Chapter 3

RADIATION CONDITIONS

3.1. Cloud cover

The Arctic, and the area of Spitsbergen in particular, is one of the cloudiest places on the globe. It is connected with a very active cyclonic circulation (the Icelandic lows often reach Spitsbergen), and a high saturation of air with water vapour, which promotes the formation of *Stratus* (*St*) clouds and fog. The greatest degree of cloudiness occurs in the summer, mainly over the areas left by retreating sea ice (Førland et al. 1997; Kukla and Robinson 1998; Beesley and Moritz 1998; Przybylak 2003). The clouds also affect Arctic radiation conditions (Walsh and Chapman 1998). As the ice cover in the basin of the Arctic Ocean continues to shrink, more cloudiness is expected in the region due to the increased rate of evaporation and intensified transport of humidity in the middle and upper troposphere (Vavrus et al. 2011).

Cloudiness is one of the least analysed meteorological elements because it requires visual observation. Analysing satellite images of cloud cover is unreliable, considering the similar features of clouds and the snow and glacial surfaces prevailing in the Arctic.

Literature dealing with the Spitsbergen cloud cover is scarce. A few studies describe the cloudiness in the area of Hornsund (Kosiba 1960; Baranowski 1977; Pereyma 1983). Przybylak (1992) provides an overview of the frequency of occurrence of cloudless (clear), cloudy and overcast days in relation to the atmospheric circulation. A summary of the nephological conditions in that area can be found in the monograph '*The climate of the area of the Polish Polar Station in Hornsund*' (Marsz and Styszyńska 2007), in the Chapter '*Cloud cover and sunshine duration*' (Marsz 2007), where cloud amount and types of clouds over Hornsund are described in detail. As regards the area of Kaffiøyra, none of the expedition reports referred to in the monograph have devoted much attention to it.

3.1.1. Cloud amount

On the Kaffiøyra Plain, the degree of cloudiness (cloud amount) is determined using a scale of 0–10. The monitoring conditions are most favourable and the clarity of the air makes it possible to observe the clouds in a range of 100 km. Moreover, in the summer season fogs are not frequent.

The summers of 2010 and 2011 were different in terms of circulation conditions. In 2010 cyclonic patterns outnumbered (51.7%) anticyclonic patterns (39.7%) and the share of indefinite patterns was quite sizeable (8.6%). In 2011, on the other hand, Spitsbergen was more often under the influence of anticyclones (53.8%) than cyclones (44.2%), whereas indefinite patterns were recorded in just 1.9% cases (see Chapter 2 for more details).

The average cloud amount in 2010 (7 July–2 September) was 8.6 (Tab. 3.1). The greatest amount of clouds in ten-day periods occurred between 11 and 20 July (9.6), and the smallest between 11 and 20 August (7.8). Not a single cloudless day (C ≤ 2) was observed in the whole summer season, whereas there were 13 partly cloudy days and 45 cloudy days (C ≥ 8), including 23 days with an overcast sky.

Table 3.1. Average cloud amount (0-10) on the Kaffiøyra Plain in the summer seasons of 2010 and 2011

Year	7–10 Jul	11–20 Jul	21–31 Jul	1–10 Aug	11–20 Aug	21–31 Aug	Summer season	21 Jul–31 Aug
2010	9.4	9.6	8.5	8.8	7.8	7.9	8.6	8.2
2011		7.6	7.8	7.5	6.9	9.6	7.8	8.0

On the Kaffiøyra Plain, in both summer seasons there were sequences of overcast weather, lasting a few days, interrupted by periods of partly cloudy days (Fig. 3.1).

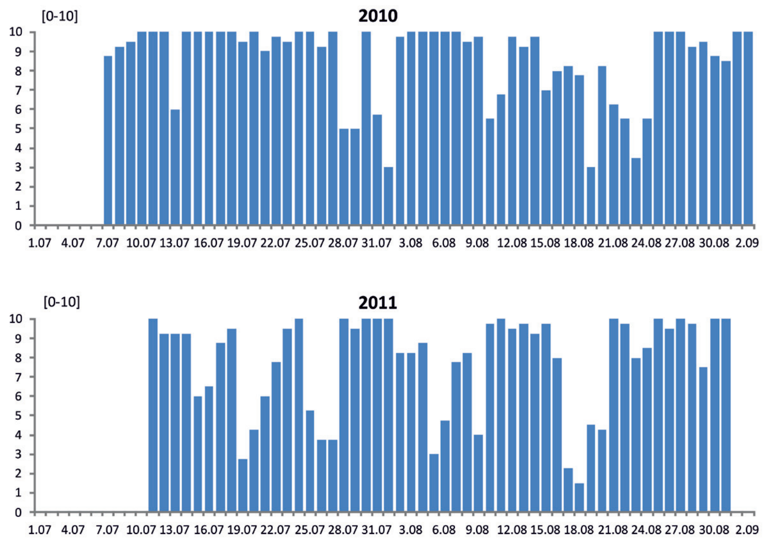

Figure 3.1. Cloudiness on the Kaffiøyra Plain in the summer seasons of 2010 and 2011

In 2011 (11 July–31 August) the average cloud amount was much smaller (7.8), however there were cloudy days, for example in the period of 21–31 August the degree of cloudiness reached 9.6, as well as sunny days with the cloud amount of 6.9 (between 11 August and 20 August). In the whole summer season there was one clear day, 16 partly cloudy days and 35 cloudy days, including 12 days of overcast weather. In the period from 21 July to 31 August the sky was slightly more cloudy in 2010 (8.2.) than in 2011 (8.0).

The smallest degree of cloudiness was characteristic of anticyclonic patterns (8.4 in 2010 and 7.5 in 2011), especially such as E+SEa (5.2 in 2011) and NWa+Na+NEa (7.0 in 2010 and 6.9 in 2011). A very high degree of cloudiness (9.9) occurred with Ca+Ka in 2010, but decreased to 7.0 in the subsequent summer season. With cyclonic patterns the cloud amount was greater, reaching an average of 8.6 in 2010 and 8.1 in 2011. The Sc+SEc+Wc type was particularly cloudy (9.8 in both years), just as in the case of Hornsund summers, when the greatest degree of cloudiness and the most cloudy days occurred with this circulation pattern (Przybylak 1992).

