Climate, river discharge and suspended sediment transport in the Zackenberg River drainage basin and Young Sound/ Tyrolerfjord, Northeast Greenland, 1995–2003

Sebastian H. Mernild*[1]*, Charlotte Sigsgaard*[1]*, Morten Rasch*[2]*, Bent Hasholt*[1]*, Birger U. Hansen*[1]*,
***Michael Stjernholm*[3] *and Dorthe Petersen*[4]**

[1]Institute of Geography, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen, Denmark
[2]Danish Polar Center, Strandgade 102, DK-1401 Copenhagen, Denmark
[3]National Environmental Research Institute, Vejlsøvej 25, DK-8600 Silkeborg, Denmark
[4]ASIAQ, Greenland Survey, Qatserisut 8, Box 1003, DK-3900 Nuuk, Greenland

Cite as: Mernild, S. H., Sigsgaard, C., Rasch, M., Hasholt, B., Hansen, B. U., Stjernholm, M. & Pedersen, D. 2007. Climate, river discharge and suspended sediment transport in the Zackenberg River drainage basin and Young Sound/Tyrolerfjord, Northeast Greenland. In: Rysgaard, S. & Glud, R. N. (Eds.), Carbon cycling in Arctic marine ecosystems: Case study Young Sound. Meddr. Grønland, Bioscience 58: 24-43.

Abstract

Climate control on river discharge, suspended sediment transport and conductivity was investigated based on high-resolution time series (1995–2003) from a High Arctic drainage basin at Zackenberg, Northeast Greenland. Data from the Zackenberg River drainage basin (512 km^2) was extrapolated to estimate the total transport from land of freshwater, sediments and organic matter to the Young Sound/Tyrolerfjord system (3,016 km^2). During the investigation period, a 14-day increase in thawing period, a 50-day decrease in snow cover period, an increasing release of meltwater from exposed glacier surfaces and an increasing annual runoff were recorded. The total annual runoff from the Zackenberg River drainage basin ranges between 122 and 306 million m^3 (239–598 mm yr^{-1}), while the total annual runoff to the entire Young Sound/Tyrolerfjord system ranges between 630 and 1,570 million m^3 yr^{-1}. Suspended sediment discharges from the Zackenberg River drainage basin and the entire catchment area to Young Sound/Tyrolerfjord are 15,000–130,000 t yr^{-1} and 77,000–670,000 t yr^{-1}, respectively. For organic matter yield the ranges are, respectively, 1,100–11,500 t yr^{-1} and 6,000–59,000 t yr^{-1}. In 2003 the total transport of carbon was 1,180 t yr^{-1} and 6,000 t yr^{-1} and of nitrate 13 t yr^{-1} and 66 t yr^{-1}, respectively, for the Zackenberg River drainage basin and the entire catchment area to Young Sound/Tyrolerfjord.

2.1 Introduction

Over the last 100 years mean global surface air temperature has increased by 0.3 to 0.6°C (Maxwell, 1997; Kane, 1997). In this period, nine of the ten warmest years measured globally occurred between 1990 and 2001 (WHO, 2001), and it is likely that the 1990s was the warmest decade during the past 1,000 years (Crowley, 2000), the largest air temperature changes being seen in winter (Box, 2002; Sturm et al., 2005). Simulations of future climate by Global Circulation Models indicate an increase in global air temperature, and that warming will occur more intensively in northern latitudes than elsewhere (e.g. Maxwell, 1997; Flato & Boer, 2001; Rysgaard et al., 2003). For Northeast Greenland, atmosphere-ocean models indicate an air temperature increase of up to 6–8°C during this century (Rysgaard et al., 2003), with the largest changes occurring in autumn and winter (Sælthun & Barkved, 2003). As a result, the contribution of fresh water from Northeast Greenland to the Greenland Sea will increase during the next century. Combined with a pronounced reduction of sea ice within the Arctic Sea, including the Greenland Sea (Serreze et al., 2002; Sturm et al., 2005), this might affect the density-driven sinking of cold surface water – the thermohaline circulation – in the sea off Northeast Greenland (e.g. Broecker et al., 1985; Broecker & Denton, 1990).

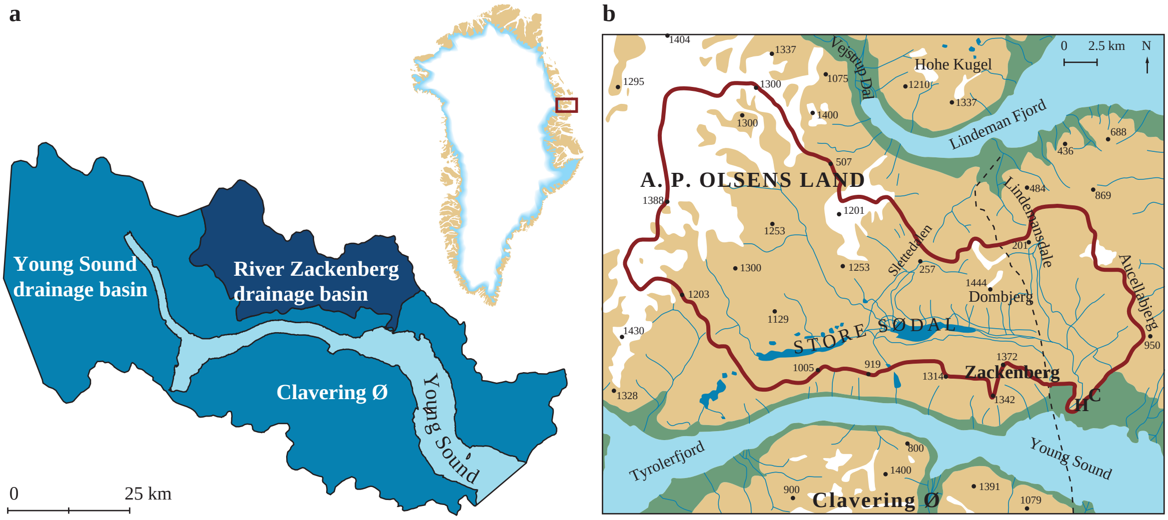
Information on climate and river discharge in Northeast Greenland was more or less non-existent before the establishment of the Zackenberg Research Station in 1995. The Zackenberg Research Station is situated near the fjord Young Sound/Tyrolerfjord in Northeast Greenland (74°28'N; 20°34'W). The station is maintained by the Danish Polar Center (DPC), and it runs an extensive monitoring programme, Zackenberg Basic, on ecological effects of climate change. The two sub-programmes, ClimateBasic and GeoBasic, provide information on the dynamics of the physical landscape processes, including climate and hydrology, in the Zackenberg River drainage basin. The ClimateBasic program is operated by ASIAQ (Greenland Survey), while the GeoBasic program is operated in cooperation between the Danish National Environmental Research Institute (NERI) and the Institute of Geography, University of Copenhagen. A third sub-programme, MarinBasic, focusing on the marine environment and operated by the Greenland Institute of Natural Resources and NERI, was implemented in 2002.

