little loose windblown sand.

5b. max. 26.2° min. 9.4° mean temp. 15.5°
6b. „ 20.4° „ 7.4° „ 11.0°
7b. „ 23.1° „ 8.0° „ 11.7°

Size of the oval steam hole at the opening, 15-20 cm in diameter. Hot steam is continuously blown out, generally in a southward direction down the slope. The steam moves continuously over a narrow field from the opening of the hole to 5 dm to the S of it. The field between 5-8 dm is less in contact with the steam and is wetted by the condensation of water from the cooled steam. During windy weather the steam is frequently forced down by the winds on to a small area to the S of 6b, which explains the higher maximum and minimum and mean temperatures at probe 7b than at 6b. There was less wind after 07.00 14/8 and the steam could not then reach probe 7b so easily. — There is moss cover in a narrow band from 5-8 dm to the S of the steam hole. — Bryophytes: *Bryum argenteum, Funaria hygrometrica.*

Probes 8a, 9a, 10b and 11b (fig. 1:4).

Position: To the N of the opening in the roof of the cave. (8a ——) in densely packed sand 5 cm below the surface, 2 dm to the N of the edge of the opening in the roof of the cave, (9b . . . . .) same locality but at the surface, (10a — — — — —) in densely packed sand 5 cm below the surface, 8 dm to the N of the edge of the opening in the roof of the cave, (11b —.—.—.—) same locality but at the surface.

8a. max. 44.6° min. 33.4° mean temp. 39.0°
9b. „ 27.2° „ 7.8° „ 18.0°
10a. „ 39.0° „ 30.0° „ 34.3°
11b. „ 31.2° „ 8.8° „ 17.4°

Steam permanently warms the sand of the roof of the cave. The air at the surface is, however, cooled down by the permanent turbulence round the cave. Slightly higher maximum and minimum temperatures at 11b than at 9b might be explained by random downward movement of the steam by the winds. There is moss cover between 9b and 11b where moisture is provided by the cooled steam. — Bryophytes: *Funaria hygrometrica, Dicranella crispa.*

Probes 12a and 13 b (fig. 1:5).

Position: 5 m SW of "the Bell" between small steam holes. (12a ——) 5 cm below the surface in densely packed sand; (13b . . . . .) same locality at the surface.

