20. GROUND TEMPERATURES AT HORNSUND

Ground temperature (GT) is not a meteorological parameter *sensu stricto*; however, it carries information on heat exchange between the ground and the atmosphere. For this reason, it is useful to pass on basic information on behaviour of GT at Hornsund here.

Ground temperature at Hornsund is measured at five depths: 5, 10, 20, 50 and 100 cm below the ground surface. Measurements were made three times a day with bent-stem soil thermometers at depths 5, 10, 20 and 50 cm. At the depth of 100 cm, measurement was done with a thermometer with a large time constant were suspended in the plastic pipe once a day.

Together with measurement of ground temperature, the diurnal minimum air temperature above the ground was recorded. During the measurement period (July 1978 – December 2009)[1] the location of the instruments was changed once, when they were moved a few meters. The geologic and soil moisture conditions were the same at both points. In 2001 thermistor sensors were installed for measurements of ground temperature at depths of 5, 10, 20 and 50 cm; measurement at 100 cm is still made with the thermometer with a large time constant.

There are numerous observational gaps and breaks in the ground temperature measurements, many of them not simultaneous at the different levels. This makes statistically correct characterization of real changes during the observations impractical. Besides omission of the observations in the years, 1981–1982, the most frequent cause of breaks was damage to the thermometers or sensors and of the impossibility of changing them when they were frozen into the ground.

Ground temperature at Hornsund is reported in numerous papers. The most complete discussions are by Miętus and Filipiak (2001 a, b, 2004), based on sequences of observations from 1979–1999 and 1978–2000. The information below follows their methods and adds the data from 1999–2005 and 2007–2009.

The annual course of multiyear mean monthly ground temperature for 1990–2009 at the respective depths is shown in Fig. 20.1. These particular monthly observations do not contain more than three gaps in the term observations. Hence mean monthly values are calculated from 14 to 19 records for each month.

There is ground permafrost at Hornsund. The active layer (i.e. outer layer of annually thawing and freezing ground) is thawing on average for around four months in a year, gradually changing in its thickness. On average, passage of soil temperature through 0°C in the near to the surface layers (at the depth 5–10 cm) occurs sometime between the last decade of May and second decade of June. Ground temperatures reach their maximum in the middle of July. Chilling of the surface layer through 0°C occurs in the last decade of September – first decade of October. The timing the lowest temperature in the active layers is very variable. In different years of the period of record it has ranged from the second decade of January to the second decade of March. Maximum ground temperatures, recorded at the shallowest depth, 5 cm, range 13–14°C (recorded

[1] Measurement of ground temperature at the depth of 100 cm was started in 1980 (Miętus and Filipiak 2001).

a few times), and minimum ground temperatures have ranged from –24 to –26°C. Maximum mean monthly GT ranges from 7 to 9°C, minimum from –19 to –17°C. Such values of mean monthly GT at the depth of 5 cm should be treated as extreme.

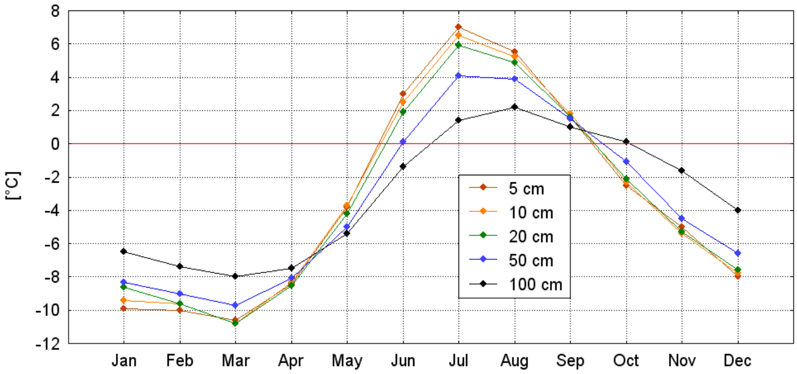

Fig. 20.1. The pattern of multiannual mean monthly ground temperatures at the depth of 5, 10, 20, 50 and 100 cm at Hornsund, based on data for the period, 1990-2009.

