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Carbon dioxide in the tundra soils of SW Spitsbergen and its role in chemical denudation

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ABSTRACT: Measurements of CO_2 concentrations in soil air were taken in the summer seasons of 1998 and 2001 in SW Spitsbergen. The measurements were carried out in three small non-glaciated catchments in the Hornsund region close to the Polish Polar Station. The preliminary measurements were made using a Dräger's pump and ampules which contained an alkaline absorbent (1998). Later (2001), a new more accurate apparatus which uses a gravimetric method was tested. A variety of different geographical situations was chosen for the CO_2 measurements. These included areas which differed in respect of the local hydrology, terrain relief, exposure to solar radiation, distance from the sea and quantity of seabird excrements in the soil. The measured concentrations of soil CO_2 varied between 0.05 and 0.3% (with one exceptionally high value close to 0.5%). Owing to the local conditions, the differences between CO_2 concentrations seem closely to relate to the specific properties of each catchment. Much of the biogenic CO_2 present in water that circulates in tundra catchments which have a limestone foundation becomes involved in the dissolution of that limestone. In July 2001, about 40% of the CO_2 was used in the dissolution of the carbonate rocks (30.3 kg/km^2 month), the "free" CO_2 being transported to the sea at Isbjørnhamna Bay (40.4 kg/km^2 month). In contrast, the water flowing through acidic rocks are rich in "free" CO_2. The concentrations of dissolved and transported HCO_3^- ions from the polar catchments are closely correlated with variations in the daily production of biogenic CO_2.

Key words: Arctic, Spitsbergen, Hornsund, carbon dioxide, chemical denudation.

Introduction

The decomposition of organic matter in soils is the main source of biogenic carbon dioxide on the Earth and the release of this CO_2 to the atmosphere is due to soil respiration and groundwater transport. Soil respiration is the product of microbiological decomposition and root respiration whereas the transfer of dissolved CO_2 in groundwater to the ground surface represents a secondary process. Although owing to severe climatic conditions tundra soils are poor producers of CO_2 they can, nevertheless, accumulate 11–14% of the earth's soil carbon pool as peat and dead organic matter (Post *et al*. 1982, Gorham 1991). Thus, the great sensitivity of this fragile polar ecosystem is obviously an important issue in respect of our changing climate (Christensen *et al*. 1999, Grogan and Chapin 2000).

Carbon dioxide is the main factor to affect the intensity of the dissolution of carbonate rocks (limestones and dolomites) in water. Certainly, on Spitsbergen, chemical denudation rates measured in non-glaciated catchments which have a foundation of carbonate rocks are evidently quite intensive (Pulina 1984, Pulina *et al.* 1984). Therefore, one may expect a high production of CO_2 in the arctic tundra there. However, with respect to the island, it is far from impossible that CO_2 also enters the soil hydrology system by way of deep fissures in the bedrock.

Undoubtedly global climate changes have contributed to the significant increase of tundra in areas of glacial retreat and where deeper summer thawing of permafrost has taken place. Thus, an increase in the production of biological CO_2, followed by an increase in the effects of chemical denudation is to be expected. These effects may also change the volume of dissolved rocks and of the free CO_2, which is transported into the littoral zone of Spitsbergen coast. In turn this must affect the development of biological life here. In this paper, the authors describe the results of researches from the 1998 and 2001 summer seasons in non-glaciated catchments situated in the area of Hornsund Fiord (SW Spitsbergen) and discuss their significance.

Methods of CO_2 measurements

The investigations concern measurement of CO_2 concentrations in the air which is contained in rocks and soil. Hitherto, these have mainly been carried out in caves (Koepf 1952, Hilger 1963, Delecour 1965, Ek and Gewelt 1985). An electrochemical method was also used in the research. Although this is time-consuming in its application, it ensures the relatively high precision of measurement (±0.1 mg CO_2/dm^3 air). Other semi-quantitative chemical methods were also applied; by using absorbers containing alkaline compounds and an appropriate colour indicator, the airflow through the absorbent was induced by means of hand-held tube called a Dräger's pump (Miotke 1974, Renault 1982). These allowed the measurements of CO_2 to be made within the wide range of 0.03–3.00%. The analysis of higher CO_2 concentrations in soil-air can also be conducted using gas chromatography (GC) (Zjawiony *et al.* 1984) although this apparatus is not easily portable. In recent years the most often cited and applied method of CO_2 analysis is the IRGA spectral method, which measures the activity of CO_2 particles in a range of infra red waves (Bekku *et al*. 1997, Vourlitis and Oechel 1997). Other chemical methods based on well-known ionic reactions (*i.e.* a precipitation of salts), use gravimetric analysis for quantitative determination of CO_2 concentration in the air (Pulina and Burzyk 2002).

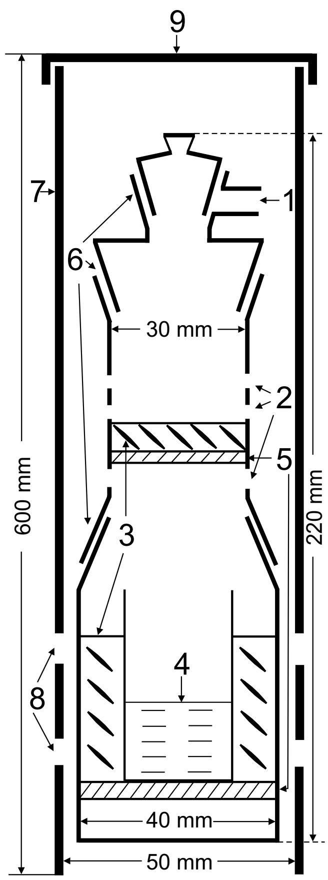

Fig. 1. Sketch of glass vessel used for absorbing CO_2 from tundra soil. Abbreviations: 1 – tap with lateral hole, 2 – perforation which permit the flow of the gas from the tube to the interior of vessel, 3 – layers of absorbent (magnesium perchlorate), 4 – layer of absorbent (ascarite), 5 – glass sinter G-1, 6 – ground glass joints, 7 – metal tube set in the ground, 8 – perforation in the metal tube, 9 – airtight plug of the tube.