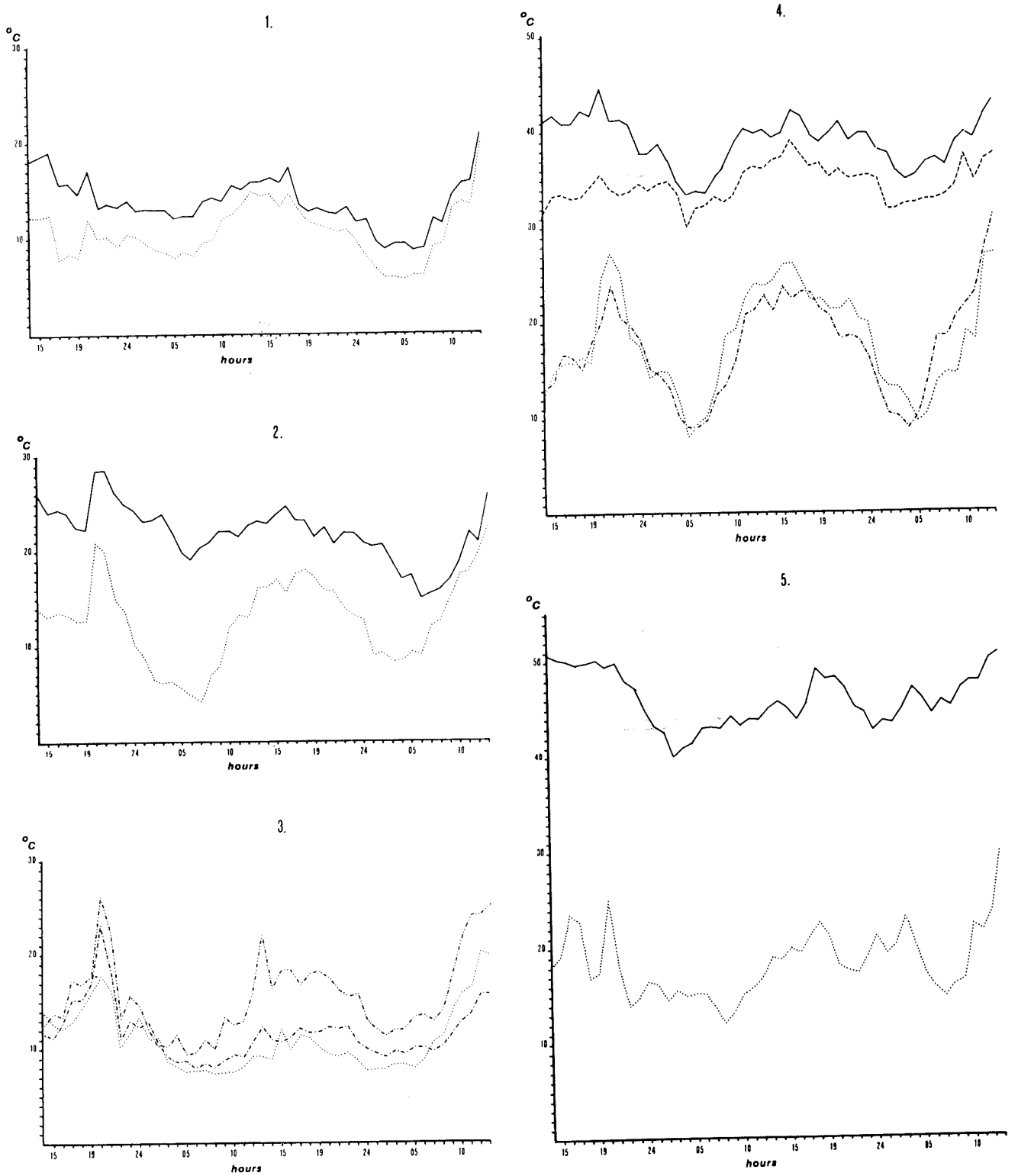

Fig. 1:1—5. Temperatures recorded with 13 thermistor probes at intervals of 1 hour, inside and close to "the Bell", section J 13 in the thermal area. (The position of the probes is described in the text).

12a. max. 50.8° min. 41.1° mean temp. 46.1°
13b. „ 28.8° „ 12.1° „ 18.2°

These were the highest maximum, minimum and mean temperatures recorded with soil thermistors within the area. Turbulence in the air strata close to the ground is most efficient in the locality, but the high soil temperatures mean that 13b recorded the highest minimum temperatures of the air thermistors in the area. — Bryophytes: *Bryum argenteum, Pohlia albicans.*

Comments: Temperatures in the thermal area in and around "the Bell" are already comparatively high at a depth of 5 cm in loose sand or in tephra. They are characterized by rather small diurnal amplitudes. Low air temperatures at night seem to have only a small effect on the ground temperatures, which are regulated by the hot steam penetrating from below. The diurnal temperature amplitudes are thus much larger at the soil surface as shown, especially clearly by the probes of fig. 1:4. In the temperature gradients indicated by Jóhannesson (1972, p. 129 ff.), there is no information about temperatures between 0-20(30) cm depth. His curve of point 11 ("the Bell") indicates temperatures of only 35° at a depth of 30 cm, which seems to be much too low for this area (cf. also Jakobsson 1972, p. 122).

B. Northern part of "Surtur I" (70-72 m above sea level).

Time period: 14/8 14.00–15/8 13.00 (1972).

Weather: 14/8, 14.00 to 18.00, 75-100% cloud cover, winds 5-10 m/sec. 15/8, after 04.00, winds below 5 m/sec. and 75-100% cloud cover.

All measuring points (fig. 2:1-9): Temperatures measured at intervals of one hour have been connected in the diagrams. Values from 21 probes will be discussed below. Probes with numbers followed by (a) are situated below the soil surface and those by (b) at the surface.