In this study, high-resolution climate and hydrology data from the first eight years (1995–2003) of measurements at Zackenberg are presented to describe the variation in meteorological conditions and its effects on river discharge, suspended sediment load, suspended organic matter load and on river water conductivity. Furthermore, the data from the Zackenberg River drainage basin is extrapolated to give an estimate of the river discharge, suspended sediment yield and dissolved yield from land to the Young Sound/Tyrolerfjord system.

2.2 Physical setting

The study area is the drainage basin to the Young Sound/Tyrolerfjord system in High Arctic (according to: Bliss & Matveyeva, 1992) Northeast Greenland (Fig. 2.1a). The low-lying valley floors in the drainage basin (e.g. the valley Zackenbergdalen, ‘dalen’ means ‘valley’ in Danish) are located at the borderline between the continental and oceanic parts of the bioclimate subzone C – the Middle Arctic climate zone – with a mean July air temperature of about 5.0–7.0°C (Bay, 1999; Walkers et al., 2002). The drainage basin is situated in the Northeast Greenland National Park. It has a total area of 3,016 km^2 (landcover only

Figure 2.1 **(a)** Location map showing the drainage basin of the Young Sound/Tyrolerfjord system (3,016 km^2) and the Zackenberg River drainage basin (512 km^2). **(b)** Location map showing the Zackenberg River drainage basin (512 km^2). H and C in the lower right-hand corner indicate the location of the hydrometric station and the meteorological station, respectively. The dashed line indicates the fault separating Caledonian gneiss and granite to the west (422 km^2) from Cretaceous and Tertiary sandstones and basalts to the east (90 km^2) (Modified from Rasch, 2000).



2,620 km^2) and drains into the more or less east-west oriented Young Sound/Tyrolerfjord with a total length of c. 90 km. The altitude of the drainage basin varies between 0 and 1,700 m above sea level (ASL), and lakes and glaciers cover 0.4% and 25%, respectively, of the drainage basin. Geologically the area mainly consists of Caledonian gneiss and granite to the west and Cretaceous and Tertiary sandstones and basalts to the east (Koch & Haller, 1971). The two settings are separated by a fault running through the valleys Zackenbergdalen and Lindemansdalen (Fig. 2.1b). Generally, the landscape is characterised by wide U-shaped valleys with gently sloping sides in the sandstone/basalt regions and narrow and deeper U-shaped valleys with steep valley sides in the gneiss regions. Quaternary deposits occur mainly in the lower part of the landscape as tills in various moraines and as marine/deltaic deposits in raised marine deltas below 70 m ASL.

Almost all data on meteorological conditions, river discharge and sediment yield from land to the Young Sound/Tyrolerfjord system has been collected in the Zackenberg River drainage basin, situated close to the Zackenberg Research Station. River discharge, sediment and solute discharge from the Zackenberg River are being measured approximately 2 km upstream from the mouth of the Zackenberg River. The Zackenberg River drainage basin has an area of 512 km^2 (1/6 of the Young Sound/Tyrolerfjord drainage basin) of which 101 km^2 (or approximately 20%) is glacierized by ice caps, valley glaciers, and cirques, mainly in the western part (Rasch et al., 2000; Rysgaard et al., 2003) (Fig. 2.1b). The Zackenberg River drainage basin is not connected to the Greenland Ice Sheet. The altitude of the drainage basin varies between 0 and 1,450 m ASL. (Fig. 2.1b), extensive plateaus with glaciers occur above c. 1,000 m ASL. (79% of the glacier cover), and wide U-shaped valleys carved out by glacial erosion occur below the plateaus (c. 200 m ASL) with extensive and nearly horizontal valley floors. Most of the lakes in the drainage basin are minor except for the lake Store Sø (4.9 km^2; c. 1%) occurring as a widening of Zackenberg River in Store Sødal. The aspect is almost homogeneous, with the majority (16.8%) of slopes facing SE and 8.3% of slopes facing NW.

The two different geological settings, i.e. Caledonian gneiss and granite to the west, Cretaceous, and Tertiary sandstones and basalts to the east constitute 422 and 90 km^2, respectively, of the drainage basin. Well-developed soils mainly occur in the lower part of the landscape as Inceptisols and weakly developed Spodosols (Soil Survey Staff, 1999). The vegetation in the lowland varies from wet *Eriophorum scheuchzeri-Carex atrofusca* meadows to well-drained heaths characterised by *Cassiope* and *Dryas* characteristic of the bioclimate subzone C (Bay, 1999; Walkers et al., 2002). Vegetation is almost absent on the high-lying plateaus. The river regime in the area is intermediate between the "Arctic nival regime" and the "proglacial regime" according to Church (1974) (Rasch et al., 2000).

The nearest town is Scoresbysund c. 450 km to the south, while the nearest settlements are Daneborg and Danmarkshavn situated c. 20 km southeast and c. 200 km north of Zackenberg Research Station, respectively. Meteorological stations are present at all three locations.

2.3 Methods

This study is based on meteorology and hydrology data from 1995–2003 measured by the Zackenberg Basic monitoring programme.

The meteorological station in Zackenberg (UTM Zone 27: 8264700 mN; 513400 mE, 43 m ASL.) on a dry *Cassiope* heath. Since 1995 continuous time series of air temperature, ground temperature, relative humidity, air pressure, radiation, wind velocity have been recorded (Table 2.1). The variation in snow depth has been logged since 1997 using a Campbell Scientific SR50 Sonic Range Sensor. Spatial variation in snow cover and snow depletion in the central part of the valley lowland has been monitored since 1997 using digital camera images from cameras mounted 477 m ASL on the Zackenberg Mountain (Table 2.1).

The solid precipitation is calculated from the rise in the accumulation curves of the recorded snow depth. When noise is removed, the rise in snow depth is multiplied by a variable density for snow (from 69.5 kg m^{-3} to 199.2 kg m^{-3}, average 81.4 kg m^{-3}) as a function of air temperature (Brown et al., 2003) and by an hourly settling rate for the snow pack (Anderson, 1976), to estimate the snow-water-equivalent precipitation (Table 2.2).

In Søgaard et al. (2001) basin evapotranspiration including sublimation for Zackenberg (1995/1996 to

Table 2.1 Parameters measured and sensors used for measurements of the meteorological conditions at the meteorological stations in the valley Zackenbergdalen.