The authors measured CO_2 concentrations in the soil air in SW Spitsbergen in the summer seasons of 1998 and 2001. In 1998, the measurement of CO_2 in the ground and plant cover was carried out using PVC tubes ($\varphi = 20$ mm) which were inserted into the soil to a depth of 10–60 cm. The bottom end of each tube was plugged but its walls were perforated so as to enable air to enter into the tube. On the upper part of the tube a rubber seal ensured a tight connection with a glass ampule which contained chemical absorbents. Measurements with a 0.01–0.02% accuracy were accomplished in this way. In order to determine the precise concentrations of CO_2 serial measurements were taken. The relatively low accuracy this apparatus yielded data which may be considered to be minimal values.

A new extending apparatus (Pulina and Burzyk 2002) was used (Fig. 1) in the summer season of 2001. This was found significantly to improve the accuracy of the CO_2 measurements. Two absorbents were placed in the interior of a glass vessel. Magnesium perchlorate was used for the absorption of the moisture from the air and ascarite for the CO_2.

The measurements took place in three non-glaciated catchments. In those situated near Hyttevika and Nottinghambukta Bays 28 sets of measurements were taken between 15. 07 and 25. 08 of 1998. The third catchment, called Fugle is situated close to the Polish Polar Station in Hornsund (77˚00'N, 15˚33'E) and is bordered on the east by the Hansbreen Glacier. Four sets of measurements were taken at 4 stations between 15. 07 and 13. 09 in 2001. Additionally, single measurements were taken in many similar places along the Hornsund Fiord coast, usually on dry days.

Area of the research – the north coast of Hornsund Fiord

The investigations were carried out in areas of arctic tundra located on raised marine terraces along the north coast of Hornsund Fiord between Austre Torellbreen and Hansbreen Glaciers (Wedel Jarlsberg Land) on SW Spitsbergen (Fig. 2).

The bedrock of the studied areas comprises crystalline rocks – mainly metamorphic (gneiss and phyllite) with subordinate carbonates (marbles) (Birkenmajer 1990).

The arctic tundra consists of several different plant communities in which lichens, mosses and higher plants are all present (Kuc 1963, Fabiszewski 1975, Klekowski and Opaliński 1984). Peats and soils bearing a considerable concentration of organic carbon have developed mainly from the virgin soils, which covered the slopes of coastal mountains on deglaciation of the area. These soils have became enriched by the addition of seabirds' excrements mainly that from the huge colonies of Little Auk *(Alle alle)* Barnacle Goose (*Branta leucopsis*) and Pink-footed Goose (*Anser brachyrhynchus*) (Jakubiec 1982, Stempniewicz 1992).

The climate of SW Spitsbergen coast is much affected by oceanic influences in this of the subpolar zone. The polar night and day contrast determines the fundamental character of the seasons, especially the spring, which is quite short but very intensive. The raised marine terraces, which are covered by the discontinuous tundra patches, receive relatively small amounts of precipitation (300–600 mm/year). Measurements in recent years show that the distribution of precipitation in summer and winter seasons is similar and that there is an appreciable rise in both (Fig. 3).

The annual average air temperature measured in the last 24 years (1978–2001) ranged between –2.3 and –7.3˚C. Only in four months of the year (July–September) are the mean values positive. Thus, permafrost has developed; this thaws in summer to a depth of c. 1 m on the coastal terraces of Spitsbergen. The total precipitation in the 1998 in Hornsund region was unusually low (c. 300 mm/year), of which only 84.4 mm was summer rainfall. The air temperature in the summer