Table 3.2. Average cloud amount (0–10) and sunshine duration (h/day) by circulation patterns on the Kaffiøyra Plain in the summer seasons of 2010 and 2011

Circulation types*	2010			2011		
	Days	Cloudiness	Sunshine duration	Days	Cloudiness	Sunshine duration
NWa+Na+NEa	10	7.0	8.4	6	6.9	6.4
Ea+SEa	·	·	·	5	5.2	12.3
Sa+SWa+Wa	6	9.1	2.4	7	9.0	2.1
Ca+Ka	7	9.9	1.1	10	7.9	5.5
NWc+Nc+NEc	14	7.7	8.2	8	7.8	6.2
Ec+SEc	1	10.0	0.1	5	6.9	10.8
Sc+SWc+Wc	12	9.8	0.8	3	9.8	0.9
Cc+Bc	3	7.9	8.2	7	8.7	1.9
X	5	9.3	3.0	1	9.3	0.3
Antycyclonic	23	8.4	3.9	28	7.5	6.1
Cyclonic	30	8.6	4.5	23	8.1	6.4

Explanations: * - after Przybylak (1992); · - circulation type did not occur

3.1.2. Cloud types

The types of clouds occurring in the Kaffiøyra in summer depends on the processes in the atmosphere, both on the macro scale and locally. The barometric centre determines the cloud genera, therefore in anticyclonic weather high-level: *Cirrus (Ci), Cirrocumulus (Cc)* or medium-level: *Altocumulus (Ac)* clouds are formed. Intensive insolation leads to warming up of the ground surface, particularly in non-glaciated areas, to an unstable equilibrium of the air and 'cauliflower' clouds *Cumulus (Cu)*. At a low barometric pressure layered clouds are formed: *Cirrostratus (Cs), Altostratus (As)* and *Nimbostratus (Ns)* on the warm atmospheric front and *Ns, As* and *Cs* on the cold front. When the cold front moves rapidly, even *Cumulonimbus (Cb)* clouds may be formed. Kaffiøyra is often subject to an occluded front, where medium- and high-level clouds often occur. High air humidity and stable stratification (sometimes inverse) of the air masses inflowing over Spitsbergen support the formation of layered clouds *Stratus* and advection fog.

The analysed summer seasons differed in terms of their prevalent baromet-ric centres and direction of advection. In 2010 low pressure centres predominated, unlike in 2011 when the area was more often subject to high pressure centres. The consequence was the difference in the cloud genera occurring on the Kaffiøyra (cf. Tab. 3.3, Fig. 3.2). In 2010 the most common were *St* (33.9%) and *Sc* (31.4%) clouds, which are rather flat. In 14.6% of the observations *Ac* clouds were identified, whereas high-level clouds, such as *Ci*, *Cc* and *Cs* made up 8.7% altogether. Other identified cloud types included vertically-developed clouds, *Cu* (5.9%), and even *Cb* clouds in three cases (0.7%). *Cu* clouds are connected with intensive insolation and unstable equilibrium of the air over non-glaciated areas, as well as the circulation that develops on sun-warmed mountain slopes (valley breezes).

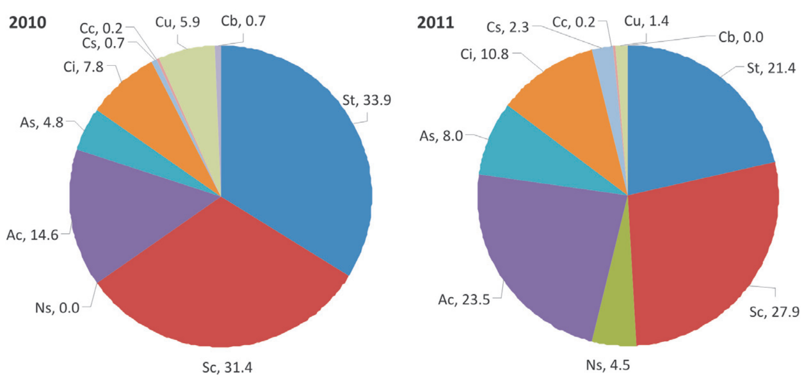

Figure 3.2. Frequency of occurrence (%) of different cloud types on the Kaffiøyra Plain in the summer seasons of 2010 and 2011

In 2011, the most common were *Sc* clouds (27.9%), followed by *Ac* clouds (23.5%). As compared to the preceding year, there were less *St* clouds (21.4%), but more high-level types (13.3%). *Cu* clouds were observed in just 1.4% cases, and no *Cb* clouds were identified. However, *Ns* clouds, which were not observed at all in 2010, occurred in 4.5% cases in the following year. Actually, in 2010 clouds of this genus were obscured by the *St* type. Just as in the case of the Hornsund area (Marsz 2007), an 'overrepresentation' of *St* clouds and an abundance of *Ac* clouds occurred on the Kaffiøyra.

Some of the cloud types demonstrated a diurnal pattern of occurrence, e.g. the *St* genus was more frequent at 1:00 am and 7:00 am than on 1:00 pm and 7:00 pm (Tab. 3.3). On the other hand, *Cu* clouds appeared more often at 1:00 pm and 7:00 pm. The reason was the changes of the surface thermal conditions and the atmospheric stratification, which was stable when the sun was low and became unbalanced in the afternoon and evening.

Table 3.3. Frequency of occurrence (%) of different cloud types on the Kaffiøyra Plain at main standard times (LMT) in the summer seasons of 2010 and 2011

Clouds	1:00		7:00		13:00		19:00		Mean	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
St	39.6	24.8	38.8	21.9	27.7	18.6	30.7	20.6	33.9	21.4
Sc	34.7	26.7	28.2	27.6	29.4	30.1	33.3	27.1	31.4	27.9
Ns	·	4.0	·	5.7	·	4.4	·	3.7	·	4.5
Ac	12.9	23.8	12.6	25.7	16.0	21.2	16.7	23.4	14.6	23.5
As	4.0	5.9	6.8	6.7	5.9	8.8	2.6	10.3	4.8	8.0
Ci	5.9	12.9	6.8	10.5	10.1	8.8	7.9	11.2	7.8	10.8
Cs	·	2.0	·	1.9	1.7	2.7	0.9	2.8	0.7	2.3
Cc	·	·	·	·	·	0.9	0.9	·	0.2	0.2
Cu	3.0	·	5.8	·	8.4	4.4	6.1	0.9	5.9	1.4
Cb	·	·	1.0	·	0.8	·	0.9	·	0.7	·

Explanations: · - type did not occur

In the area of the Kaffiøyra and on the whole of Spitsbergen, lens-shaped orographic clouds of the *Sc len* and *Ac len* (*lenticularis*) type are often observed. These occur on the lee side of mountain ranges. The surroundings of the Kaffiøyra are favourable for the forming of these types of clouds in different wind directions. The lenticularis clouds are the most often observed at an eastern advection (when the air masses flow over Spitsbergen) and when the wind blows from the west, crossing the mountains on Prins Karls Forland. The clouds occur everywhere on Spitsbergen, as it features considerable relative height differences, and are often observed in the area of Hornsund (Marsz 2007).

All of the cloud types that occur in the Forlandsundet area have been shown in Photographs 3.1 to 3.12.