Parameter	Unit	Period	Sensor type	Location	Above terrain	Frequency	Accuracy
Wind Direction	Deg.	Since 17 August 1995	Theodor Friedrichs & Co, 4121	8264700 mN, 513400 mE (43 m ASL)	7.5 m	10-min. intervals	± 5 deg.
Wind Speed	m s^{-1}	Since 17 August 1995	Theodor Friedrichs & Co, 4033	8264700 mN, 513400 mE (43 m ASL)	2.0 m	10-min. intervals	± 0.3 m s^{-1} for v > 15 m s^{-1}
Wind Speed	m s^{-1}	Since 17 August 1995	Theodor Friedrichs & Co, 4034	8264700 mN, 513400 mE (43 m ASL)	7.5 m	10-min. intervals	± 0.3 m s^{-1} for v > 15 m s^{-1}
Air Temperature	°C	Since 17 August 1995	Vaisala, HMP 35	8264700 mN, 513400 mE (43 m ASL)	2.0 m	1-hour intervals	± 0.3°C
Air Temperature	°C	Since 17 August 1995	Vaisala, HMP 35	8264700 mN, 513400 mE (43 m ASL)	7.5 m	1-hour intervals	± 0.3°C
Relative Humidity	%	Since 17 August 1995	Vaisala, HMP 35	8264700 mN, 513400 mE (43 m ASL)	2.0 m	1-hour intervals	± 2% for 0-90% RH ± 3% for 90-100% RH
Air Pressure	mbar	Since 17 August 1995	Vaisala, PTB200A	8264700 mN, 513400 mE (43 m ASL)	1.6 m	1-hour intervals	± 0.15 mbar
Incoming Shortwave Radiation	W m^{-2}	Since 17 August 1995	Kipp & Zonen, CM7B	8264700 mN, 513400 mE (43 m ASL)	2.0 m	1-hour intervals	± 1%
Outgoing Shortwave Radiation	W m^{-2}	Since 17 August 1995	Kipp & Zonen, CM7B	8264700 mN, 513400 mE (43 m ASL)	2.0 m	1-hour intervals	± 1%
Net Radiation	W m^{-2}	Since 17 August 1995	Kipp & Zonen	8264700 mN, 513400 mE (43 m ASL)	2.0 m	1-hour intervals	-----
Precipitation (Tipping bucket)	mm w.eq.	Since 17 August 1995	Belfort with Nipher (Universal Precipitation Gauge, serie no 5-780-4.8)	8264700 mN, 513400 mE (43 m ASL)	1.5 m	when bucket is full	0.5% (0.2 mm at one tip)
Snow depth	m	Since 26 June 1997	Campbell SR50	8264774 mN, 513480 mE (43 m ASL)	1.66 m	3-hour intervals	+/- 1 cm or 0.4% of distance to target (whichever is greatest)
Automatic Digital Camera:							
Camera 1		Since Summer 1999	Kodak DC-50	8265315 mN, 510992 mE (477 m ASL)	-----	Daily pictures at solar noon, 1.20 pm	756*504 pixels per inch (~20 m resolution)
Camera 2		Since Summer 1997	Kodak DC-50				
Camera 3		Since Summer 2001	Kodak DC-120				

Table 2.2 Parameters measured and sensors used for hydrological measurements, Zackenberg.

Parameter	Unit	Periode	Sensor type	Location	Frequency	Accuracy
Water level	m	Since August 1995 (automatic)	Campbell SR50	8264582 mN; 512538 mE (14 m ASL)	15-minute intervals	+/- 1 cm or 0.4% of distance to target (whichever is greatest)
Water discharge	m^{3} s^{-1}	Summer season (manual)	Ott C31 current meter	8264582 mN; 512538 mE (14 m ASL)	10-15 per season	+/- 5-10%
Suspended sediment	g l^{-1}	Summer season (manual)	Nilssons depth-integrating sampler	8264582 mN; 512538 mE (14 m ASL)	Daily, 8 am	-----
Water conductivity	µS cm^{-1}	Summer season (manual)	YSI 30	8264582 mN; 512538 mE (14 m ASL)	Daily, 8 am	+/- 0.5% (full scale)

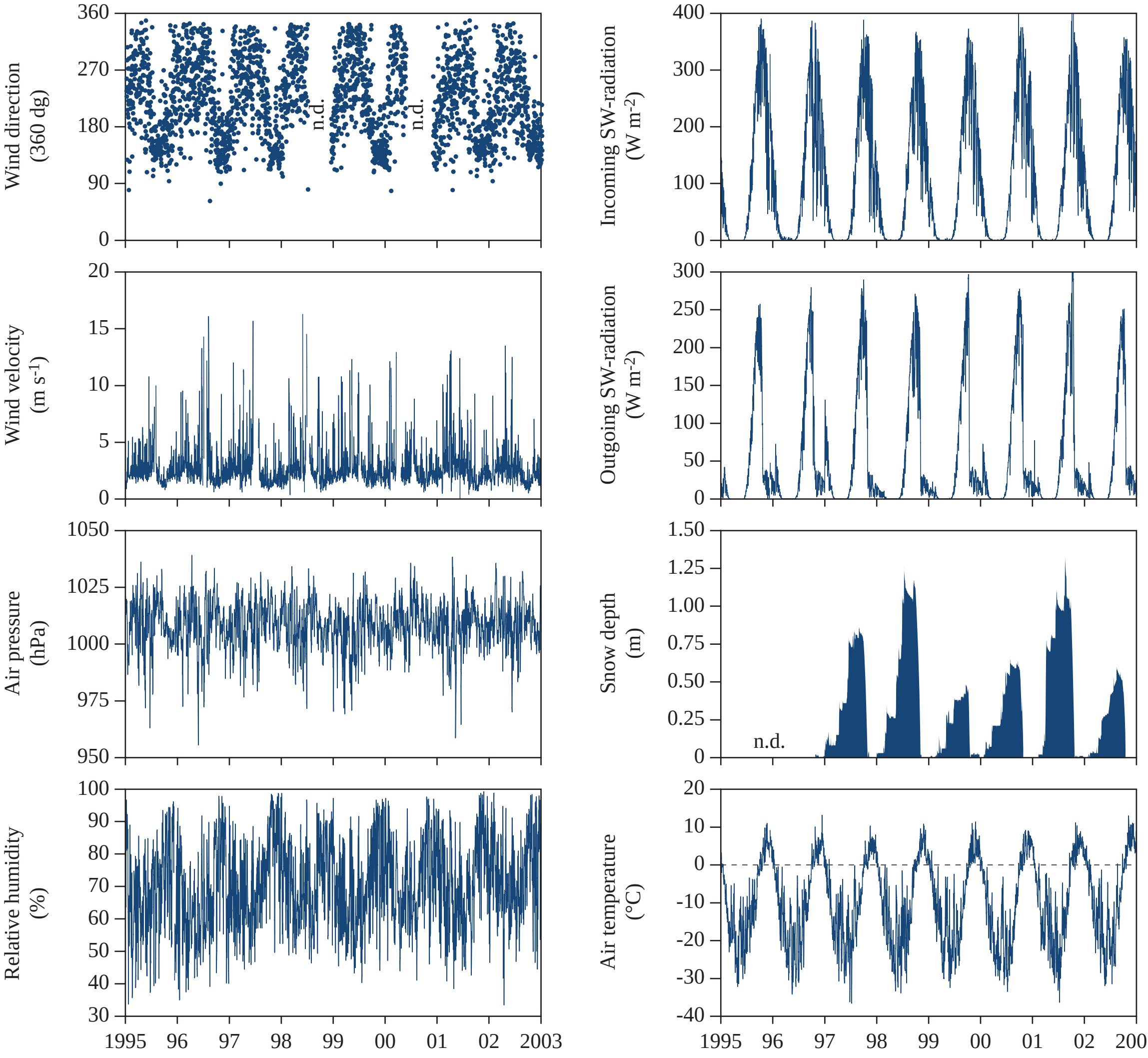


Figure 2.2 Daily mean values of meteorological parameters and snow cover at Zackenberg, 1995–2003. Note the difference in ordinate scale.