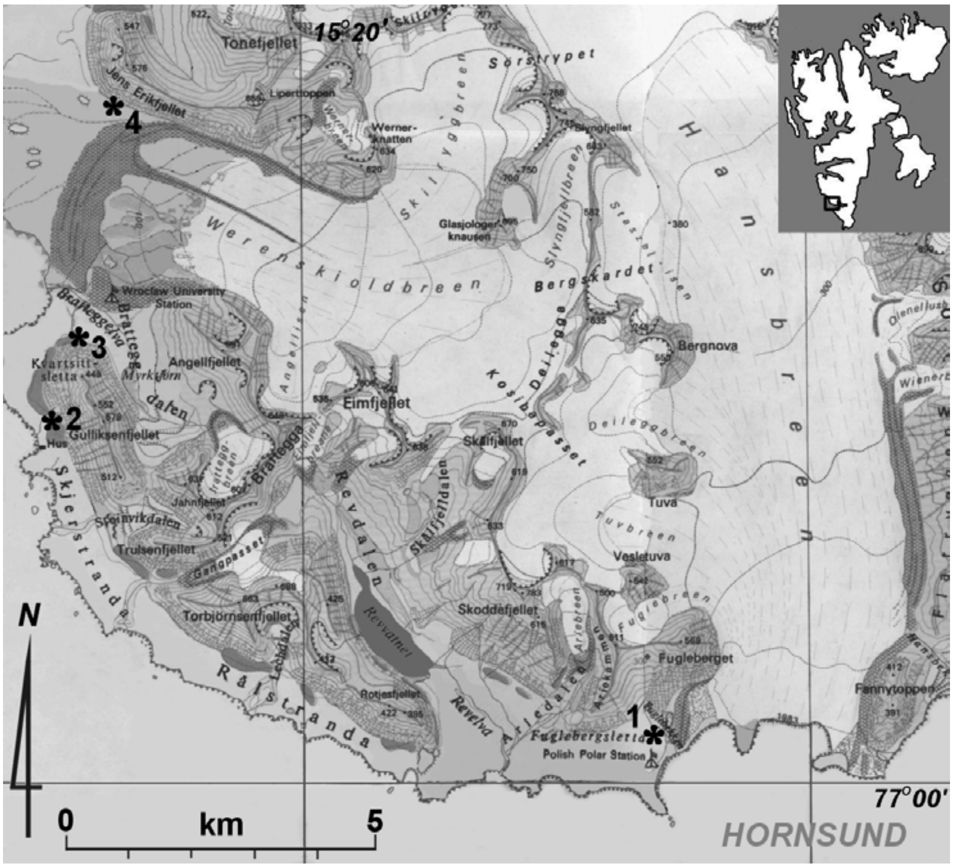

Fig. 2. Map of the north-west coast of Hornsund Fiord with location of catchments and sites of CO_2 measurements (1 – Fugle, 2 – Hyttevika, 3 – Brattegg, 4 – Jens Erik). Source of map: Karczewski *et al.* (1984).

months (June–August) is high and, sometimes, the average daily air temperature exceeds +6°C. It can reach as much as +10.8°C. The average hourly air temperature values in this period sometimes exceed +10°C and reach even +13.4°C the maximum in the second part of July (Fig. 4A).

The values of meteorological elements in 2001 were markedly different from those of the previous seasons. That summer was very dry (the total of precipitation for July and August was only 29.4 mm); in contrast, the autumn and the beginning of winter were very rainy (92.2 mm in the period of 01–20. 09. 2001), the rainfall sometimes being very intensive (43.9 mm on 12. 09. 2001). The air temperature in the summer was similar to the annual averages (+4.7°C for July and August), whereas the temperature in autumn and the beginning of winter showed positive values. Even in the first part of September the daily average temperature exceeded those of the summer months (+5.1°C in the period of 01–15. 09. 2001) (Fig. 4B).

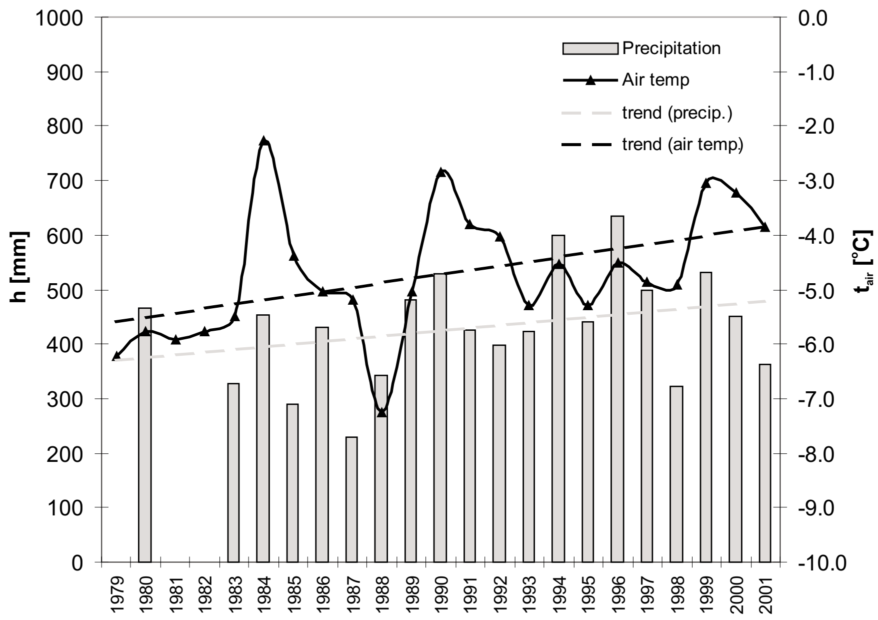

Fig. 3. Air temperature (yearly average) and precipitation (yearly total) on the north coast of Hornsund Fiord in the period of 1979–2001 (Polish Polar Station – Hornsund).

The characteristics of the measurement sites at Hyttevika and Nottinghambukta Bays

A common feature of these two sites was their carbonate – free acidic crystalline rock basement. However, in respect of their hydrology, relief, solar exposure, distance from the sea and excrement content of their soils they are quite different. With respect to their CO_2 content they make an interesting contrast.

The Hyttevika Bay station (No. 2 on the Fig. 2) received its soil water from numerous springs in the local debris. Flows are channelled into four streams; three of which are active throughout the summer. Patches of tundra have developed mainly on the banks of the streams where they have been enriched by seabird excrements from the closely adjacent Little Auk colony (Krzyszowska 1992). The soil profiles in the tundra are well developed in this area.

The Nottinghambukta Bay site is located on the flat alluvial cone, present between the rocky entrance to the Brattegg valley and the slope of Gulliksenfjellet (No. 3 on the Fig. 2). This was supplied by water discharged from a large patch of snow, from thawing permafrost and from water issuing from debris cones and scree. Some small streams formed by the outflows supplied numerous small lakes in the lower part of the catchment. Towards the end of the summer most of these dried up together with the tundra patches. Seabird excrements do not notably enrich this catchment.