Changes of GT at the depth of 100 cm show a clear time lag behind the near surface layer. Ground temperature at this depth passes through 0°C around 3–4 weeks later, reaching its maximum in the second or the third decade of August. On average GT at 100 cm is higher than 0°C for around 3.5 months. In around half of recorded cases the minimum temperature at 100 cm was not delayed for more than 1–2 weeks after the minimum in the near surface layer. Both lowest temperatures occur in the month of March. For 2000–2005 the mean annual temperature of the top one metre of the soil (0–100 cm)[2] considered as a whole was –3.9 (±0.56)°C. In 2007–2009 this temperature increased to –2.3 (±0.76)°C. The striking trend of monthly GT at 5 and 100 cm over this period is shown on Fig. 20.2 for a time lag of one month in maximum of ground temperature at the depth of 100 cm in relation to 5 cm, while most often there is near-synchronous occurrence of minima at both depths.

Mean annual values of GT in 2000–2009 at 5, 10, 20, 50 and 100 cm were –2.88(±0.40)°C, –2.93(±0.41)°C, –2.70(±0.41)°C, –2.62(±0.46)°C and –2.66(±0.32)°C, respectively. If the standard errors of estimation are taken into account, the differences between them are not statistically significant. These values are significantly higher than the annual means for 2000–2005 (Marsz 2007 b).

The monthly values of ground temperature at particular depths show essential differences in the range of their variability, steadily shrinking with increasing depth (Fig. 20.3). Such regularity is typical for behaviour of ground temperatures.

In the first, or more often, in the second decade of September, there is a quasi-isothermal state in the vertical profile of the ground. Ground temperature at all levels is around +1(±0.3)°C. In

[2] Calculated as: GT of the layer = $[0.1 \cdot TG_5] + [0.1 \cdot ((TG_{10} + TG_{20})/2)] + [0.3 \cdot ((TG_{20} + TG_{50})/2)] + [0.5 \cdot ((TG_{50} + TG_{100})/2)]$, where: TG_5 – ground temperature at the depth of 5 cm, TG_{10} – ground temperature at the depth of 10 cm, etc. Mean annual air temperature at Hornsund is –4.4(±0.25)°C.

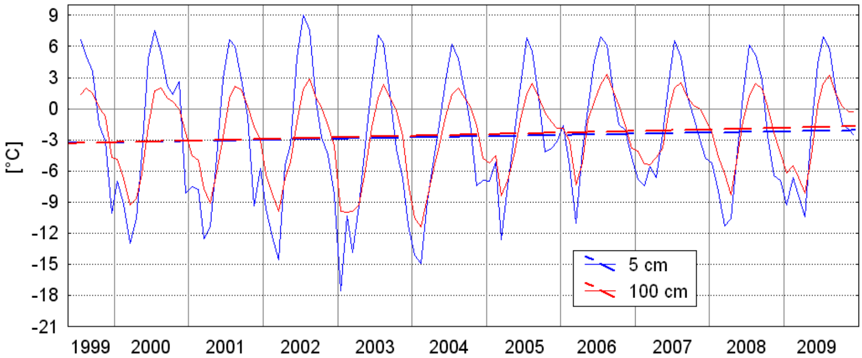

Fig. 20.2. Plot of monthly ground temperature at 5 and 100 cm, from June 1999 to December 2009.

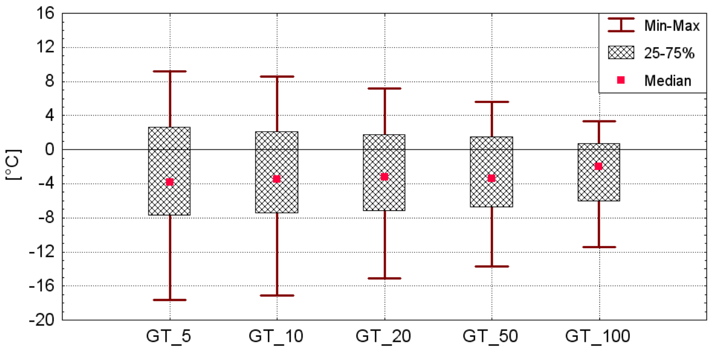

Fig. 20.3. Ranges of variability of monthly ground temperature (GT) at 5, 10, 20, 50 and 100 cm.