Photo 3.1.
Cirrus
(Photo by A. Pospieszyńska)

Photo 3.2.
Cirrocumulus
(Photo by M. Kejna)

Photo 3.3.
Cirrostratus
(Photo by A. Pospieszyńska)

Photo 3.4.
Altocumulus
(Photo by A. Pospieszyńska)

Photo 3.5.
Altostratus
(Photo by M. Kejna)

Photo 3.6.
Nimbostratus
(Photo by M. Kejna)

Photo 3.7.
Stratocumulus
(Photo by M. Kejna)

Photo 3.8.
Stratus
(Photo by M. Kejna)

Photo 3.9.
Cumulus
(Photo by M. Kejna)

Photo 3.10.
Cumulonimbus, Cumulus and Altocumulus
(Photo by R. Przybylak)

Photo 3.11.
Orographic cloud Altocumulus lenticularis
(Photo by M. Kejna)

Photo 3.12.
Orographic cloud Stratocumulus lenticularis
(Photo by A. Pospieszyńska)

3.2. Sunshine duration

The duration of sunshine on the Kaffiøyra Plain was recorded using two heliographs located on the terminal-lateral moraine of the Aavatsmark Glacier, at 11 m a.s.l. The horizon in that location is favourable, as the sun is not obstructed throughout most of the summer season. Only at the end of August do the mountains in the north block the sunrays, which reduces the potential sunshine duration by 2-3 hours. The polar day on the Kaffiøyra occurs until 25 August, and then the day quickly becomes shorter (e.g. 19.4 hours on 31 August). At low angles the sun is often covered by clouds.

The pattern of sunshine duration reveals a substantial influence of cloudiness and other phenomena that limit the influx of solar radiation (e.g. fog). In the period of 7 July – 31 August 2010 the recorded duration of sunshine was 259.8 h. The last eleven days of August were the sunniest (76.8 h), whereas the cloudiest period was from 11 July to 20 July (24.5 h) – Table 3.4. The relative sunshine duration was merely 19.6%. The day with the longest sunshine duration was 1 August 2010 (18.7 h). In the whole summer season of 2010 no sunshine was recorded on 14 days altogether (Fig. 3.3).

Table 3.4. Actual (h) and relative (%) sunshine duration on the Kaffiøyra Plain in the summer seasons of 2010 and 2011

Period	2010		2011	
	hours	%	hours	%
7–10 Jul	15.4	16.0		
11–20 Jul	24.5	10.2	88.9	37.0
21–31 Jul	55.4	21.0	58.2	22.0
1–10 Aug	37.9	15.8	54.6	22.8
11–20 Aug	49.8	20.8	76.2	31.8
21–31 Aug	76.8	29.1	11.0	4.2
Season	259.8	19.6	288.9	23.5
21 Jul–31 Aug	219.9	22.3	200.0	20.2

In the following year, in the period from 11 July to the end of August 2011, there were 288.9 hours of sunshine and the relative sunshine duration reached 23.5%. The period of 11 July – 20 July was particularly sunny (88.9 h), whereas the least sunshine was recorded in the last eleven days of August (11.0 h). The days with the longest sunshine duration were 5 July and 20 August (22.3 h in both cases), and there were 23 days without sun (Fig. 3.3).

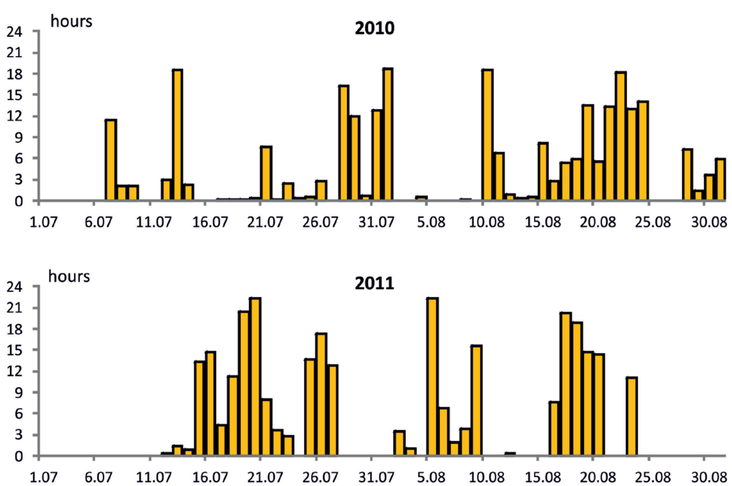

Figure 3.3. Sunshine duration on the Kaffiøyra Plain in the summer seasons of 2010 and 2011

In a diurnal course, most of the sunshine occurs at the highest positions of the sun over the horizon. For example, sunshine duration averaged 0.36 hours between 12:00 pm and 1:00 pm in the summer of 2010, and 0.27 hours between 1:00 pm and 2:00 pm in 2011 (Fig. 3.4). At the lower culmination the plausibility of sunshine is lower because of the low clouds and the mountains which obstruct the sunrays.

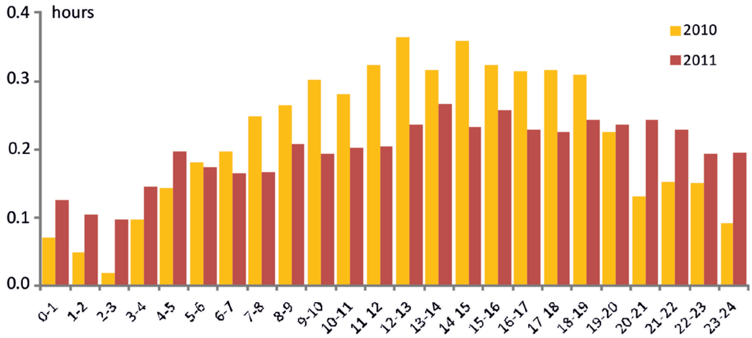

Figure 3.4. Diurnal courses of sunshine duration on the Kaffiøyra Plain in 2010 and 2011 (21 Jul–31 Aug)

In the comparable period of 21 July – 31 August, sunshine duration was somewhat longer in 2010 (219.9 h, 22.3%) than in 2011 (200.0 h, 20.2%) – Table 3.4. This was due to the type of prevalent atmospheric circulation. In 2010, the longest sunshine duration occurred with NWa+Na+NEa patterns (8.4 h/day), and Cc+Bc and NWc+Nc+NEc (8.2 h/day). In 2011, on the other hand, the longest sunshine duration was connected with an easterly and south-westerly advection (Ea+SEa– 12.3 h/day, Ec+SEc– 10.8 h/day). The smallest amount of sunshine was recorded with Sc+SWc+Wc pattern (less than 1 h/day) – Table 3.2.

3.3. Solar radiation

The radiation balance of the surface defines the Earth's energy budget, or the balance between the incoming and the outgoing shortwave and longwave radiation. When the balance is positive the surface becomes warm, and when losses predominate, it cools down. Therefore, the radiation balance affects the temperature of the surface and – indirectly – the temperature of the air and a number of other processes that occur in the atmosphere. It determines the heat balance of the surface, which in turn influences the thermal properties of the ground, such as the depth to which it will freeze over and thaw.