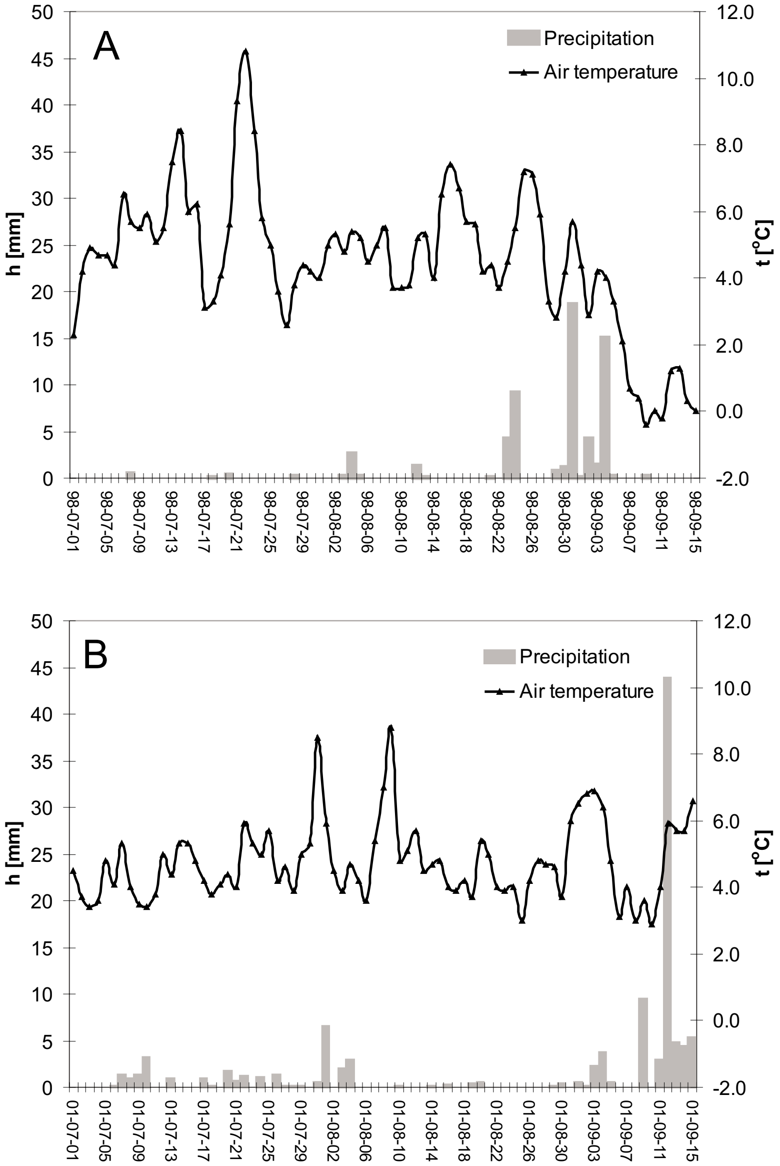

Fig. 4. Air temperature and precipitation on the north coast of Hornsund Fiord in 1998 (A) and 2001 (B) (Polish Polar Station – Hornsund).

A comparable programme of CO_2 measurements was also carried out in an area which has a carbonate rock foundation, this is situated at the bottom of the debris cone of Jens Erikfjellet mountain (576 m a.s.l.) in the northern part of Nottinghambukta Bay (No. 4 in Fig. 2). Fertile tundra patches are present here on the banks of the small stream.

The environment of the Fugle catchment

The Fugle catchment is located partly on the raised marine terraces and mainly on the slopes of coastal mountains (Ariekammen 512 m a.s.l. and Fugleberget 569 m a.s.l.) from 15 m a.s.l. up to more than 500 m a.s.l. (No. 1 in Fig. 2). This basin is 1.36 km^2 in area. The catchment is situated within area of metamorphic rocks (phyllites and schists) of the Ariekammen Formation (Isbjørnhamna Group) (Birkenmajer and Narębski 1960, Smulikowski 1965, Birkenmajer 1990). Carbonate rocks (grey marbles and calcareous schists) are also present here. Both the slopes and the terraces are covered by rich tundra, which is represented by different plant communities. Four ornithocoprophilous plant communities were distinguished as a direct effect of Little Auk colony on tundra vegetation here (Dubiel and Olech 1992). The soils there have a high concentration of organic carbon which may be also attributed to the enrichment of the seabird colony situated nearby on the slope of Ariekammen (Remmert 1980, Klekowski and Opaliński 1984, Stempniewicz 1992).

In 2001 the period of hydrological activity in the catchment lasted from May to the end of September and was clearly divided into three parts (Fig. 5). The first phase started with a rapid flow of water derived from snowmelt (up till 19. 07. 2001). Observations in the second phase showed that medium and low levels of

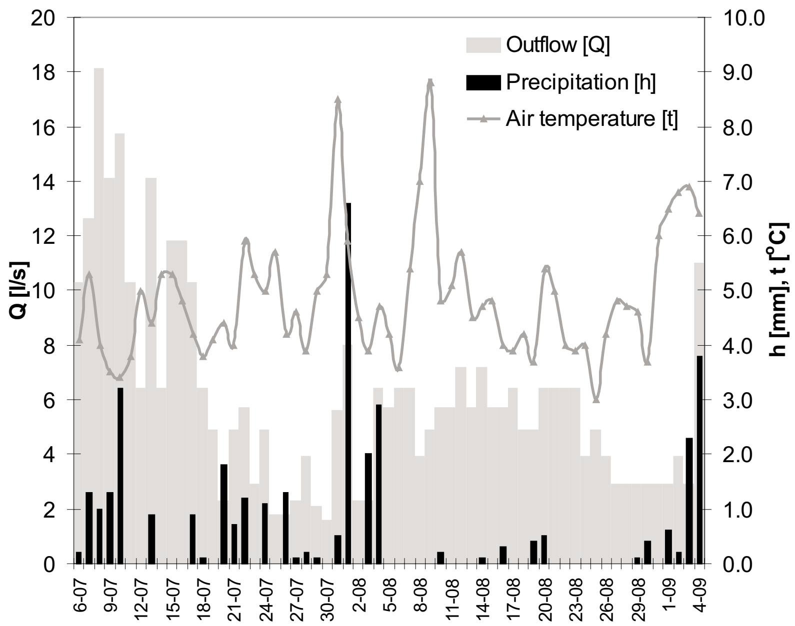

Fig. 5. Average daily discharge of Fuglebekken stream (Q), average daily air temperature (t_{air}) and daily total of precipitation (P) at the north coast of Hornsund Fiord in 2001 (Polish Polar Station – Hornsund).

water correlated closely with precipitation. The last phase was formed by the “autumn-winter hydrological season”. This was characterized by high flows produced by heavy rainfall. Thus the outflows from the Fugle catchment in July were high (7.6 l/s km^2) whereas those in August (3.7 l/s km^2) were low (Table 1).