Probes 1a and 2b (fig. 2:1).

Position: 2 dm above vertical oval opening with steam emission. Diameter of the hole is 10-15 cm. (1a ——) 1 cm below the surface in loosely accumulated moist sand; (2b . . . . .) same place at the surface.

1a. max. 25.6° min. 7.1° mean. temp. 17.1°
2b. „ 24.3° „ 9.1° „ 19.9°

Steam emission in the vicinity of the hole during the morning hours with rather light winds clearly increases the temperatures in the air close to the ground surface above the temperatures in the sand. Between 14.00-24.00, the winds blow the steam downwards in a SW direction from the hole (cf. probes 12a and 14b).

Probes 3a and 4b (fig. 2:2).

Position: 3 m SW of the same steam hole as above. (3a ——) 1 cm below surface in moist, fine, densely packed sand; (4b . . . . .) same place at the surface of the sand.

3a. max. 19.2° min. 12.2° mean temp. 14.5°
4b. „ 18.7° „ 8.9° „ 12.4°

The winds do not continuously blow the steam as far as 3 m from the hole. Sand temperatures are thus almost continuously higher than air temperatures. Values should be compared with the lower values recorded at 15a and 17b, at the same distance from the steam hole but in a place with loose sand where the percentage content of fine grain material is small and penetration of steam is apparently easier.

Probes 5a and 6b (fig. 2:3).

Position: 5 m E of rim of the crater, on slope facing E. (5a ——) 1 cm below the surface in dry loose sand; (6b . . . . .) same place, at the surface.

5a. max. 17.9° min. 8.7° mean. temp. 11.3°
6b. „ 18.5° „ 7.9° „ 10.1°

Lowest minimum and maximum air temperatures recorded within the area. Comparatively low minimum temperatures and the lowest maximum temperatures recorded at a depth of 1 cm in the area. The lowest mean temperatures were at these probes.

Probes 7a and 8b (fig. 2:4)

Position: Rim of crater, 1 m to the E of steam hole mentioned above and 5 m W of position of 5a and 6b. (7a ——) 1 cm below the surface in moist sand; (8b . . . . .) same place, at the surface.

7a. max. 18.5° min. 10.7° mean temp. 13.0°
8b. „ 19.7° „ 9.6° „ 13.0°

During morning hours with light winds, only slight influence of steam at probe 8b, much weaker than at 2b. Comparatively low minimum and maximum values at both probes. — Bryophytes: *Dicranella crispa, Leptobryum pyriforme.*

Probes 9a, 10a and 11b (fig. 2:5).

Position: 3 dm W of steam hole (same as above). (9a ——) 1 cm below the surface in moist sand; (10a — — — —) same place, 5 cm depht; (11b . . . .) same place, at the surface.

9a. max. 27.2° min. 11.1° mean temp. 18.9°
10a. „ 32.2° „ 21.3° „ 26.4°
11b. „ 27.6° „ 8.3° „ 16.7°