1997/1998) is calculated based on atmospheric fluxes measured by eddy correlation technique. High correlation exists (linear regression) between annual evapotranspiration and annual sum of Thawing Degree Days (TDD) (September to August) (see definition in section 2.4) for the seasons 1995/1996 to 1997/1998. Therefore, TDD is used to estimate evapotranspiration (ET) (Eq. 1):

$$\mathrm{ET\,(mm)} = 0.44\mathrm{TDD} - 77.5 \; (R^2 = 0.98;\, p<0.01) \qquad (1)$$

from the Zackenberg drainage basin for the seasons 1998/1999 to 2002/2003. Evapotranspiration from a basin comes from snow and glacier surfaces, water surfaces and soil and vegetation surfaces. Therefore, ET as a function of TDD may to some extent be overestimated, because soils dry up during the summer.

In the lower part of the Zackenberg River, a hydrometric station (Fig. 2.1) has been measuring water level since 1995 and water conductivity since 2003. Water level is logged automatically once every 15 minutes throughout the year using a sonic range sensor (Campbell Scientific SR50) and water conductivity in runoff seasons, only, using a conductivity and temperature probe (Campbell Scientific 247). Manual river discharge measurements are carried out at the hydrometric station 8–10 times during the runoff season with an Ott C31 current meter to validate the stage-discharge relation and to describe the runoff in the period when riverbanks and riverbed are still covered by snow and ice. During the first c. 1–2 weeks after river break-up, the river discharge measured automatically is probably unreliable, as the river bed and banks are partly covered by snow and ice, leading to changes in river bed cross profile, less friction at the river bed and raised water level due to snow at the river bed. The stage-discharge relation gradually becomes more and more valid as snow and ice melt. The stage-discharge relation is based on river discharge measurements from the period 1995–1998. Manual river discharge measurements in 1999–2003 indicate that the river cross profile has remained stable and that the stage-discharge relation is still valid. Total annual river discharge is quantified from the water level measurements and the stage-discharge relation. River water conductivity is measured manually in the field at 8 am using an YSI 30 incorporated conductivity meter.

Water samples have been collected every day at 8 am during the runoff season since 1997 using a Nilsson's depth-integrating sampler (Nilsson, 1969). In the summer of 1997, samples were collected at both 8 am and 6 pm. Suspended sediment concentrations are measured by filtering water samples (0.8 l) onto Whatmann GF/F filters (0.7µm) pre-weighed, and drying at 105°C and weighed again. Suspended organic matter concentration is estimated as LOI (Loss On Ignition), *i.e*. the difference between dry weight (105°C) and ash-free dry weight (520°C) (Sykes et al., 1999). An additional daily water sample is collected for chemical analyses. Major anions and cations are measured in filtered subsamples (0.45 µm). Analysis of dissolved organic carbon (DOC) is now incorporated in the monitoring programme but results in this paper are based on only nine DOC analyses on samples selected at regular intervals throughout the runoff season 2003. Dissolved inorganic carbon is based on daily alkalinity analyses.

Total annual transport of suspended sediment and suspended organic matter from the Zackenberg River to Young Sound/Tyrolerfjord is calculated by multiplying the concentrations measured in water samples at 8 am by average daily river discharge and summing these results up for the whole runoff season.

Since the geology and the glacier cover is almost the same in the Zackenberg River drainage basin (c. 20% glacier cover) as in the Young Sound/Tyrolerfjord drainage basin (c. 25%) this should probably not affect the rough upscaling of the suspended sediment transport to the entire Young Sound/Tyroler-fjord.

2.4 Indices and parameters

The following air temperature indices "degree day models" were calculated as estimates of the influence of the climate on the surrounding environment: (1) the accumulated Freezing Degree Days (FDD) is the sum of the numeric values of negative mean daily air temperatures and the number of Freezing Days (FD) is the sum of days with negative mean daily air temperatures per year; (2) the accumulated number of Thawing Degree Days (TDD) is the sum of values of positive mean daily air temperatures and the number of Thawing Days (TD) is the sum of days with mean positive daily air temperatures per year (Bay, 1992; Hinkler et al., 2002). TDD and TD are related to release of water from the annual snow pack and the exposed surfaces, when the annual snow cover has melted away. An increase of both will cause higher evaporation rates from wet surfaces and in particular cause increased runoff from the glaciated areas, and (3) the accumulated number of Growing Degree Days (GDD) is the sum of the values of mean daily air temperatures above 5°C and the number of Growing Days (GD) is the number of days with mean air temperatures above 5°C per year. Plant growth is more or less absent when daily mean air temperature is below 5°C. Therefore, GD and GDD are useful as threshold temperatures for defining the length and the intensity of the growing season (Hansen et al., 2003).

The elements of the water balance for a drainage basin depend on drainage basin characteristics and processes. The water balance equation (Eq. 2) is:

$$P - ET - R \pm \Delta S = 0 \pm \eta \qquad (2)$$

Where P is the precipitation input from snow and rain (possible condensation); ET is the evapotranspiration (possibly sublimation); R is runoff throughout the entire period of flow; ΔS is change in surface storage (lake, wetlands, channels, etc.), subsurface storage of groundwater, storage in the unsaturated (vadose) zone, storage in glacier and storage in snow pack, (including snowdrifts) and η is the balance discrepancy (error).

The total runoff ($R_{surface} + R_{subsurface} + R_{rain} + R_{snow} + R_{glacier}$) is normally the most reliable component measured in the water balance if the stage-discharge relation is stable and valid. The runoff is an integrated response of the hydrological processes in the catchment, and contrary to most other parameters in the water balance it is therefore not affected by the representativity of the measuring station (Killingtveit et al., 2003).

2.5 Results

2.5.1 Meteorological conditions

Daily mean values of meteorological parameters and snow cover at Zackenberg, 1995-2003, is shown in Fig. 2.2.

The Mean Annual Air Temperature (MAAT) at the Zackenberg Meteorological Station was –9.6°C (2.0 m) for the period 1995–2003 (Table 2.3). The MAAT variation is between –10.1°C (1997) and –8.6°C (2002) (Fig. 2.3a) and the mean monthly air temperatures (MMAT) (1995–2003) for January and July were, respectively, –21.1°C and 5.5°C (Table 2.3). In general, air temperatures above 0°C occur from early June to mid September (Table 2.3; Fig. 2.3b). The lowest air temperature (–38.9°C) measured at Zackenberg occurred on 23 February 1998 (DOY 54), while the highest air temperature (21.3°C) was recorded on 12 August 1997 (DOY 224). The air temperature indicates an annual warming of c. 0.1°C yr^{-1} (1996–2002) (based on linear regression, non-significant), and a warming in all seasons except spring (March–May). In spring, the air temperature decreases 0.7°C yr^{-1} ($p<0.01$; root mean square (rms) = 0.05), while the highest air temperature increase (0.4°C yr-1) occurs in autumn (September–November; $p<0.05$; rms = 0.25; Fig. 2.3a). Fig. 2.3b and Table 2.6 illustrate the increasing autumn air temperature, indicated by a longer thawing period in autumn (16 days) and a decreasing thawing period in spring (2 days) and resulting in a net increase of the thawing period of 14 days yr^{-1} from 1996–2003. In the same period, TDD increased from 385 to 561 yr^{-1} (Fig. 3.b and Table 2.6).