Table 1

Selected hydro-meteorological elements and the volume of CO_2 and $CaCO_3$ transport from the Fugle catchment in the summer season of 2001.

Month	Daily T_{air}	Precip.	CO_2	Daily Q	HCO_3^-	CO_2 [kg/km^2/month]			$CaCO_3$ [kg/km^2/month]		
[2001]	[°C]	[mm]	[mg/l]	[l/s km^2]	[mg $CaCO_3$/l]	1	2	3	1	2	3
July	4.6	15.9	3.5	7.6	61.6	40.4* 30.3** 70.7***	29.1	40.0	1245.3	785.3	974.5
August	4.6	13.5	5.0	3.7	67.6	30.1 20.1 50.2	33.6		679.1	760.7	
September	5.1	78.4	-	-	-						

1 CO_2 = f (Q, "free" CO_2) * transport of "free" CO_2
2 n=11 direct measurements ** intake of CO_2 in dissolving of $CaCO_3$
3 Average (max and min) *** production of biogenic CO_2

Concentration of CO_2 in the Spitsbergen tundra

The role of polar areas in the Earth’s carbon cycle is not well understood (Ciais *et al*. 1995, Daoxian 1997), but the active, upper layer of permafrost appears to be a very important source of that element (Post *et al*. 1982). In respect of an increase of air temperature in the winter months, some authors have emphasised the importance of the winter season on CO_2 production (Zimov *et al*. 1996, Oechel *et al*. 1997, Fahnestock *et al*. 1998). In recent years, the number of studies concerning the emission of CO_2 from the polar tundra into the atmosphere in several places in the Arctic has increased significantly (Vourlitis and Oechel 1999), this is also the case in respect of Spitsbergen (Nakatsubo *et al*. 1998, Lloyd 2001, Lauriol and Clark 1999, Wüthrich *et al.* 1999). Much relevant ecological data concerning the “production” of CO_2 has been documented but we have scarce data concerning the concentration of this gas in the tundra soils. Usually, the data concerns only the concentration of CO_2 above the surface of tundra, from which calculations about the amount of CO_2 delivered into the atmosphere (often expressed as [ppm] or [mg CO_2 m^{-2} h]) may be derived. Our measurements used the gravimetric method for determination of CO_2 in the soil air (the CO_2 being determined as a percentage) whereas the concentration of “free” CO_2 in the water and in the form of hydrocarbons of Ca^{2+} and Mg^{2+} are expressed in terms of mg/l.

The measurements of CO_2 in the soil air were conducted both as one-off events in many different places along the coastal tundra zone in Hornsund region and also regularly in the areas of the three non-glaciated catchments within the regular sur-

Table 2

Concentration of „free” CO_2 (A) and dissolved $CaCO_3$ (B) in the waters draining coastal tundra areas of SW Spitsbergen in the summer season of 1998.

A

Basin	Surface [km²]	Month	Q	CO_2	"free" CO_2 in water						
			[l/s]	[%]	[mg/l]	[g/h]	[kg/24h]	[kg/mth*]	[kg/km²/24h]	[kg/km²/mth]
Hyttevika	0.384	VII	8.0	0.15	5.5	158.4	3.80	117.8	9.9	306.8
		VIII	3.0	0.05	2.5	27.0	0.65	20.1	1.7	52.3
Nottingham-bukta	0.312	VII	2.0	0,10	3.5	25.2	0.61	18.7	2.0	59.9
		VIII	2.0	0.13	4,0	28.8	0.69	21.4	2.2	68.6
Jens Erik	0.230	VII	4.5		2.0**	32.4	0.78	24.1	3.4	104.8
					3.0***	48.6	1.20	36.2		
				0.10	5.0****	81.0	1.90	60.3		

B

Basin	Surface [km²]	Month	Q	CO_2	$CaCO_3$				
			[l/s]	[%]	[mg/l]	[kg/24h]	[kg/mth]	[kg/km²/24h]	[kg/km²/mth]
Hyttevika	0.384	VII	8.0	0.15	2.5	1.7	53.6	4.4	139.6
		VIII	3.0	0.05	10.0	2.6	80.3	6.8	209.1
Nottingham-bukta	0.312	VII	2.0	0.10	3.0	0.5	16.1	1.7	51.6
		VIII	2.0	0.13	4.0	0.7	21.4	2.2	68.6
Jens Erik	0.230	VII	4.5		80.0	31.1	964.2	135.2	4192.2
				0,10					

* month
** "free" CO_2 transported from the catchment
*** "free" CO_2 used to dissolution of $CaCO_3$
**** theoretical value of "free" CO_2 transported from the catchment

vey network. The measured concentrations of soil CO_2 fluctuated between 0.05 and 0.30% (in some individual measurements) there being a single exceptionally high value close to 0.5%. The mean of 40 measurements was 0.1%. The most complete set of results obtained in 1998 came from the net of stations localized on the coast of Hyttevika and Nottinghambukta Bays (Table 2A, B).

The measurements of soil CO_2 concentration were carried out by means of PVC tubes installed permanently in the ground. With a view to obtaining the most comprehensive data, the measurements were conducted in different climatic conditions, and several times a day. Furthermore, between these regular measurements, some additional measurements were taken so about 60 results were obtained.

In the small catchment near Hyttevika, the highest measured values of CO_2 (0.2–0.3%) were noted in the middle of July. After that, a slow decrease was observed (0.1–0.2% in the end of July), and, in the end of August the measured values were close to normal atmospheric values (0.03–0.06%). Slightly lower values of CO_2 (about 0.1%) were measured in a second small catchment close to Nottinghambukta Bay. The additional measurements taken in tundra soils on the debris cone under Jens Erikfjellet resulted in similar values.