the third decade of September or the first decade of October temperature in the near surface layers becomes clearly lower than at depths of 50 and 100 cm. Usually on the turn of September to October GT passes through 0°C at the 50 cm depth. A dozen days later, early in October, the temperature falls below 0°C at the 100 cm depth. The state in which the vertical profile of GT shows increase of temperature with the depth is sustained on average until the last decade of April – turn of April and May. Then once again GT in the vertical profile becomes nearly isothermal, at around –6.9(±0.3)°C. From this moment, temperature in the near surface layer becomes higher than in the deeper layers of the ground. Passage of GT through 0°C at the depth of 100 cm follows on average in the last decade of June, although in some years it may be delayed for a dozen days (e.g. in 1998, when on June 30 GT at 100 cm was still –0.6°C, and in 2002 GT at the same depth passed through 0° only on July 4). The highest temperature recorded at 100 cm was +3.6°C. Occurrence of such a high GT has been recorded a few times during recent years (e.g. on August 1, 2006 and on August 10–12, 2009). Earlier such high temperatures were not recorded at this depth.

Miętus and Filipiak (2001 a, 2004) used two independent methods to estimate the maximum depth of ground thawing (i.e. thickness of the active layer) at the GT plot at Hornsund. From the equation of the first harmonic a depth of 185 cm was obtained (Miętus and Filipiak 2001 a). The second method (extrapolation of vertical profiles through the moments of occurrence of extreme values of GT; Miętus and Filipiak 2004) yielded a depth of 195 cm. The very good convergence of results by both methods allows us to judge that such estimates were close to reality in 1979–2000. After 2006 (Fig. 20.2) ground temperature increased at the depth of 100 cm. Estimates suggest that the zero isotherm in the middle of August 2009 could have been as deep as 210 (±20) cm below the surface. One may suppose that in the terrace on which ground temperature is measured at Hornsund in the last few years the thickness of the active layer has increased some 20–35 cm compared to the beginning of the 1990s. It does not appear however, that such changes of the thickness of the active layer support hypotheses of catastrophically rapid permafrost degradation at Hornsund.

The character of temporary changes of the depth of ground thawing shows the maximum thickness of the active layer at nearby Calypsostranda[3] behaving in a similar manner to Hornsund (Repelewska-Pękalowa and Pękala 2006). A maximum depth of seasonal thawing of 185–195 cm before 2002 at Hornsund is confirmed by measurements of active layer thickness at Calypsostranda, where none of the ten measurements of maximum depth of thawing before 2002 was greater than 186 cm. In 2005 and 2006 an abrupt increase of thawing depth was marked, four points at Calypsostranda giving maximum depths of 200 cm or more. At one point the maximum depth was as much as 225 cm, and in 2008 maximum depths of thawing decreased insignificantly (Pękala, personal communication). Increase of ground temperature in the region around the Polish Polar Station at Hornsund is a manifestation of regional changes encompassing all Spitsbergen (e.g. Humlum *et al.* 2006).

Mean monthly changes of GT at Hornsund show strong connections with the air temperature changes there (Miętus and Filipiak 2001). At depths 5, 10, 20 and 50 cm mean monthly values of GT show close correlations with monthly mean air temperature in the same month ($r = 0.97, 0.98, 0.97$ and 0.96, respectively). Changes of ground temperature at the depth of 100 cm from March to July are most strongly correlated with the air temperature of the preceding month. In August ground temperature at this depth correlates more strongly with the air temperature of the previous June ($r = 0.85$), than with the preceding July ($r = 0.77$). During the rest of the year correlations of GT at the depth of 100 cm become synchronous, those in November and March not being statistically significant. Influence of variance of air temperature on ground temperature variability is the strongest during the winter. This influence is considerably weaker during the summer (Fig. 20.4), closely correlated with great interannual air temperature variance in the cold season of the year but much smaller variation in the warm season.

Associations of soil temperatures with minimum air temperatures above the ground are not stronger than monthly mean air temperatures at the height of 200 cm. The strongest correlations between mean monthly minimum air temperature are with GT at the depth of 10 cm ($r = 0.98$). Correlations at depths 5, 20 and 50 cm are insignificantly weaker than this. Monthly GT at the depth of 100 cm shows the strongest correlations with mean monthly minimum temperature above ground in the preceding month.