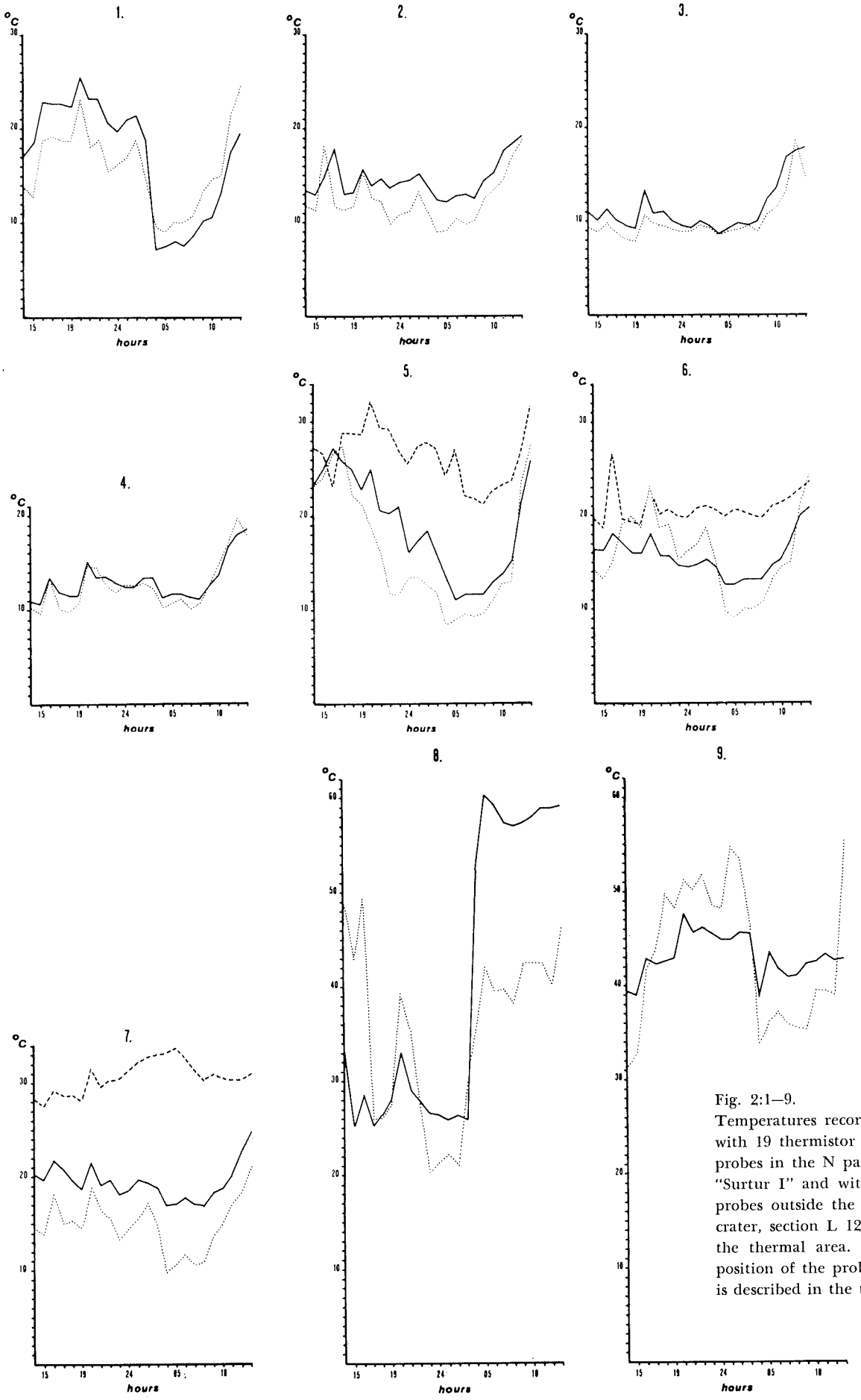

Fig. 2:1–9. Temperatures recorded with 19 thermistor probes in the N part of "Surtur I" and with 2 probes outside the crater, section L 12 in the thermal area. (The position of the probes is described in the text.)

There is a steep rise in temperature from the surface to a depth of 5 cm in the sand. — Bryophyte: *Pohlia nutans.*

Probes 12a, 13a and 14b (fig. 2:6).

Position: 1 m W of the steam hole. (12a ——) 1 cm below the surface in moist sand; (13a - - - -) same place, 5 cm depth; (14b . . . . .) same place, at the surface.

12a. max. 20.8° min. 12.6° mean temp. 15.7°
13a. „ 26.7° „ 18.8° „ 21.0°
14b. „ 24.4° „ 9.1° „ 15.8°

The three probes measured series of temperatures of special importance to the understanding of conditions close to steam emission holes. The increase of temperatures with depth of only 5 cm is very marked. The air temperatures at the surface are influenced by steam blowing down from the hole in the first half of the time period; during the second half the influence decreases as the wind decreases. A comparison of air temperatures at a distance of 3 dm and 1 m from the hole shows that the steam emerges from the hole in a steep upward direction and then is carried down by winds to the ground further away. These conditions were also observed at probes 6b and 7b outside "the Bell" (fig. 1:3).