The original method of measuring the soil CO_2 in the tundra soils of the Fugle catchment was used in the summer of 2001. During the four series of measurements carried out in the net of permanently installed sites, a concentration of CO_2 in the range of 0.035–0.075% was determined (Table 3).

Table 3

Concentration of CO_2 in the soil air and HCO_3^- ions in the tundra water, as measured in 4 fixed measurement sites in the Fugle catchment.

No	Data	15.07.2001		25.07.2001		10.08.2001		13.09.2001	
	Point of measure (GPS position)	CO_2 [%]	HCO_3^- [mv/l]	CO_2 [%]	HCO_3^- [mv/l]	CO_2 [%]	HCO_3^- [mv/l]	CO_2 [%]	HCO_3^- [mv/l]
1	N 77°00'23.0" E 15°33'22.3"	0.062	1.25	0.069	1.3	0.075	1.36	0.061	1.32
2	N 77°00'22.3" E 15°33'05.0"	0.045	0.98	0.048	1,00	0.045	1.16	0.042	1.19
3	N 77°00'28.1" E 15°32'45.1"	0.049	1.12	0.043	1.15	0.047	1.17	0.049	1.22
4	N 77°00'30.1" E 15°31'48.3"	0.038	-	0.035	-	0.035	-	0.036	0.76

The volume of CO_2 transported in surface water

The precipitation water and that which infiltrates through the plant cover and tundra soils intercepts part of the CO_2 present there. The dissolved CO_2 in the water may then take part in the dissolution of carbonate rocks hence it may be transported to the sea (in the form of "free" CO_2) or, alternatively, into the atmosphere. Estimates of the volume of transported loads of CO_2 are based on both hydrological and hydrochemical measurements so such factors as water balance, chemical composition and physical quality of water have to be determined (Pulina *et al.* 1984).

In the Table 4, selected elements of the chemical composition of that water circulating in the raised marine terraces and coastal mountains in those parts of Spitsbergen close to the points of soil CO_2 measurement are presented. It should be emphasised that water mineralization is obviously influenced by the type of bedrock.

Within that area of soil CO_2 measurements close to Hyttevika and Nottinghambukta Bays, where the bedrock consists of acidic crystalline rocks and marine gravels, the mineralization of waters is low. Chloride ions, which dominate in the chemical composition, are known to have their source in marine aerosols, and the $CaCO_3$ content of this may be as much as several percent. By contrast, the mineralization of waters, which flow through the areas, which have a carbonate foundation (*e.g.* partly the Fugle catchment), is much higher and a concentration of Ca^{2+} and HCO_3^- ions predominates. This may amount to over 90% of total chemical composition and maximum values of 90–100 mg/l $CaCO_3$ are present. The concentrations of "free" CO_2 in surface waters fluctuated between 2.0 and 7.7 mg/l here. High concentrations of CO_2 were noted also in those areas where carbonate rocks are absent but which were enriched by seabird excrements.

The amount of "free" CO_2 in the surface waters which issue from the small, non-glaciated catchments in 1998 and 2001 amounted to 30–307 kg/km^2 per

Table 4

Physicochemical properties of water circulating in the tundra located on the raised marine terraces in the area of Hornsund Fiord.

River	Date	T H_2O [°C]	pH	CO_2 [mg/l]	C_{25} [μS/cm]	TH [mv/l]	HCO_3^- [mv/l]	TAC*	Cl^- [mg/l]
Hyttevika	15.07.98	2.0		5.5	58.2	0.30	0.04	0.17	
	25.08.98	3.1		3.5	118.9		0.20	1.00	
Nottingham-bukta	19.07.98	5.1	6.56	4.4	19.5	0.10	0.06	0.30	
	25.08.98	4.5		2.5	23.0		0.08	0.40	
Brattegg river	16.07.98	3.1		3.3	17.7	0.07	0.20	1.00	7.1
	19.07.98	3.1	6.91	3.7	19.4				
	23.08.98	5.3	7.00	3.3	24.6	0.20	0.20	1.00	6.4
Fugle-bekken	29.07.79	4.8	7.20	3.3	117.9	1.00			
	25.08.79	3.2	7.00	5.3	128.0	1.24	1.40	7.00	11.0
	06.09.79	1.0	7.40	5.3	135.0	1,40	1.30	6.50	11.3
	16.08.98		7.14		156.0	1.58	1.60	8.00	15.3
	05.09.98		7.98		170.0	1.76	1.10	5.50	14.9
	15.07.01	8.7	6.90		127.1		1.15	5.75	12.4
	10.08.01	6.0	7.90		152.9		1.33	6.65	11.5
	28.08.01	6.2	7.20		139.4		1.35	6.75	15.1

* 1 TAC = 10 mg/l $CaCO_3$

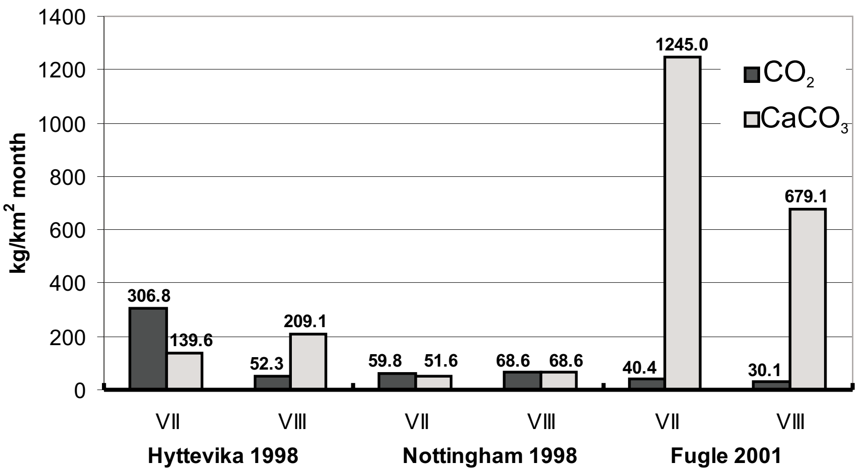

Fig. 6. The volume of „free” CO_2 and $CaCO_3$ transport in waters draining the catchments situated on the raised marine terraces in the area of Hornsund Fiord (summer seasons of 1998 and 2001).

month (Table 2A, B; Fig. 6). The lowest values of CO_2 were typical of the carbonate bedrock catchments. In respect of the basins, which are not notably enriched by seabirds and built from non-carbonate rocks, the values were somewhat higher. In catchment where seabird excrements was present and where the bedrock consisted of non-carbonate rocks much higher values of CO_2 were noted. In the waters of the first type of catchment, a load of dissolved carbonate rocks predominated.