Measurements of solar radiation and the components of the radiation balance have been performed on Spitsbergen in a few regions only. In the area of the Polish Polar Station at Hornsund, actinometric observations were carried out by such researchers as Kosiba (1960), Baranowski (1977), and Pereyma (1983). In 1980-1981, the heat balance (including the radiation balance) of the active surface was measured by Głowicki (1985), whereas in the summer season of 1985 actinometric observations in the area of the Werenskiöld Glacier were carried out by Brázdil et al. (1988). In a study from 1993, Niedźwiedź presented the results of albedo measurements, and in 1997 Styszyńska compiled all solar radiation data available at the time and calculated the amount of total radiation on the basis of monthly sums of sunshine duration and cloudiness. The data series were subsequently extended to 2006 (Marsz and Styszyńska 2007). In 2009, Budzik et al. presented the results of measurements of the components of the radiation balance, taken throughout a whole year at Hornsund and on the Hans Glacier.

In the summer of 1988 and 1990, Prošek and Brázdil (1994) carried out actinometric observations in other areas of Spitsbergen – Barentsburg and Reindalen. In 2001, Gluza and Siwek (2005) studied the variability of albedo in the area of Calypsostranda. A study of the spatial diversity of the total radiation in the Wedel Jarlsberg Land was then developed using the r.sun model by Kryza et al. (2010). In NW Spitsbergen, observations of solar radiation are performed in Ny-Ålesund. Their results for 1981–1997 were collected in the study by Winther et al. (2002), and the relevant values were compared with satellite data (Ørbaek et al. 1999). Budzik (2004) analysed the Ny-Ålesund records for 1989–2003, and Kupfer et al. (2003) the components of the radiation balance for the period from 1992 to 2001. These observations were gradually extended to include the neighbouring glaciers, and Arnold and Rees (2009) measured the total amount of radiation on the Midtre Lovén Glacier, using a LIDAR.

In the Kaffiøyra region (Oscar II Land) actinometric measurements, especially as far as direct radiation is concerned, were initiated by Gabriel Wójcik in 1977 (Wójcik 1989) and continued during subsequent expeditions (Wójcik and Marciniak 1993, 2002). In 1999 the amount of albedo on the Waldemar Glacier was measured by Kejna (2000), whereas on the Aavatsmark Glacier the radiation balance in the spring season was determined by researchers from the University of Silesia (Caputa et al. 2002; Budzik 2003). In 2010, studies of the spatial diversity of the radiation balance were commenced as part of the AWAKE project (Kejna et al. 2011).

3.3.1. Research methodology

The radiation balance consists of the sum of shortwave radiation (K*) and of longwave radiation (L*), and is described in the full spectrum by the following equations (Oke 1996):

$Q^* = K^* + L^*; \qquad K^* = K{\downarrow} - K{\uparrow}; \qquad L^* = L{\downarrow} - L{\uparrow}$

$Q^* = (K{\downarrow} - K{\uparrow}) + (L{\downarrow} - L{\uparrow})$

where:

Q^* – net radiation balance,

K* – net shortwave solar radiation,
L* – net longwave solar radiation,
K↓ – incoming shortwave solar radiation (direct and diffuse),
K↑ – outgoing shortwave solar radiation, reflected by the active surface,
L↓ – incoming longwave radiation,
L↑ – outgoing longwave radiation, reflected by the active surface.

The net radiation balance (Q*) is diversified topoclimatically due to various characteristics of the surface, especially its albedo. Moreover, the transparency of the atmosphere changes with absolute height and the content of water vapour and aerosols in the atmosphere.

The actinometric measurements in the area of Kaffiøyra were taken using a Kipp&Zonen CNR 4 net radiometer, which consisted of two pyranometers and two pyrgeometers, facing upwards and downwards. This set up was used to measure the energy balance of the incoming shortwave and longwave solar radiation, and the outgoing shortwave and longwave solar radiation, reflected by the active surface. All of the instruments were calibrated and verified. The specification of the instruments is shown in Table 3.5. The CNR 4 is also equipped with a Pt-100 temperature sensor, used for the correction of longwave radiation. The instruments were not vented.

Table 3.5. Specification of Net Radiometer CNR 4 (Kipp&Zonen)

Specification	Pyranometer	Pyrgeometer
Spectral range	300-2800 nm	4500-42000 nm
Sensitivity	5 to 20 μV/W·m^{-2}	5 to 20 μV/ W·m^{-2}
Temperature dependence of sensitivity (-10ºC to +40ºC)	<4%	<4%
Response time	<18 s	<18 s
Non-linearity	<1%	<1%
Operating temperature	-40 - 80°C	-40 to 80°C
International standards (WMO)	Good Quality WMO	Good Quality WMO

The measurements were taken in four locations (Fig. 1.1) with different surfaces and absolute heights. In 2010 the sites were located as follows:

- Kaffiøyra-Heggodden (KH) - on the terminal-lateral moraine of the Aavatsmark Glacier, sparsely covered with tundra vegetation, 11.5 m a.s.l.
- Front of the Waldemar Glacier (LW1) – on a recent ground moraine, 10 m from the front of the glacier, 130 m a.s.l.
- Firn field of the Waldemar Glacier (LW2) – in melting snow and glacial ice, 375 m a.s.l. A review of the results (Kejna et al. 2011) showed little differences between the data from KH and LW1, therefore in 2011 the latter site was replaced by a measurement point in the tundra:
- Tundra (KHT) – in the tundra, 8 m a.s.l.

At all sites, the sensors were situated at a height of 2 m over the ground. In 2010, recording was carried out from 16 July to 31 August, and in 2011 from 21 July to 31 August. The individual radiation flux values were registered using a Logbox SD data logger at an interval of 1 minute. The data series at the KH and KHT sites were complete, however at LW1 and LW2 breaks occurred in the periods of 20-24 July 2010, and 2-9 August 2011, respectively. The missing data was provided by records from the KH site, using the strong linear correlation between the two measurement points. Using the radiation flux data, the total amount of energy, both incoming and lost in the surface, was calculated for intervals of 1 minute, 1 hour and 1 day. The albedo, the net shortwave radiation and the net longwave radiation were determined, and then their net radiation balance.

3.3.2. Results

Shortwave radiation

In the parallel period of 21 July–31 August of both years, the mean diurnal sum of incoming shortwave radiation (K↓) in the Kaffiøyra was comparable, and amounted to 11.12 MJ·m^{-2} in 2010 and 11.07 MJ·m^{-2} in 2011 (Tab. 3.6). Similarly, at LW2 the respective values were 10.59 MJ·m^{-2} and 10.36 MJ·m^{-2}. On the other hand, at LW1 K↓was 10.72 MJ·m^{-2} in 2010, and in 2011 (at KHT) – 11.14 MJ·m^{-2}. There are no significant differences between the comparable sites, except for LW2, where the values of K↓ were lower due to a greater cloudiness.