Temperatures very close to a steam hole are evidently subject to larger and more frequent changes (cf. probes 9a, 10a, 11b) than at a longer distance from it. — Bryophyte: *Bryum argenteum.*

Probes 15a, 16a and 17 b (fig. 2:7).

Position: 3 m to the W of the steam hole (2 m W of 12a, 13a, 14b). (15a ——) 1 cm below the surface in moist loose sand deposits; (16a - - - - -) same place, at a depth of 5 cm; (17b . . . .) same place, at the surface.

15a. max. 24.8° min. 16.9° mean temp. 19.4°
16a. „ 33.7° „ 27.5° „ 30.6°
17b. „ 21.1° „ 9.8° „ 14.8°

The heat provided from below to the accumulated sand and to the air above in this thermal area depends on the depth of the deposited sand layer. There was a much thinner sand layer above the lava here than at a distance of 3 dm or 1 m from the steam hole.

Probes 18a and 19b (fig. 2:8).

Position: At a distance of 1 m W of the large steam hole, 10 cm from the opening of a small round steam hole with horizontal opening 3 cm in diameter. (18a ——) 1 cm below the surface in moist loose sand; (19b . . . .) same place, at the surface.

18a. max. 60.3° min. 25.2° mean temp. 40.3°
19b. „ 49.4° „ 20.1° „ 35.2°

Largest temperature ranges recorded within the area both in air and sand. The very large increase in temperatures between 03.00-05.00 can not be correlated with similar changes in conditions at the other probes. Temperatures very close to steam holes change rapidly and frequently (cf. 20a, 21b).

Probes 20a and 21b (fig. 2:9).

Position: At a distance of 1 m W of the big steam hole, 3 cm from 2 dm long narrow fissure in the sand. (20a ——) 1 cm below the surface in moist loose sand; (21b . . . .) same place, at the surface.

20a. max. 47.6° min. 39.1° mean temp. 43.1°
21b. „ 55.4° „ 31.3° „ 46.6°

Highest maximum air temperature recorded. Highest mean temperatures both in air and sand. — Bryophytes: *Pohlia albicans, Bryum argenteum.*

Comments The series of records have shown the same conditions as within the first described area: generally lower temperatures at the soil surface than at a depth of 1 cm in sand or tephra. The further increase in temperatures until the depth of 5 cm appears to be very steep. Strength and direction of winds influence air temperatures, in relation to the contribution of hot steam in localities close to steam emission holes. Depth of accumulated sand probably has an influence on amounts of heat penetrating up to the surface but not on the frequency and time of change in temperatures.

Steam from holes and fissures is apparently carried by the wind in a curve from the opening down to areas around, unless the winds are very weak. Amounts of steam emitted depend on the size of the holes; the direction of the steam depends on the inclination of the holes and the exposure of the situation to the wind.

DISCUSSION

Thermal areas on Surtsey locally provide suitable conditions for colonization by mosses. Such localities are situated in the vicinity of steam emission holes and fissures. In these places there are now coherent moss carpets with fairly large degrees of cover. The colonized areas are frequently distinctly limited, with few specimens growing outside the dense carpets.

Fig. 3. "The Bell", situated on the S facing slope to the N of the crater "Surtur I". Steam emission from several places in the area. — 14.88.1972. E. Sjn.

The steam provides heat and condensed water to areas close to the emission holes. It was supposed by Bjarnason & Fridriksson (1972, p. 10) that water condensed from the steam is a more probable explanation of the development of bryophyte diaspores than the heat. The stabilizing effect of the steam on the sand was also mentioned. This supposition can be further verified.

The large amount of heat with no steam emission provided to several places in the thermal area where mosses are absent supports this idea. There is an increase in heat towards the opening of big steam holes, but often a sharp limit of moss cover at some distance from them. However, high temperatures are tolerated around small emitting holes. The high temperatures, often reaching 60°C, are thus not likely to be able to support or to hinder the moss colonization.