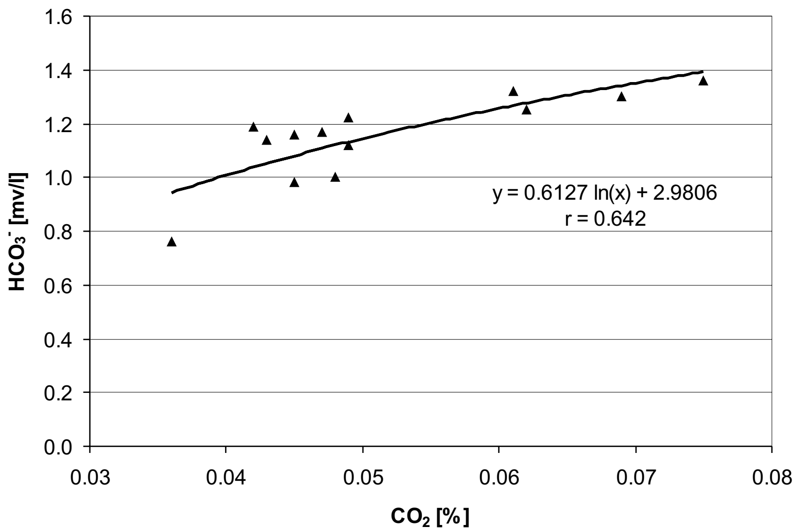

Fig. 7. Concentration of $HCO_3^-{}_{tun}$ in the water from tundra as a function of soil CO_2 concentration (%). Summer season of 2001 in the Fugle catchment.

The influence of CO_2 on the ionic composition of carbonates in the surface waters and the volume of transported loads

In the period of July–September 2001, close to the measurement point of soil CO_2 the analysis of the anion HCO_3^- concentrations in the waters circulating in the tundra formation within the Fugle catchment showed a positive correlation between the two mentioned parameters (r = 0.64, Fig. 7). The dependence may be described as follows:

$$HCO_3^-{}_{tun} = 0.6127 \ln (CO_2) + 2.9806$$

A high correlation was also obtained between concentration of HCO_3^- anions in the waters flowing out from the catchment and concentration of CO_2 in the soil air (r = 0.997; Fig. 8). The function may be described as follows:

$$HCO_3^-{}_{Fugle} = 20000 (CO_2)^2 - 1904 (CO_2) + 46.429$$

Such a high correlation between the production of biogenic CO_2 and the concentration of HCO_3^- ions in the Fuglebekken stream which drains the Fugle catchment suggests the following:

- In the waters which flow through the tundra the concentration of "free" CO_2 corresponds to the concentration of ground CO_2 in the soils.
- A relatively low concentration of CO_2 measured in the tundra soils constitutes that part which remains after the carbonate rocks dissolution process has taken place in the catchment, and which is expressed by the concentration of HCO_3^- in the water of both the tundra and the Fuglebekken stream.

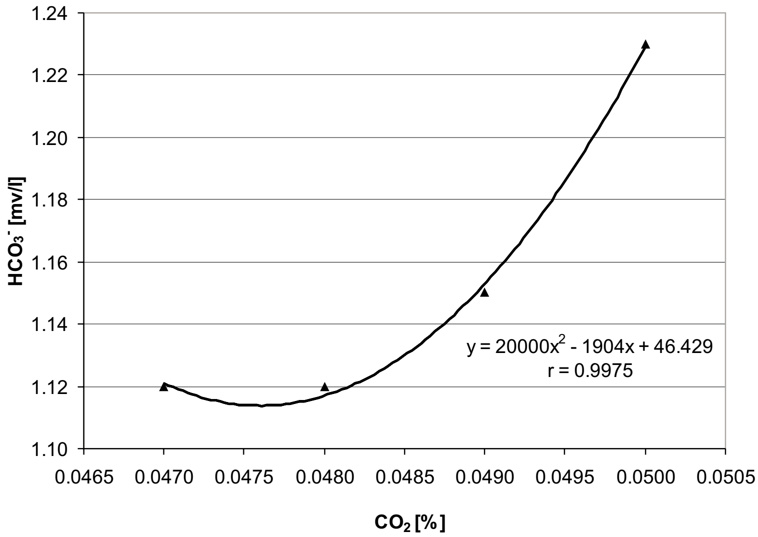

Fig. 8. Concentration of $HCO_3^-{}_{Fugle}$ in the water of Fuglebekken stream as a function of CO_2 concentration in the tundra soil. Summer season of 2001.