Table 3.6. Daily K↓ (MJ·m^{-2}) in the Kaffiøyra region in the summer seasons 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	10.31	8.30	10.67			
21–31 Jul	13.43	11.39	11.72	15.44	16.00	14.00
1–10 Aug	10.66	10.34	10.86	12.45	12.63	11.58
11–20 Aug	10.87	10.99	10.07	11.94	11.64	11.22
21–31 Aug	9.47	10.13	9.68	4.65	4.48	4.84
21 Jul–31 Aug	11.12	10.72	10.59	11.07	11.14	10.36

In the second half of the summer season, the amount of solar energy reaching the ground becomes smaller and smaller as the position of the sun lowers. For example, in 2011 at KH the sum of energy fell from 15.44 MJ·m^{-2}, in the period of 21–31 July, to 4.65 MJ·m^{-2} towards the end of August. Besides, periods of limited cloud amount were quite frequent, which created favourable conditions for the solar radiation to reach the ground, for example on 1 August 2010 the diurnal sum of K↓ at KH was 22.9 MJ·m^{-2}, and on 26 July 2011 even 25.51 MJ·m^{-2}. On cloudy days the diurnal sums of K↓ went below 5 MJ·m^{-2}, dropping to, for example, 2.20 MJ·m^{-2} on 29 August 2011 (Fig. 3.5).

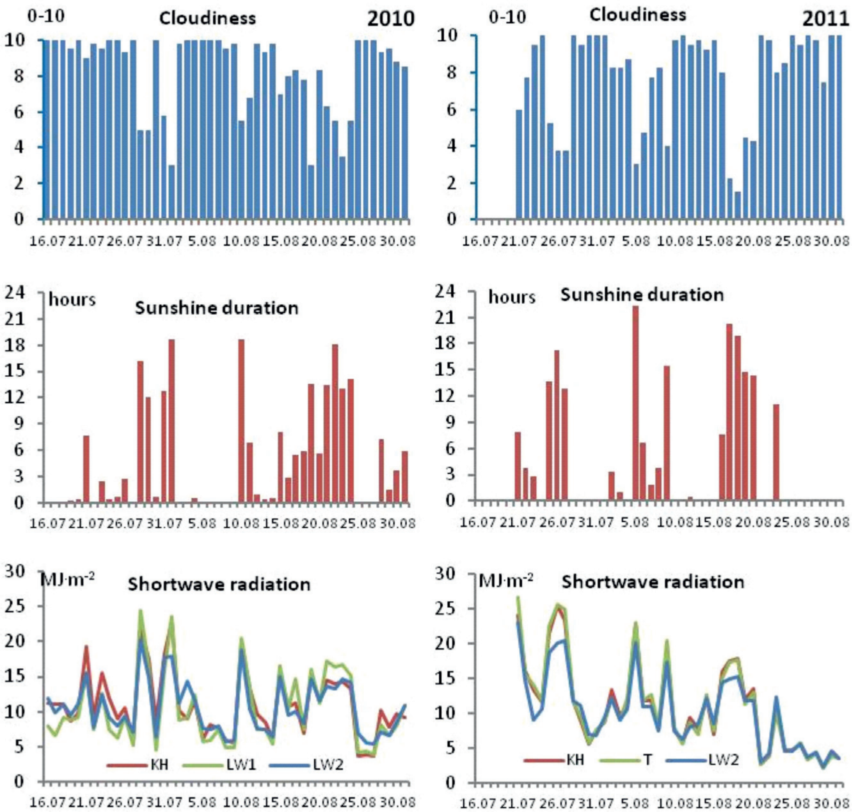

Figure 3.5. Courses of cloudiness (0-10) and sunshine duration (hours) at the KH site and diurnal sums of shortwave solar radiation (MJ·m^{-2}) at KH, LW1, KHT and LW2, in the summer seasons of 2010 and 2011

The maximum intensity of total incoming solar radiation reached 709 W·m^{-2} at KH in 2010, and the following year even 881 W·m^{-2} (Tab. 3.7). It was also high at the other sites, reaching 882 W·m^{-2} at LW1 (2010), 881 W·m^{-2} at LW2 (2011) and 805 W·m^{-2} at KHT (2011).

A portion of solar radiation is reflected by the surface. The average diurnal sum of outgoing shortwave solar radiation (K↑) in the Kaffiøyra in the two periods of 21 Jul – 31 Aug amounted to 1.66 MJ·m^{-2} in 2010, and 2.56 MJ·m^{-2} in 2011 (Tab. 3.8). Similar values (1.22 MJ·m^{-2} and 2.09 MJ·m^{-2}) were recorded at LW1 in 2010 and at KHT in 2011. At LW2, however, the values of outgoing radiation were much greater, reaching 7.25 MJ·m^{-2} in 2010 and 6.05 MJ·m^{-2} in 2011.This was due to the different reflective characteristics of the active surfaces, i.e. the moraine (KH, LW1), the tundra (KHT) and the snow and glacial ice (LW2).

Table 3.7. Maximum of K↓ (W·m^{-2}) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	709	299	364			
21–31 Jul	709	882	836	881	805	880
1–10 Aug	521	829	744	601	580	622
11–20 Aug	609	838	763	622	677	440
21–31 Aug	475	552	603	435	342	601
21 Jul–31 Aug	709	882	836	881	805	881

Table 3.8. Daily K↑ (MJm^{-2}) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	1.24	0.82	6.63			
21–31 Jul	1.85	1.41	7.54	2.56	2.09	6.05
1–10 Aug	1.46	1.28	4.93	2.37	1.75	5.49
11–20 Aug	1.57	1.60	7.11	2.33	1.58	6.38
21–31 Aug	1.38	1.47	5.37	0.79	0.61	1.70
21 Jul–31 Aug	1.66	1.22	7.25	2.56	2.09	6.05

Table 3.9. Albedo (%) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	13.0	10.6	62.6			
21–31 Jul	14.2	12.5	67.3	16.3	12.8	41.5
1–10 Aug	14.5	12.6	46.1	19.5	13.8	48.9
11–20 Aug	15.7	15.2	69.4	19.4	13.4	61.4
21–31 Aug	15.3	13.7	60.4	17.4	13.9	35.3
21 Jul–31 Aug	14.9	13.5	60.9	18.1	13.5	46.7

The amount of reflected radiation in relation to the amount of incoming radiation is called an albedo. At the KH site the average albedo was 14.9% in 2010 and 18.1% in 2011. It was slightly lower at LW1 and KHT (13.5% at each site) (Tab. 3.9). The highest value of albedo was recorded on the snow/ice cover of the firn field of the Waldemar Glacier (LW2). However, there were some differences in the analysed seasons: in 2010 the albedo reached 60.9%, whereas in 2011 it fell to 46.7%.This was connected with the degree of ablation, which caused the winter snow to melt quickly in 2011, and the uncovered blue ice was built up by dark rock material from the surrounding hills. Also, in 2010 summer snowfalls were more frequent, which increased the surface albedo (Fig. 3.6). After the snowfalls the albedo increased to 80-90%. Comparable results of albedo measurements on the firn field of the Waldemar Glacier were obtained by Kejna in 1999 (Kejna 2000). At that time, the albedo changed in the range from 40 to 75%, depending on the snowfalls and the extent of "contamination" of the glacier's surface by dust carried from the surrounding hills.