The mean annual wind velocity (1995–2003) was 2.7 and 3.2 m s^{-1}, respectively, 2.0 m and 7.5 m above terrain (Table 2.3), with a maximum 10-minute mean of 29.5 m s^{-1} (14 February 1998, DOY 45) during a period with northerly winds. In general, the wind velocity was relatively high during autumn and winter and somewhat lower during summer (Table 2.3). Mean monthly air temperature in the outer parts of Young Sound is shown i Table 2.4. A high frequency (44.0%) of winds (7.5 m above terrain) coming from northerly directions (Table 2.5) typical during winter, while easterly and southerly winds are normal during summer (Fig. 2.2). The mean annual relative humidity was 72% (1995–2003) (Table 2.3), and the uncorrected mean liquid precipitation for June, July and August (1995–2003) was 44 mm (Table 2.3), which is lower than the highest monthly precipitation of 55 mm (August 1998). The highest precipitation rate recorded was slightly above 4.8 mm h^{-1} (16 August 2002, DOY 228). The annual precipitation (September to August) varies between 199 mm (1999/2000) and 403 mm (1998/1999), with an average of 273 mm (1997–2003) (Table 2.3). Approximately 75% of the precipitation falls as snow (Soegaard et al., 2001; Rasch & Caning, 2003). Continuous winter snow cover (1997–2003) is established each year between the beginning of September and the end of October, and lasts until mid-late June (Table 2.6). The length of the snow-cover period has decreased 50 days (10 days in spring and 40 days in autumn), from 304 days (1997/1998) to 253 days (2002/2003) (Table 2.6). This reduction is probably not caused by reduced snow precipitation but by increased thawing rates during summer and autumn (Table 2.6). The maximum annual snow depth varies between 0.48 m (1999/2000) and 1.32 m (2001/2002), and the average annual snow depth varies between 0.26 m (1999/2000) and 0.72 m (2001/2002) (Table 2.6).

In the period 1996–2003, the annual average FDD was –3,865 and the mean number of FD was 266, with an annual variation between –4,015 and –3,619 for FDD and 246 and 277 for FD (Table 2.6). The annual average (1996–2003) TDD was 408 and the number of TD was 100. From 1996 to 2003, TDD increased from 385 to 561 (46%) (Fig. 2.3b) indicating a higher thawing rate and a prolonged thawing period. The thawing period was prolonged 14 days (12%), indicating a longer thawing season in autumn (Table 2.6; Fig. 2.3b). For 1996–2003, the annual average GDD was 77 and the number of GD was 37. Since 1999, GD has increased from about 30 up to 49 yr^{-1} (a 63% increase) (Table 2.6).

Meteorological time series since 1961 exist for Daneborg, with an almost continuous gap betwee

Table 2.3 Monthly maximum, average and minimum values of air temperature, wind velocity, relative humidity, air pressure, shortwave radiation in and out, albedo, net radiation and uncorrected summer liquid precipitation based on Zackenberg data, 1995–2003. Winter precipitation (from September to June) is calculated from rise in the accumulation curves of recorded snow depth, 1997–2003. (*) indicates precipitation sum instead of average value.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Average
Air temperature 2.0 m (°C)													
Maximum	-2.9	-6.6	5.2	7.0	9.3	14.9	19.1	21.3	10.7	4.2	-3.1	6.8	-----
Average	-21.1	-20.0	-19.8	-14.5	-5.5	1.9	5.5	4.8	-1.5	-10.1	-15.8	-19.2	-9.6
Minimum	-36.7	-38.9	-38.4	-32.1	-21.8	-6.2	-2.6	-4.0	-13.0	-25.0	-27.8	-34.7	-----
Air temperature 7.5 m (°C)													
Maximum	-3.9	-0.3	-5.3	7.3	8.6	14.4	18.8	21.1	10.4	5.0	4.0	7.1	-----
Average	-19.9	-19.0	-12.6	-13.4	-5.3	1.8	5.2	4.7	-1.2	-9.3	-11.8	-18.0	-8.2
Minimum	-34.6	-37.0	-37.1	-30.8	-20.1	-5.6	-2.8	-3.5	-10.9	-23.7	-25.7	-33.0	-----
Wind velocity 2.0 m (m s^{-1})													
Maximum	20.7	25.6	22.3	22.6	17.6	13.1	13.0	12.3	16.9	25.6	20.1	21.6	-----
Average	3.1	3.9	2.8	2.4	2.2	1.7	2.4	2.3	2.5	3.1	3.0	3.0	2.7
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-----
Wind Velocity 7.5 m (m s^{-1})													
Maximum	29.5	22.5	17.1	24.5	19.9	15.1	15.9	14.9	15.6	20.1	24.2	25.4	-----
Average	3.7	4.7	3.5	2.7	2.6	1.9	2.7	2.6	2.9	3.7	3.5	3.7	3.2
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-----
Relative humidity													
2.0 m (%)	96.7	98.9	95.1	97.6	98.5	99.9	100.0	100.0	99.3	99.4	96.3	97.1	-----
Maximum	63.7	69.3	68.1	69.2	77.3	82.7	82.3	79.5	73.5	69.3	66.0	63.8	72.0
Average	18.6	27.9	22.4	18.3	27.0	23.0	21.6	18.4	22.0	25.5	16.7	22.7	-----
Minimum													
Air Pressure (hPa)													
Maximum	1,036.9	1,042.0	1,066.3	1,034.9	1,35.4	1,023.3	1,026.4	1,028.6	1,037.9	1,035.6	1,035.6	1,042.5	-----
Average	1,004.5	1,003.1	1,009.6	1,013.3	1,013.0	1,009.8	1,006.2	1,005.9	1,007.4	1,008.7	1,008.6	1,007.6	1,008.1
Minimum	953.0	956.2	961.3	955.8	992.8	989.2	983.5	968.6	962.5	960.6	960.6	972.0	-----
Short-wave Rad In 2.0 m (W m^{-2})													
Maximum	15.7	166.2	469.2	730.9	833.0	920.0	863.0	748.0	537.3	281.5	24.2	11.9	-----
Average	0.6	6.8	61.8	172.1	270.5	292.9	218.9	148.9	78.0	16.0	0.7	0.3	105.6
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-----
Short-wave Rad Out 2.0 m (W m^{-2})													
Max	6.2	127.3	386.0	661.5	682.6	741.0	348.0	255.2	370.3	192.6	17.6	3.2	-----
Average	0.5	5.7	53.0	140.8	218.3	144.0	25.2	18.2	23.4	10.2	0.3	0.1	53.5
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-----
Albedo	81.8	83.2	85.6	81.7	80.8	49.6	11.5	12.2	29.9	64.0	61.0	88.4	60.8
Net Rad 2.0 m (W m^{-2})													
Maximum	17.4	34.2	73.8	106.1	172.7	633.6	609.4	537.5	328.8	124.8	12.3	16.8	-----
Average	-23.2	-19.5	-21.5	-20.1	-4.4	86.8	127.8	69.8	5.7	-26.5	-24.7	-17.3	11.1
Minimum	-92.8	-74.0	-101.5	-83.9	-165.4	-128.5	-60.9	-101.6	-123.7	-169.9	-198.9	-186.4	-----
Precipitation sum (mm w.eq.)	30.7	56.0	16.7	14.5	15.5	10.4	15.9	18.1	8.4	21.7	39.1	26.2	273.2(*)
Maximum summer intensity (mm/h)	-----	-----	-----	-----	-----	6.3	4.7	4.8	-----	-----	-----	-----	-----

Table 2.4 Mean monthly air temperature (MMAT)(°C) at Daneborg meteorological station approximately 20 km southeast of the Zackenberg River drainage basin, 1995–2002 (www.dmi.dk).