Influence of the changeability of such climatic elements as cloudiness and sunshine duration on the variability of GT at Hornsund is irregular, reflecting the uneven impact of their effects. The

[3] An area of uplifted marine terrace on the western coast of Recherche Fjord (77°33.5'N, 14°30.7'E), 67 km NNW of Hornsund. On Calypsostranda, year-long measurements of ground temperature are not made, the maximum thickness of the active layer being determined by the method of ground sounding.

monthly mean variations of cloudiness affect changes of ground temperature considerably more strongly than changes of sunshine duration. One should remember, however, that cloudiness is one of the important factors controlling changes of air temperature, so that correlation between GT and cloudiness is also evident via the influence of air temperature changes. Sunshine duration shows positive associations of moderate strength with ground temperature at 5 cm only (exceeding the threshold of statistical significance), at the scale of diurnal means in the summer months (June, July, August). These associations are mostly non-significant between the monthly means. From February to May and in September and October they become negative (like the relationship of air temperature with sunshine duration). On average, increase of the duration of sunshine corresponds with a drop in ground temperature (Chapter 7). Cloudiness shows statistically significant positive correlations with temperature of the soil layers near to the surface from September to April. In May this relation is still positive but loses statistical significance. In June, July and August the relationship shifts to the negative, becoming statistically significant at depths of 5, 10 and 20 cm in July.

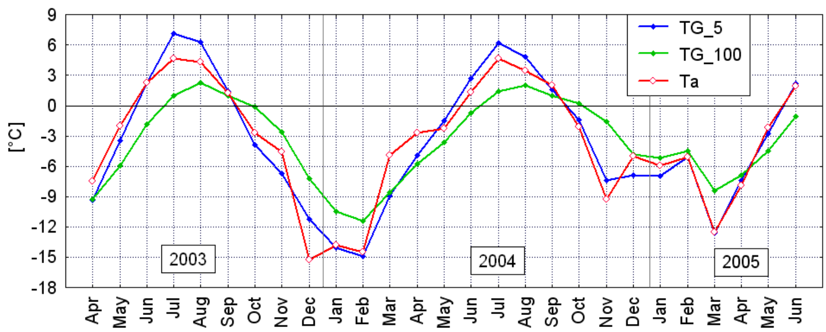

Fig. 20.4. The course of monthly air temperatures at Hornsund (Ta) and ground temperatures at the depths of 5 cm (GT_5) and 100 cm (GT_100) in April 2003 – June 2006.

Ground temperature at the scale of monthly means also shows associations with the monthly totals of precipitation. At the depth of 5 cm temperature from September to April is positively correlated with precipitation totals. In some of these months these relations become statistically significant[4]. The strongest positive relationship with monthly total precipitation is found in September ($r = +0.74$, $n = 15$). From May to August the character of the relationship changes; negative correlations begin which become statistically significant in July ($r = -0.58$, $n = 19$), and at the depth of 10 cm in July and August ($r = -0.68$ and -0.51, respectively; $n = 18$). These associations continue to the depth of 100 cm; there, GT in August shows statistically significant correlations with precipitation totals in July and August, GT in September negatively correlates significantly with precipitation totals in August and positively correlates with precipitation totals in September. Occurrence of negative correlations between GT and the monthly precipitation totals in the warm season of the year may be connected with the increase of heat losses due to evaporation from the

[4] Lengthening of the observation series would mean that in all of the months mentioned, excluding may be January, they would be significant.

soil surface. Also it should be taken into account that increase of monthly precipitation totals is accompanied by increase of cloudiness. Positive relations of ground temperature with precipitation totals in the cold season of the year most probably result from control of long wave radiation by cloud cover to a greater degree than from the insulating effects of the snow cover.

On average in a year, monthly ground temperature at the depth of 5 cm is 0.27 deg higher than annual air temperature measured in the instrument shelter 200 cm above the surface. In the warm season such a state is the rule; in June on average GT is higher than air temperature by around 1.3 deg, in July by 2.4 deg and in August by 1.4 deg. In September the average difference between GT at 5 cm, and mean air temperature falls to zero, in the Septembers of particular years fluctuating only in the range of a fraction of a degree above or below it. In the other months although temperature differences are most often positive, negative differences of temperature do occur (soil at 5 cm is colder than the air). Negative differences are most often recorded in October – January and in March – May. Appearance of such differences between ground and air is evident when after a month or more of low air temperatures there are one or few advections of clearly warmer air in the ensuing month. An extreme example of such cases occurred in March 1998, when mean monthly ground temperature at 5 cm was 2.6°C lower than the air temperature. Previously, in January 1998, air temperature dropped to –15°C (GT = –9.9°C); in February the temperature was again lower at –16.1°C and GT declined to –14.1°C. The mean March GT (–13°C) thus did not "lag behind" the increase of mean air temperature to –10.4°C. From the average differences between ground temperature at 5 cm and air temperature at screen height of 200 cm, a consistent heat flux from the ground to the atmosphere is evident from June to August inclusive. In other months heat fluxes may change signs depending on the course of preceding and current weather conditions.