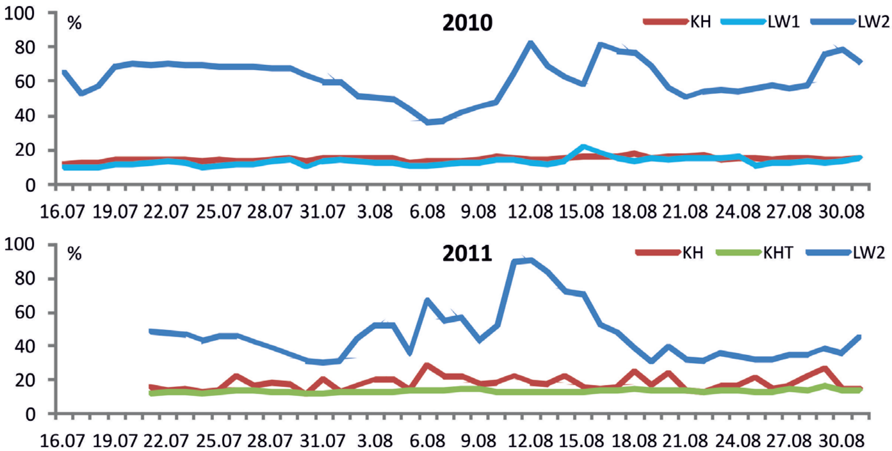

Figure 3.6. Courses of albedo in the Kaffiøyra region in the summer seasons of 2010 and 2011

Longwave radiation

The ground surface emits longwave radiation (L↑) to the atmosphere and the intensity of the radiation depends on the temperature of the active surface. The average diurnal sum of the upward terrestrial radiation, L↑, at the KH site amounted to 30.25 $MJ \cdot m^{-2}$ in 2010, and 30.30 $MJ \cdot m^{-2}$ in 2011 (Tab. 3.10). Higher values were recorded at KHT (31.28 $MJ \cdot m^{-2}$), and lower ones at LW1 (29.86 $MJ \cdot m^{-2}$) and on the firn field of LW2 (30.05 $MJ \cdot m^{-2}$ in 2010 and 28.54 $MJ \cdot m^{-2}$ in 2011).

A substantial portion of infrared radiation emitted from the ground surface is absorbed by the atmosphere and – in particular – water vapour, carbon dioxide and other greenhouse gases. In this way the atmosphere becomes a secondary source of longwave radiation. Some of the energy is returned to the surface as downward atmospheric radiation (L↓). The average diurnal sum of L↓ reaches 27-28 $MJ \cdot m^{-2}$, for example, at the KH site it was 27.26 $MJ \cdot m^{-2}$ in 2010, and 27.01 $MJ \cdot m^{-2}$ in 2011 (Tab. 3.11).

Table 3.10. Fluxes of L↑ (MJ·m^{-2}) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	30.85	30.05	30.47			
21–31 Jul	30.87	30.24	30.28	31.09	31.93	28.47
1–10 Aug	30.70	30.21	30.14	30.70	31.26	28.54
11–20 Aug	29.55	29.26	29.80	29.55	31.41	28.64
21–31 Aug	29.84	29.72	29.97	29.84	30.54	28.51
21 Jul–31 Aug	30.25	29.86	30.05	30.30	31.28	28.54

Table 3.11. Fluxes of L↓ (MJ·m^{-2}) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	29.30	29.27	29.09			
21–31 Jul	27.82	28.20	28.11	27.83	28.20	27.37
1–10 Aug	28.28	28.37	28.24	28.28	27.12	26.38
11–20 Aug	25.83	26.23	26.32	25.83	27.45	26.98
21–31 Aug	26.13	26.22	26.02	26.13	29.41	28.70
21 Jul–31 Aug	27.26	27.25	27.17	27.01	28.08	27.39

Radiation balance

In the Kaffiøyra region, between the moraine sites (KH, LW1) and the Waldemar Glacier (LW2) there are significant differences in net shortwave solar radiation (K*). In 2010 at KH the average amount of K* was +9.56 MJ·m^{-2}, and in 2011 +9.07 MJ·m^{-2} (Tab. 3.12). Similar values were recorded at LW1: +9.09 MJ·m^{-2} (2010) and KHT +9.64 MJ·m^{-2} (2011). The much less favourable values of K* were observed in the snow and ice areas, ranging from +4.31 MJ·m^{-2}at LW2 in 2010 to +5.40 MJ·m^{-2} in 2011. The reason for this was, firstly, the differences in the amount of incoming solar radiation due to cloudiness in the upper parts of the glacier, and chiefly the high albedo of that area.

The average values of net longwave solar radiation (L*) are negative and the greatest losses of radiation occurred on the coast: -3.05 MJ·m^{-2} in 2010 and -3.29 MJ·m^{-2} in 2011 at KH, and -3.20 MJ·m^{-2} at KHT in 2011(Tab. 3.13).The lowest values were recorded at LW1 (-2.61 MJ·m^{-2} in 2010) and at LW2 (2.89 MJ·m^{-2} in 2010 and -1.14 MJ·m^{-2} in 2011). Particularly low levels of longwave radiation occurred on sunny days, when the amount of radiation returned by heated surfaces was much greater than the amount of pure downward radiation from a clear, cloudless sky. On the other hand, the values of L* at LW2 and cloudy weather were small and, on some days, L↓ even exceeded the surface energy losses (L* became positive).

Table 3.12. Net shortwave radiation values (K*, MJ·m^{-2}) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	9.06	7.49	4.04			
21–31 Jul	11.58	9.98	4.18	12.88	13.92	7.94
1–10 Aug	9.20	9.06	5.93	10.08	10.88	6.09
11–20 Aug	9.30	9.40	2.96	9.61	10.06	4.84
21–31 Aug	8.09	8.66	4.31	3.86	3.87	3.14
21 Jul–31 Aug	9.56	9.28	4.34	9.07	9.64	5.40

Table 3.13. Net longwave radiation values (L*, MJ·m^{-2}) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	-1.55	-0.78	-1.38			
21–31 Jul	-3.05	-2.04	-2.18	-3.27	-3.73	-1.10
1–10 Aug	-2.42	-1.84	-1.90	-2.42	-4.14	-2.15
11–20 Aug	-3.72	-3.03	-3.48	-3.72	-3.95	-1.66
21–31 Aug	-3.71	-3.50	-3.95	-3.71	-1.13	0.19
21 Jul–31 Aug	-3.23	-2.61	-2.89	-3.29	-3.20	-1.14