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Average
Mean monthly air temperature,°C	-19.8	-19.9	-18.9	-13.3	-4.9	2.1	4.7	4.7	-1.5	-9.9	-14.7	-19.2	-9.2

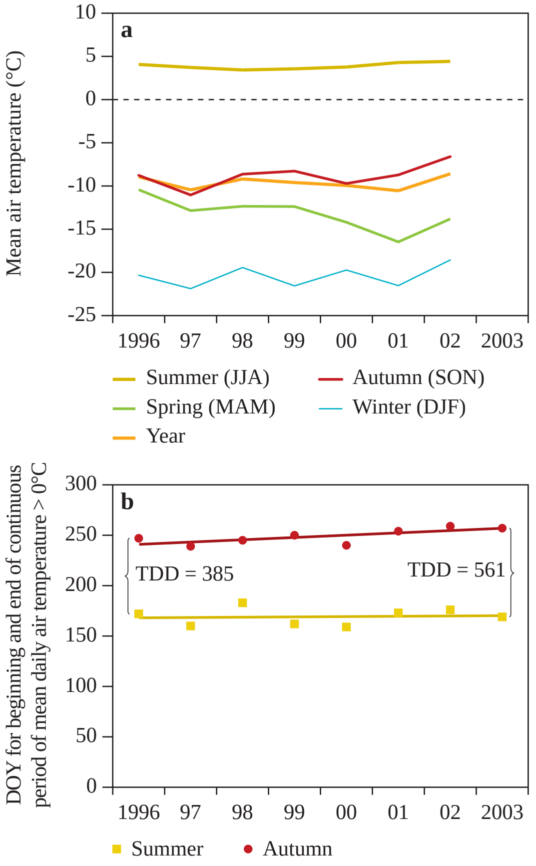


Figure 2.3 (a) Mean annual and seasonal air temperature at Zackenberg in the period 1996–2002. The abbreviations mean: DJF (December–January–February), MAM (March–April–May), JJA (June–July–August) and SON (September–October–November). **(b)** Day of year (DOY) for the beginning and the end of the continuous period of mean daily air temperatures above 0°C in Zackenbergdalen (1996–2003). The trend lines (linear regression) indicate lengthening of the thawing season in autumn (16 days) (1996–2003) and shortening in spring (2 days), indicating a net lengthening of the thawing season of 14 days. Furthermore, the increase in Thawing Degree Days (TDD) from 385 (1996) to 561 (2003) (46% increase) is illustrated.

AT at Zackenberg (–9.6°C) (1995–2003). A linear relation exists for MMAT between Zackenberg and Daneborg (1995–2002) (Eq. 3):

$$\mathrm{MMAT_{Zackenberg}}\,(°\mathrm{C}) = 1.03\mathrm{MMAT_{Daneborg}}\,(°\mathrm{C}) + 0.24\ (R^2 = 0.99;\ p<0.01) \qquad (3)$$

where 1.03 indicates a more pronounced continental climate at Zackenberg. Between Zackenberg and Scoresbysund (1995–1999) (Eq. 4), and between Zackenberg and Danmarkshavn (1995–1999) (Eq. 5), the linear relations are, respectively:

$$\mathrm{MMAT_{Zackenberg}}\,(°\mathrm{C}) = 1.31\mathrm{MMAT_{Scoresbysund}}\,(°\mathrm{C}) - 2.62\ (R^2 = 0.97;\ p<0.01) \qquad (4)$$

and

$$\mathrm{MMAT_{Zackenberg}}\,(°\mathrm{C}) = 0.97\mathrm{MMAT_{Danmarkshavn}}\,(°\mathrm{C}) + 1.41\ (R^2 = 0.97;\ p<0.01) \qquad (5)$$

In the period 1968–99, the MAAT in Scoresbysund, Daneborg and Danmarkshavn increased c. 4°C (p<0.01), c. 2°C (p<0.01) and c. 1°C (p<0.01), respectively, (Cappelen et al., 2001). The highest changes in MMAT for the three locations between 1968 and 1999 are in autumn and winter, while spring and summer temperatures are quite stable.

2.5.2 Runoff

At Zackenberg, the date of river break-up at the hydrological measuring station has varied from year to year between 30 May (2003, DOY 150) and 10 June (1998, DOY 161) during the period 1996–2003 (Table 2.7). Approximately 10–20% of the snow pack in the valley Zackenbergdalen normally melts before the river breaks up (Table 2.6; Table 2.7). The river discharge varies between 122 million $m^3\ yr^{-1}$ (corresponding to a runoff of 239 mm yr^{-1}) for 1996 and 306 million $m^3\ yr^{-1}$ (corresponding to a runoff of 598 mm yr^{-1}) for 2002 (Table 2.7; Fig. 2.4). The mean annual river discharge for the period 1996–2003 was 188 million $m^3\ yr^{-1}$, corresponding to a runoff of 368 mm yr^{-1}. Annual runoff generally peaks in the beginning of the runoff season between DOY 161 and 190, and is caused mainly by melting of snow, except for 1998 (16 August, DOY 228) (Table 2.7; Fig. 2.4), when an extreme flood occurred (123.0 $m^3\ s^{-1}$) after 17 hours with rain (23.9 mm) and a 60-hour period with maximum and mean air temperatures of 8.8°C and 6.5°C, respectively. Maximum river discharge (158.9 $m^3\,s^{-1}$) was measured 10 June 2002 (DOY 161) after a warm period (thirty hours with a mean air temperature of 5.3°C) resulting in increased snow melt (Table 2.7; Fig. 2.4).

2.5.3 Suspended sediment load, suspended organic matter load, organic/inorganic carbon and water conductivity

Total annual transport of suspended sediment from the Zackenberg River to Young Sound/Tyrolerfjord (1997–2003) is in the range of 15,000 to 130,000 t yr^{-1}

Table 2.5 Wind statistics: Wind direction (7.5 m) and wind velocity (7.5 m) based on data from 1997, 1998, 2000 and 2002. Wind statistics for 1995, 1996, 1999, 2001 and 2003 are not included due to lack of complete time series.