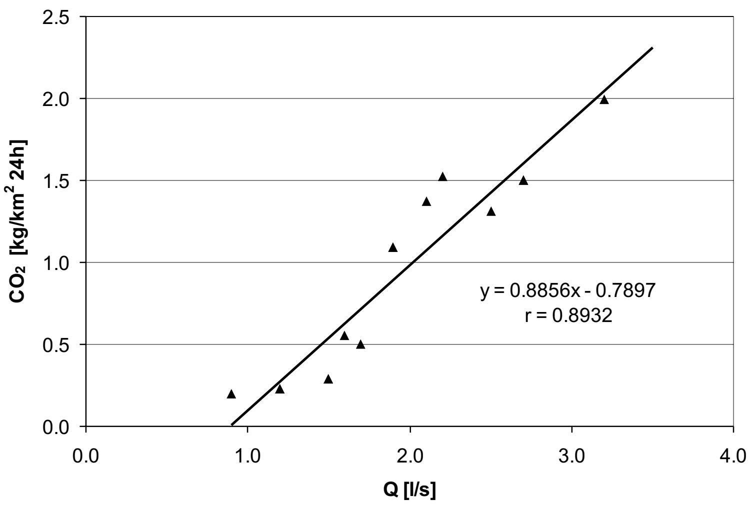

Fig. 9. Transport of CO_2 as a function of Fuglebekken stream discharge (Q). Summer season of 2001.

- The original concentration of “free” CO_2 in the water which percolates through the tundra, was a product of CO_2 necessary for the dissolution of amount of $CaCO_3$ (which is expressed by the concentration of HCO_3^- ions in the water) and the “free” CO_2 that corresponds to the concentration of CO_2 in the soil.

The results obtained in theoretical models together with the direct measurements have enabled us to determine the two basic functions which permit a calcu-

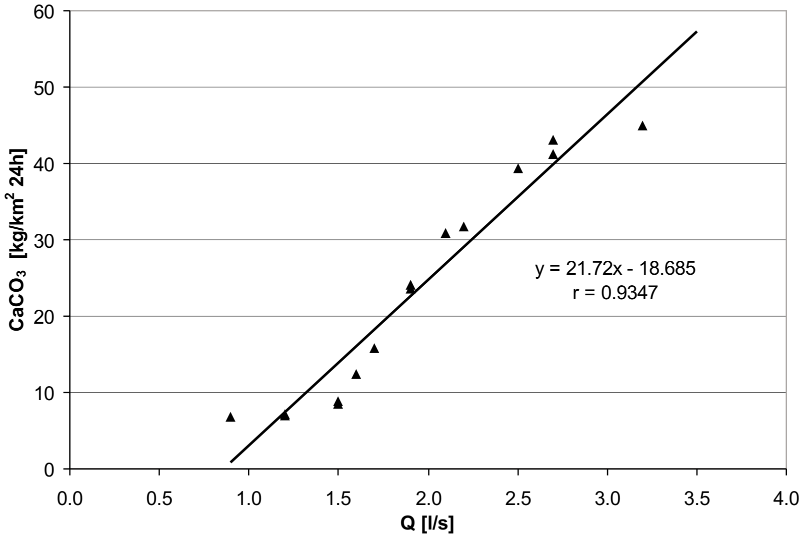

Fig. 10. Transport of $CaCO_3$ as a function of Fuglebekken stream discharge (Q). Summer season of 2001.

lation of the volumes of "free" CO_2 transported from the catchment (Fig. 9) and dissolved carbonate rocks (Fig. 10) as a function of discharge (Q). The mathematical interpretation of these functions is:

$CO_2 = 0.8856\ Q - 0.7897$, r = 0.89

$CaCO_3 = 21.72\ Q - 18.685$, r = 0.93

Conclusions

In contrast to the generation of biogenic CO_2 in soils of the temperate and tropical climatic zones of the Earth the concentration of carbon dioxide in the ground air of tundra formation of SW Spitsbergen is low. In tundra of SW Spitsbergen in the summer season of 1998 concentrations near 0.1% (and with a maximal of 0.3%) predominated. In Central Europe, CO_2 concentrations in the agricultural soils of Germany and Hungary may be as much as 2–3% in the middle of the vegetation growth period (Jakucs 1977, Gerstenhauer 1969), *i.e.* it is ten times higher than that in the tundra of Spitsbergen. In the soils of the tropical zone these values are even higher. In southern China, concentration of soil CO_2 can even reach 5% (Song Linhua and Liang Fuyuan 2001). Despite the low concentration of CO_2 in the tundra soils of Spitsbergen (maximum 0.3%) it is nevertheless large enough for the dissolution of $CaCO_3$ (even a rate of 100 mg/l). This is twice as much as in a case where biogenic CO_2 is absent and only the volume of CO_2 taken from the atmosphere (0.03%) takes part in such a reaction. Water that circulates in a tundra catchment, where carbonate rocks are present involves quite high amounts of biogenic CO_2 in the dissolution of limestones. Its mineralization is higher, "free" CO_2 is absent and the pH is generally neutral or slightly alkaline. In contrast, because of a lack of carbonate rocks water which flows through acidic rocks is rich in "free" CO_2. The overall mineralization in this case is lower and the concentration of HCO_3^- ions is low, so, with acidic pH, these waters are aggressive.

In summary, the main conclusions of this paper are:

The tundra soils may produce several times more CO_2 than is present in the atmosphere. Part of this CO_2 migrates to surface waters. These values relate only to the summer seasons of 1998 and 2001 for the catchments situated in the coastal part of SW Spitsbergen.

Biogenic CO_2 may dissolve in the water which circulates in the tundra as "free CO_2". For example in the Fugle catchment in July of 2001, about 40% of CO_2 was used in the process of dissolution of the carbonate rocks (30.3 kg/km^2 month) and the remainder, the "free" CO_2 was transported to the sea at Isbjørnhamna Bay (40.4 kg/km^2 month).

The variations in the daily concentrations of dissolved and transported HCO_3^- ions from the polar catchments seem to be correlated closely with the variable daily production of biogenic CO_2.

During the whole active hydrological season large amounts of "free" CO_2 and HCO_3^- ions are transported to the sea; these, presumably, have significant influence on the biological life in the littoral zone of SW Spitsbergen.

A proof that all measured CO_2 has biogenic source needs more accurate isotopic analysis of carbon in all phases (organic and inorganic).

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