The surface net radiation balance (Q*), encompassing all energy fluxes across the whole spectrum, was the most favourable in the moraine area at the front of the Waldemar Glacier (LW1 +6.67 MJ·m^{-2} in 2011 and KH +6.45 MJ·m^{-2} in 2010 and 5.78 MJ·m^{-2} in 2011, Tab. 3.14). The least favourable balance occurred on the snowy firn field of the Waldemar Glacier (1.58 MJ·m^{-2} in 2010 and 4.36 MJ·m^{-2} in 2011).The almost tripled value of Q* in 2011 resulted from a lower albedo. In the analysed period, considerable changes of Q* occurred there, due to the cloudiness. On sunny days, the net radiation balance for the moraine surface exceeded 10-15 MJ·m^{-2}, for example, on 28 July 2010 Q* at KH was 13.6 MJ·m^{-2} (while K* was 18.9 MJ·m^{-2}, and L* -5.3 MJ·m^{-2}), at LW1 it was 16.5 MJ·m^{-2} (while K* was 21.2 MJ·m^{-2}, and L* -4.7 MJ·m^{-2}) (Figs 4 and 5). On the same day, the net radiation balance for the snow/ice surface (LW2) was only 2.5 $MJ \cdot m^{-2}$ (while K* was 7.6 $MJ \cdot m^{-2}$, and L* -5.1 $MJ \cdot m^{-2}$). A higher value of Q* at LW2 (6.0 $MJ \cdot m^{-2}$) was recorded on 3 August when the sky was overcast.

Table 3.14. Surface radiation balance values (Q*, $MJ \cdot m^{-2}$) in the Kaffiøyra region in the summer seasons of 2010 and 2011

Period	2010			2011		
	KH	LW1	LW2	KH	KHT	LW2
16–20 Jul	7.51	6.70	2.66			
21–31 Jul	8.53	7.94	2.00	9.62	10.19	6.84
1–10 Aug	6.78	7.22	4.03	7.67	6.74	3.93
11–20 Aug	5.58	6.37	-0.52	5.89	6.10	3.18
21–31 Aug	4.38	5.17	0.37	0.14	2.74	3.33
21 Jul–31 Aug	6.32	6.67	1.46	5.78	6.44	4.36

In sunny weather the highest values of Q* occurred on the moraine surfaces (KH and LW1) and in the tundra (KHT), whereas for the snow and glacial ice-covered surfaces the net radiation balance was greatly influenced by longwave radiation (L*), whose highest values coincided with cloudy days.

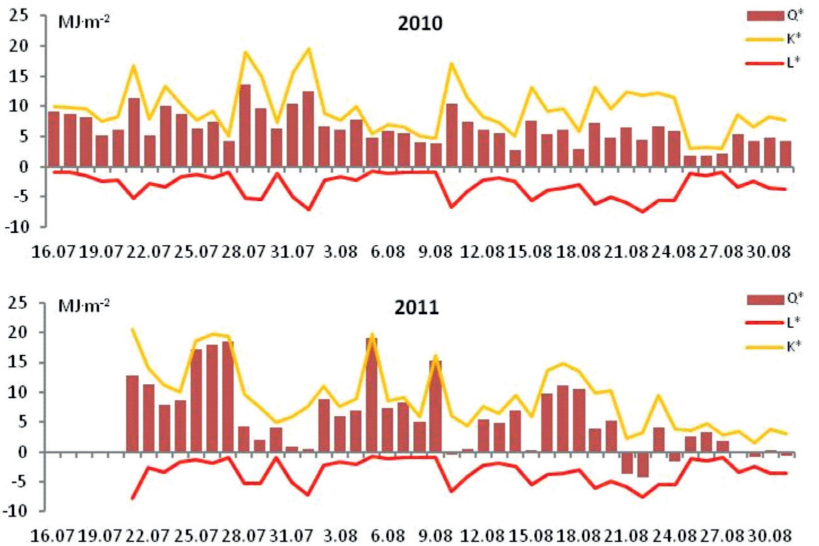

Figure 3.7. Course of surface radiation balance (Q), net shortwave radiation (K*) and net longwave radiation (L*) at KH in the summer seasons of 2010 and 2011*

At all measurement points the surface radiation balance gradually fell to the point of negative values occurring at LW2, and even at KH, which was connected with the decreasing influx of solar radiation and the end of the polar day (Fig. 3.7). This marks the end of the time of positive net radiation balance of the surface, Q*, which – according to Budzik (2003) – begins on the neighbouring Aavatsmark Glacier at the end of April and the beginning of May.

Changes in the structure of the radiation balance in diurnal cycles

In a diurnal pattern of radiation balance components, the influence of the changing solar altitude can be observed. The obtained diurnal cycles of all fluxes are symmetrical to the solar noon (Fig. 3.8), with the flux of K↓ reaching its highest mean values at midday hours, for example in 2010 at KH: 278.7 W·m^{-2}, LW1: 275.9 W·m^{-2}, and LW2: 295.2 W·m^{-2}. Similar values were recorded in 2011: at KH 239.0 W·m^{-2}, KHT 235.8 W·m^{-2} and LW2 182.6 W·m^{-2}. Around midnight the values fell respectively to: 27.2 W·m^{-2}, 19.2 W·m^{-2} and 23.2 W·m^{-2} in 2010 and to 25.5 W·m^{-2}, 23.9 W·m^{-2} and 15.4 W·m^{-2} in 2011. The albedo changes in a diurnal cycle with the solar altitude; it was the lowest at the upper culmination of the sun (in 2010 KH-12.5%, LW1-12.2% and LW2 – 55.2%, and in 2011: KH 13.3%, KHT 12.1% and LW2 44.1%). The fluxes of longwave radiation L↑ and L↓ in a diurnal cycle increased with the temperature of the surface and of the atmosphere.

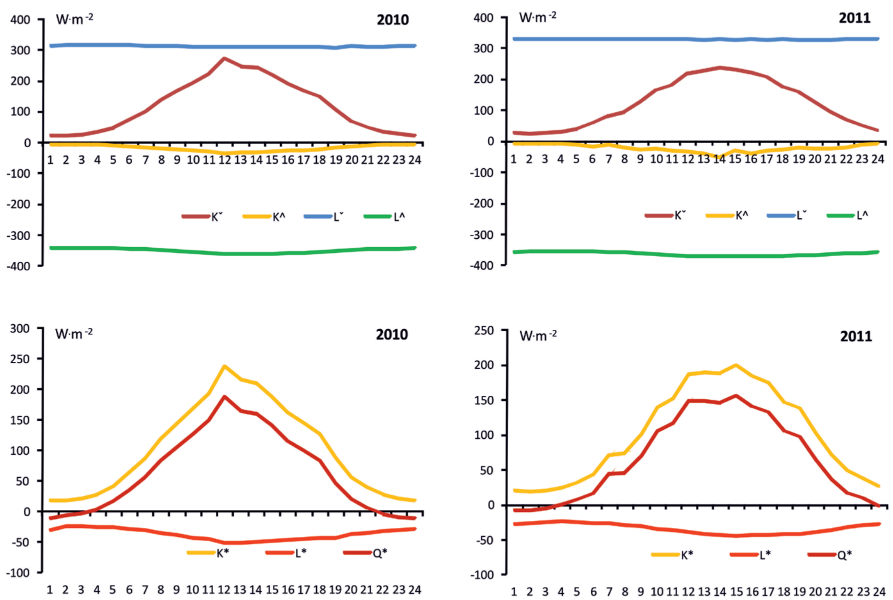

Figure 3.8. Average courses of radiation fluxes (K↓, K↑, L↑, L↓) and surface radiation balance (Q), net shortwave radiation (K*) and net longwave radiation (L*) in the Kaffiøyra in the period of 21 July–31 August 2010 and 2011*