	N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**	**S**	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	**Calm**
Wind direction, 7.5 m (%)	12.2	3.4	2.5	2.7	4.5	7.5	8.3	5.0	3.8	2.8	2.5	2.7	2.7	3.4	6.9	24.9	4.4
Mean wind velocity, 7.5 m ($m\ s^{-1}$)	4.2	2.7	2.6	2.3	2.1	2.2	2.4	2.4	2.4	2.3	2.1	2.4	2.4	2.7	3.7	5.1	
Maximum wind velocity, 7.5 m ($m\ s^{-1}$)	29.5	25.4	19.4	15.6	10.4	10.3	18.1	16.2	9.9	13.4	12.2	15.9	23.5	19.0	25.1	25.8	

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Mean annual wind velocity, 7.5 m ($m\ s^{-1}$)	No data	3.0	3.4	3.2	3.7	3.1	3.2	3.0
Maximum wind velocity ($m\ s^{-1}$) and wind direction (deg.), 7.5 m.	No data	23.1 (84 deg.)	26.2 (359 deg.)	29.5 (356 deg.)	22.0 (329 deg.)	23.5 (260 deg.)	25.0 (4 deg.)	24.5 (338 deg.)

Table 2.6 Air temperature (2.0 m), freezing degree days (FDD), freezing days (FD), thawing degree days (TDD), thawing days (TD), growing degree days (GDD), growing days (GD) and snow cover for Zackenberg (1996–2003). Snow depletion data for the valley Zackenbergdalen are from Hinkler et al. (2002, 2003). Data from 1995 is not included, due to lack of time series for the entire years.

Air Temperature, 2.0 m (C) and day of year (DOY)	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Maximum (°C)	16.6 (203)	21.3 (224)	13.8 (197)	15.2 (220)	19.1 (189)	12.6 (213)	14.9 (179)	16.7 (198)
Average (°C)	-9.2	-10.1	-10.0	-9.5	-10.0	-9.7	-8.6	-9.2
Minimum (°C)	-33.7 (4)	-36.2 (15)	-38.9 (54)	-36.3 (88)	-36.7 (29)	-35.1 (63)	-37.7 (66)	-34.0 (27)
Continuous period of mean daily air temperature above 0°C, 2.0 m	DOY 172–247 (20 JUN – 3 SEP)	DOY 160–239 (9 JUN – 27 AUG)	DOY 183–245 (2 JUN – 2 AUG)	DOY 162–250 (11 JUN – 7 SEP)	DOY 159–240 (7 JUN – 27 AUG)	DOY 173–254 (22 JUN – 11 SEP)	DOY 176–259 (25 JUN – 16 SEP)	DOY 169–257 (18 JUN – 14 SEP)
Freezing degree days (FDD) and Freezing days (FD) (air temperature < 0°C)	-3,646 (271 days)	-4,015 (271 days)	-3,855 (276 days)	-3,833 (263 days)	-4,045 (277 days)	-3,984 (263 days)	-3,619 (246 days)	-3,924 (259 days)
Thawing degree days (TDD) and Thawing days (TD) (air temperature > 0°C)	385 (95 days)	354 (94 days)	333 (89 days)	358 (102 days)	370 (89 days)	433 (102 days)	471 (119 days)	561 (106 days)
Growing degree days (GDD) and Growing days (GD) (air temperature > 5 °C)	72 (32 days)	54 (31 days)	44 (30 days)	65 (27 days)	80 (35 days)	78 (43 days)	77 (44 days)	147 (49 days)

	1996-1997	**1997-1998**	**1998-1999**	**1999-2000**	**2000-2001**	**2001-2002**	**2002-2003**
Continuous snow cover at the climate station.							
Maximum snow depth (m)	No data	0.87	1.23	0.48	0.65	1.32	0.60
Average snow depth (m)		0.43	0.56	0.26	0.35	0.72	0.20
Period with snow cover (days)		DOY 241–180 (304 days)	DOY 244–187 (308 days)	DOY 303–168 (230 days)	DOY 266–176 (275 days)	DOY 287–172 (250 days)	DOY 280–168 (253 days)
10% snow depletion in Zackenbergdalen (DOY)	163	158	175	-----	152	157	-----
20% snow depletion in Zackenbergdalen (DOY)	169	166	179	159	156	162	152
50% snow depletion in Zackenbergdalen (DOY)	176	182	186	164	167	170	163
75% snow depletion in Zackenbergdalen (DOY)	183	192	195	169	177	179	166
90% snow depletion in Zackenbergdalen (DOY)	195	198	214	175	186	189	173
100% snow depletion in Zackenbergdalen (DOY)	-----	-----	-----	238	238	-----	221