Condensation of water takes place around the steam holes, up to a certain distance not generally reached by the steam. The steam is carried further from the holes during windy weather. The transport of steam from the holes with inclined openings seems to be always in one direction, even if winds are blowing towards the opening of the hole, For example, this was the case at the large steam hole at a distance of 1 m W of "the Bell" on 13/8, when strong SW winds were blowing. Steam was then first carried from the S-facing opening in a southwards direction, to nearly exactly the far limit of the moss cover situated to the S of the hole. It was then carried by the wind in a curve towards the N. The emission of steam from the holes during very windy conditions takes place in a curved direction in a way probably providing less steam and heat to places very close to the holes and more to a more distant area. These conditions have been illustrated by the temperature series both from "the Bell" and from "Surtur I".

The correlation between position of moss cover and contribution of steam — condensation of water — seems to be well-established. However, the reason for the absence of mosses in areas closest to big steam holes remains to be discussed. In that connection, the stabilization of sand and finer material by the condensed water should be

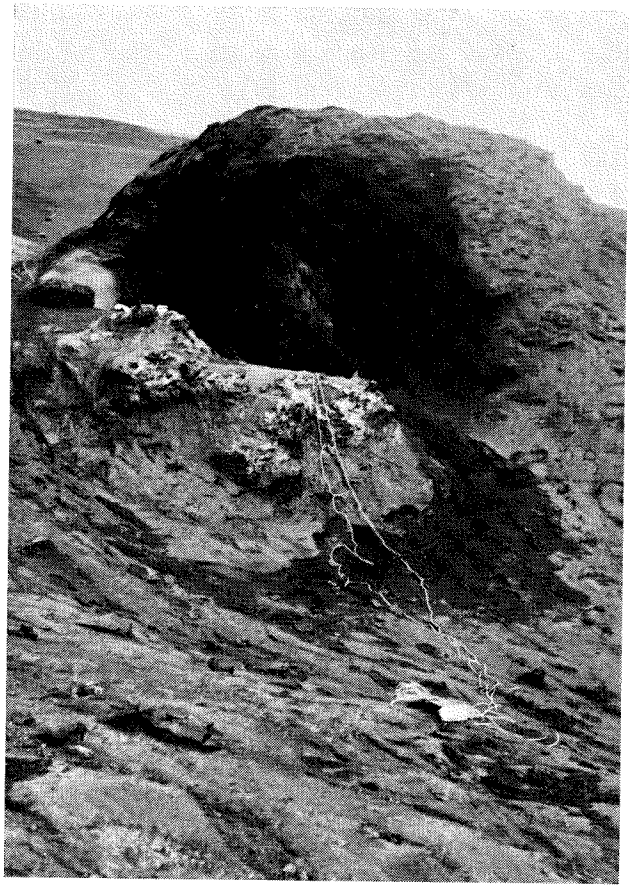

Fig. 4. "The Bell" seen from S (cf. temperature diagrams fig. 1:1—5). In the foreground, probes 12a and 13b (fig. 1:5). To the left, probes 5b, 6b and 7b (fig. 1:3), located 1 m W of the entrance to the cave and to the S of the steam hole. — 14.8.1972. E. Sjn.

Fig. 5. Northernmost part of "Surtur I" with temperature recording instrument (cf. fig. 2: 1—9). To the left, probes 18a, 19b, 20a and 21b (fig. 2: 8, 9). To the right, rim of crater, position of probes 7a and 8b (fig. 2:4). Behind the instrument, which was protected by a plastic envelope, are probes 1a, 2b, 9a, 10a and 11b (fig. 2:1, 5). — 15. 8. 1972. E. Sjn.