The variability of snow cover thicknesses causes substantial additional non-periodic variations of ground temperatures at Hornsund. The snow cover protects the ground from drops of temperature to a lesser degree, because of its generally limited thickness over much of the winter, than the increase of the snow cover at the end of winter and in the spring causes extension of the winter conditions (Miętus and Filipiak 2001 a, b, 2004). This clearly delays the increase of ground temperature and decreases depth of the summer thawing of the ground (Dolnicki 2002, 2005).

Over the course of the annual ground temperature record at Hornsund Miętus and Filipiak (2001 a, b, 2004) found a tendency for positive changes with the passage of time. In 1979–1999 ground temperature increased by 0.125°C per year at the depth of 10 cm (a statistically significant increase; $p < 0,05$), 0.094°C per year at 20 and 50 cm, and 0.089°C per year at the depth of 5 cm. The highest annual GT in this period was recorded in 1991, temperature at all measured depths becoming higher than –2°C. The lowest annual GT was recorded in 1981, when at all depths annual ground temperature[5] was lower than –8°C (Miętus and Filipiak 2001 a, Fig. 10).

This tendency of increase of ground temperature was seen up to the year 2000, when at the depth of 5 cm a mean annual temperature of –2.4°C was recorded, at 10 cm it was –3.0°C, at 20 cm –3.4°C and at 100 cm –2.9°C[6]. In the ensuing years (Fig. 20.2) despite maintaining the high values of GT in July and August, negative temperatures started to intensify in the winter months.

[5] Observation data from this year raise doubts.

[6] For the depth of 50 cm lack of data.

As a result, mean annual GT ceased to increase and in 2003 drastically decreased (mean annual T at depths of 5 and 10 cm was –5°C, and at 100 cm was –4.4°C). In general, over 2000–2005 a weak decreasing tendency of GT emerged. All trend coefficients decreased and despite the lengthening of the time series none of them exceeded the threshold of statistical significance at the 0.05 (pu = 95%) level. In the very warm year 2006 (mean annual temperature –1.5°C) and during the very mild winter of 2006/2007 ground temperatures increased again. In 2006 mean annual GT at all depths was higher than the temperatures of 1991 (the previous warmest) and also higher than any mean annual air temperature in the same year. At depths 5 and 10 cm ground temperature was –0.9°C, at 20 and 50 cm –1.0°C, and at 100 cm it was –1.3°C. After 2006, minimum ground temperatures at all depths stayed higher than in the preceding period (Fig. 20.2). Thanks to this, for the 1999–2009 period a positive sub-trend occurred again.

Overall, the 1983–2009 annual trends of ground temperatures are positive at all measuring depths but are not statistically significant. The strongest trend is at the 20 cm depth and amounts to +0.128 (±0.068)°C· yr^{-1}. The trend of annual GT at the depth of 100 cm is +0.100 (±0.51)°C· yr^{-1}. In the monthly means some statistically significant trends are recorded. At depths of 5 and 10 cm statistically significant positive trends appear for December (+0.28(±0.10) and +0.25(±0.10)°C· yr^{-1}) respectively. At the depth of 100 cm a statistically significant trend is found in August (+0.059 (±0.22))°C· yr^{-1}; $p = 0.015$) and September (+0.053(±0.016))°C· yr^{-1}; $p = 0.005$). Values of trends given here should be treated as approximate because they were calculated from incomplete temporal series.

Positive trends of ground temperature are a result of the increase of air temperature observed at Hornsund and presumably the increase of cloudiness. It is worth noting that the years 2004, 2005 and 2006, in which a general increase of ground temperature was evident, were characterized not only by increase of air temperature but also by strong increase of cloudiness. Statistically significant positive trends in December in the near surface temperatures may be connected with the shifting of the annual minimum air temperature from the first half of winter to its final phase, as discussed in Chapter 9. Significant positive trends of GT in August and September at the depth of 100 cm have a presumably more complicated genesis than merely the increase of air temperature in the summer period. They may be connected to a greater degree with the series of mild winters in the last few years, during which there was not strong cooling of the ground at this depth.