The averaged net shortwave radiation K* reached its peaks at midday (in 2010: KH +243.5 W·m^{-2}, LW1 +240.2 W·m^{-2}, LW2 +124.0 W·m^{-2}, and in 2011: KH +200.0 W·m^{-2}, KHT +207.2 W·m^{-2}, and LW2 +99.7 W·m^{-2}) (Fig. 3.9). At the lower culmination of the sun K* decreased to approx. 10-20 W·m^{-2}. The net longwave radiation L* was negative and reached its peaks in the afternoon (in 2010: KH -50.0 W·m^{-2}, LW1 -40.1 W·m^{-2} and LW2 -47.5 W·m^{-2}, and in 2011: KH - 44.6 W·m^{-2}, KHT -51.0 W·m^{-2} and LW2 -7.9 W·m^{-2}).The total net radiation balance of the active surface Q* was the highest during midday hours, particularly on the moraine (in 2010: KH +194.8 W·m^{-2} and LW1 +201.5 W·m^{-2}, and in: KH +155.4 W·m^{-2}), and in the tundra (KHT +160.9 W·m^{-2}). The snow/ice surface, on the other hand, showed a much less favourable balance (in 2010: LW2 +79.1 W·m^{-2} and 92.3 W·m^{-2} in 2011). At low solar altitudes Q* became negative, and in 2010 amounted to -6.8 W·m^{-2} (KH), -5.4 W·m^{-2} (LW1) and -19.4 W·m^{-2} (LW2) (Fig. 3.10). In 2011 Q* was -7.4 W·m^{-2} (KH) and -3.1 W·m^{-2} (KHT). It is interesting to note the positive values of Q* at the LW2 site during 'night' hours in 2011. The reason for that was the enormous cloudiness that occurred during the 'night' of the last ten days of August that year, while the values of Q* were quite high on the negative side. With a high degree of cloudiness the incoming longwave radiation L↓rises, which increases the long-term balance of L* and Q*. In polar regions the occurrence of clouds stimulates growth in the temperature of the ground-atmosphere system. It is the so-called 'radiation paradox' (Bintanja and van den Broeke 1995). Clouds limit the flux of effective radiation, whereas the downward atmospheric radiation increases.

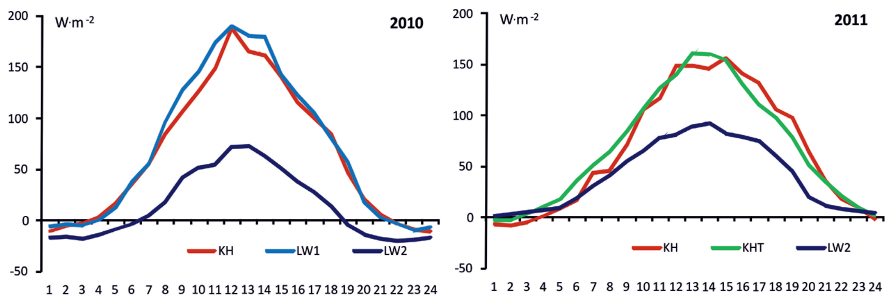

Figure 3.9. Average diurnal course of surface radiation balance in the Kaffiøyra region in the summer seasons of 2010 and 2011

On the basis of the published results concerning the components of the radiation balance of Spitsbergen (Winther et al. 2002; Kupfer et al. 2003; Budzik 2004; Gluza and Siwek 2005; Marsz and Styszyńska 2007; Budzik et al. 2009; Kejna et al. 2011), it was concluded that the values obtained in the Kaffiøyra region were similar. Comparing the values for August the maximum amounts of radiation on Spitsbergen in August ranged from 626.6 W·m^{-2} in Hornsund (in 2008) to 928 W·m^{-2} at Ny-Ålesund (1993–2001). In August 2010 in the Kaffiøyra the maximum value of K↓ was 608.7 W·m^{-2} and 622.2 W·m^{-2} in 2011. In 2010, the value at LW1 was 838.1 W·m^{-2} and at LW2 – 762.7 W·m^{-2} in 2010, and 621.2 W·m^{-2} in 2011, whereas at KHT it was 676.5 W·m^{-2} in 2011.The monthly sums of K↓ in Hornsund amounted to 300.3 MJ·m^{-2} (in the years 1978–2006), and at Ny-Ålesund – 267.6 MJ·m^{-2} (in the years 1989-2003). In the analysed years, the sums at KH amounted to 319.5 MJ·m^{-2} (2010) and 295.0 W·m^{-2} (2011). On the glaciers the values of K↓ are higher, for example 363 MJ·m^{-2} (2008) and 353 MJ·m^{-2} (2009) on the Hans Glacier, 361.5 MJ·m^{-2} (1957-1960) on the Werenskiöld Glacier, and 315.8 MJ·m^{-2} (2010) and 281.2 MJ·m^{-2} at the Waldemar Glacier (LW2).

The albedo values depend on the local characteristics of the surface. At KH the albedo was 15.2% in 2010 and 18.7% in 2011, and in the tundra (KHT)13.7% in 2011. Comparable albedos occurred in Hornsund (16% in 2008), Calypsostranda (8.5-21.2%), or at Ny-Ålesund (16.3% in the years of 1993-2001). The albedo on glaciers was definitely higher and reached 58.7% at the Waldemar Glacier (LW2) in 2010, and 48.4% in 2011. Similar levels were also reached on the Hans Glacier (58% in 2008).

The radiation balance (including shortwave and longwave radiation) in the Kaffiøyra region was considerably high, as compared to the results obtained for Spitsbergen. At KH it was 171.8 MJ·m^{-2} in 2010 and 137.2 MJ·m^{-2} in 2011. It was also very high in the tundra, reaching 158.6 MJ·m^{-2} in 2011, whereas in Hornsund it was 131 MJ·m^{-2}, and at Ny-Ålesund only 120.4 MJ·m^{-2}. On the glaciers it was much lower, and amounted to 39.1 MJ·m^{-2} at LW2 in 2010 and 107.1 MJ·m^{-2} in 2011, whereas in August 2008 the value of Q* on the Hans Glacier reached 131 MJ·m^{-2}.

The analysis demonstrates significant differences between the summer seasons of 2010 and 2011. The amount of energy that reaches the surface affects the patterns of all other meteorological elements and influences the condition of the environment, especially the mass balance of the glaciers, the ground temperature and others. The Arctic ecosystem of Spitsbergen is particularly sensitive to any such disturbances (Aguilera et al. 1999; Svendsen et al. 2002).

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