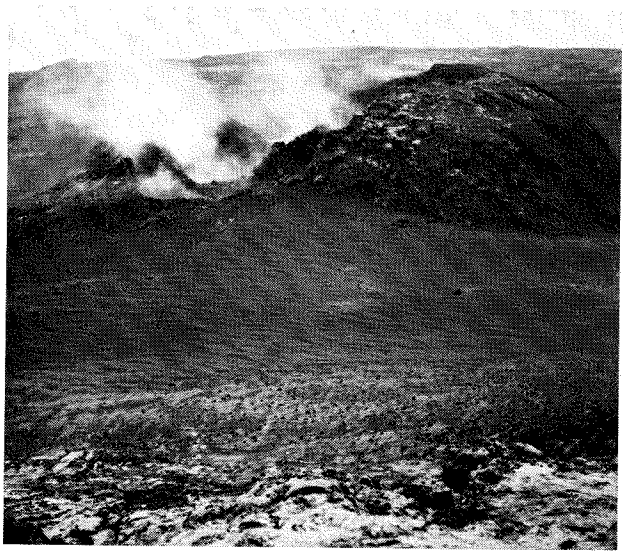

Fig. 6. "Surtur I" seen from the N from the slope just below "the Bell" The location of the temperature recording instrument is visible. Steam emission from the area is strong. — 15. 8. 1972. E. Sjn.

stressed. In the vicinity of the steam holes, there is often a building up of cones of accumulated material. The accumulation decreases away from the holes and drops rather abruptly to small amounts at the far limit of the general range of the steam. Just around the holes there is probably an accumulation of wind-transported material which is too rapid to allow diaspores of mosses to develop. Within the range of moss colonization, the water supply is certainly essential but also the stabilization of the substrate, with accumulation not rapid enough to lead to oversanding of the growing diaspores. Differences in accumulation of wind-blown material might be explained by a more permanent moistering of the zone nearest to the holes than in places further away, in the usual direction of movement of the steam emitted, where moss cover is present.

Outside the area reached by the steam, there is a lack of moisture and also frequent change between accumulation and erosion of deposited material. Such conditions are here unfavourable to the attachment and further development of moss diaspores.

The size of the steam emission holes and fissures regulate the amounts of steam provided to the surroundings. The accumulation of wind-blown material close to the holes and the building up of cones often means that the openings are inclined, situated on the slopes of the small cones. The emission of heat and steam takes place in one general direction. The development of a moss cover then depends quantitatively on the amounts of steam emitted; and its sitution depends on the direction of the steam outflow. A concentric coherent moss zone round steam holes is therefore rare. Moss cover is often observed within a narrow segment extending away from the holes.

Temperature records: One of the general features of the temperature sequences within the two measuring areas is the sharp increase in temperature from the surface down to a depth of 5 cm. There are also distinctly higher temperatures at 1 cm depth than at the surface. 5 m SW of "the Bell", the mean temperature at a depth of 5 cm in the tephra was within the temperature range (40-60°), earlier recorded in 1970 at a depth of 20 cm (cf. Magnússon - Sveinbjörnsson - Fridriksson 1972, p. 83). Temperatures recorded at a depth of 5 cm in "Surtur I" were also within the range of 20-40°, indicated from a depth of 20 cm for that area (op. cit.). The further very steep rise in temperature down to 60 cm was recorded by Jakobsson (1972, p. 122). His values seem to be more proable than those showing a much less steep gradient, obtained by Jóhannesson (1972, p. 135).

Weakening turbulence may for a short time increase the surface air temperatures close to steam holes above those measured at a depth of 1 cm in the sand, especially if the accumulated sand layer is deep. Diurnal temperature ranges at the surface are larger than within the sand or tephra. The ranges at 5 cm depth would in a larger number of series of records show comparatively very small diurnal ranges with changes not always correlated with day or night. The supply of heat to the air nearest the ground close to steam holes is parallel to the supply of steam — condensed water.

To sum up, moss cover on Surtsey is not favoured by heat supply. Localities are now numerous outside thermal areas. Mosses do not seem to be hindered from colonising habitats where there are continuously high temperatures. Lack of water is certainly limiting factor. Too much supply of water is, however, proably also unfavourable, because of the secondary effect of too rapid an accumulation of vind-transported material. A moderate water supply is required, with a favourable balance between accumulation and wind-erosion of supplied sand of finer material.

ACKNOWLEDGEMENTS

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