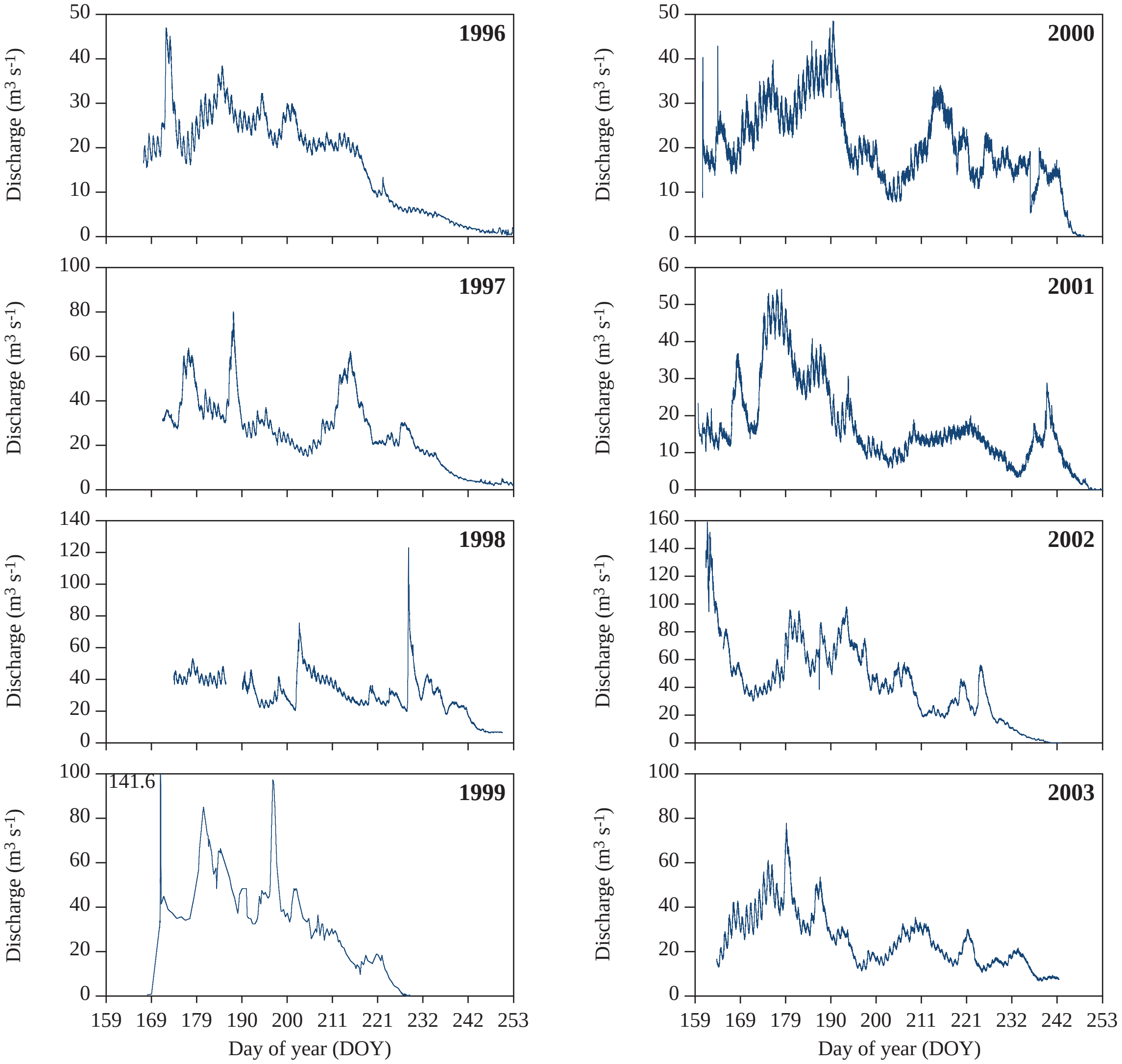


Figure 2.4 River discharge from the Zackenberg River based on 15-minute values from DOY 159–262 (1996–2003). Discharge curve for 1999 is based on manual readings, as the hydrometric station was flushed away during a violent break-up flood. Note the difference in ordinate scale.

(Table 2.8). This corresponds to a specific annual suspended sediment load between 29 and 253 t km^{-2} yr^{-1} for the Zackenberg River drainage basin. The average concentration of suspended sediment in the Zackenberg River is between 0.1 and 0.2 g l^{-1} (Table 2.8; Fig. 2.5). Peaks in suspended sediment transport are often observed during periods with high river discharge following precipitation events and high melting rates. Maximum concentration of suspended sediment (46.9 g l^{-1}) was measured in 1998 (DOY 228) during/after the 17-hour rainstorm. During this "extreme event", c. 105,000 t of suspended sediment was transported through Zackenberg River. The total suspended sediment transport during this event (c. 3 days) was 1.7 to 7.0 times larger than the total annual transport in the remaining years of the period 1997–2003 (Table 2.8).

Suspended organic matter constitutes 5–12% of the suspended sediment on an annual basis (Table 2.8). Total annual transport of suspended organic matter from Zackenberg River to Young Sound/Tyrolerfjord (1997–2003) is in the range of 1,100 to 11,500 t yr^{-1} (Table 2.8). This corresponds to a specific annual suspended organic matter load between 2 and 22 t km^{-2} yr^{-1} for the Zackenberg River drainage basin. The average concentration of suspended organic matter in the Zackenberg River is between 0.01 and 0.21 g l^{-1} (Table

Table 2.7 Date of break-up, period of measured river discharge and monthly and annual river discharge in the Zackenberg River measured at the hydrometric station (1996–2003).

	1996	1997	1998	1999	2000	2001	2002	2003
Break-up of river (DOY)	154	155	161	160	160	159	155	150
Period of measured river discharge (DOY)	167-252	172-252	174-246	168-229	160-249	159-251	161-242	164-243
Peak river discharge ($m^3\ s^{-1}$)	47.0	80.1	123.0	141.6	48.5	54.1	158.9	77.8
Date of peak river discharge (DOY)	172	188	228	171	190	178	161	180
Total measured river discharge June, million m^3 and (mm w.eq.)	32.74 (64)	44.64 (87)	50.09 (98)	41.14 (80)	47.10 (92)	52.79 (103)	110.39 (216)	71.03 (139)
Total measured river discharge July, million m^3 and (mm w.eq.)	67.30 (131)	80.22 (157)	98.50 (192)	122.82 (240)	61.32 (120)	47.40 (93)	149.73 (292)	71.16 (139)
Total measured river discharge August, million m^3 and (mm w.eq.)	21.43 (42)	60.66 (118)	78.48 (153)	16.96 (33)	46.64 (91)	33.90 (66)	46.07 (90)	42.77 (84)
Total measured river discharge September, million m^3 and (mm w.eq.)	0.73 (1)	2.43 (5)	4.28 (8)	No Data	0.37 (1)	3.17 (6)	No Data	No Data
Annual measured river discharge, million m^3 and (mm w.eq.)	122.18 (239)	187.95 (367)	231.37 (452)	180.93 (353)	155.42 (304)	137.26 (268)	306.19 (598)	185.20 (361)

Table 2.8 Suspended sediment yield, suspended organic matter yield, organic/inorganic carbon and water conductivity in the Zackenberg River measured at the hydrometric station at 8 am (1997–2003).

	1997	1998	1999	2000	2001	2002	2003
Suspended sediment transport (t) and specific suspended sediment load ($t\ km^{-2}\ yr^{-1}$)	29,444 (57.52)	130,133 (254.17)	18,761 (36.64)	14,958 (29.22)	16,906 (33.02)	60,667 (118.49)	18,245 (35.64)
Suspended sediment ($g\ l^{-1}$)							
Maximum	1.914	46.925	0.444	0.248	0.816	2.994	0.319
Average	0.112	2.587	0.089	0.160	0.119	0.132	0.096
Minimum	0.004	0.007	0.002	0.006	0.018	0.039	0.041
Suspended organic matter transport (t)	1.643	11.551	2.297	1.340	1.101	3.299	1.353
Suspended organic matter ($g\ l^{-1}$)							
Maximum	0.027	3.845	0.040	0.297	0.083	0.026	0.046
Average	0.009	0.213	0.007	0.012	0.007	0.009	0.007
Minimum	0.003	0.003	0.002	0.002	0.002	0.003	0.004
Carbon (t)							
Particulate organic carbon (POC)	No data	No data	No data	No data	No data	No data	416
Dissolved organic carbon (DOC)							421
Dissolved inorganic carbon (DIC)							342
Total transport of carbon							1,179
Water conductivity ($\mu S\ cm^{-1}$)							
Maximum	66	302	104	101	118	67	58
Average	29	100	43	31	28	24	16
Minimum	18	23	25	19	11	11	11

2.8), with a maximum concentration of $3.8\ g\ l^{-1}$ measured during the extreme event in 1998.

Organic carbon is transported through the fluvial system in both dissolved (DOC) and particulate form (POC). Results from 2003 show that the suspended organic matter determined by LOI contains 35% C (POC) (Table 2.9). The total fluvial transport of carbon also includes dissolved inorganic carbon (DIC) from dissolution of soil carbonate minerals. Based on data from the 2003 runoff season the three different forms of carbon are almost equal in amount: POC ($416\ t\ yr^{-1}$), DOC ($421\ t\ yr^{-1}$) and DIC ($342\ t\ yr^{-1}$). The total carbon transport for 2003 is accordingly estimated at approximately $1{,}179\ t\ yr^{-1}$ (Table 2.9). Peaks in POC are observed during periods with high river discharge, and the relation between suspended sediment concentration (Cs) and POC concentration is linear (Eq. 6):

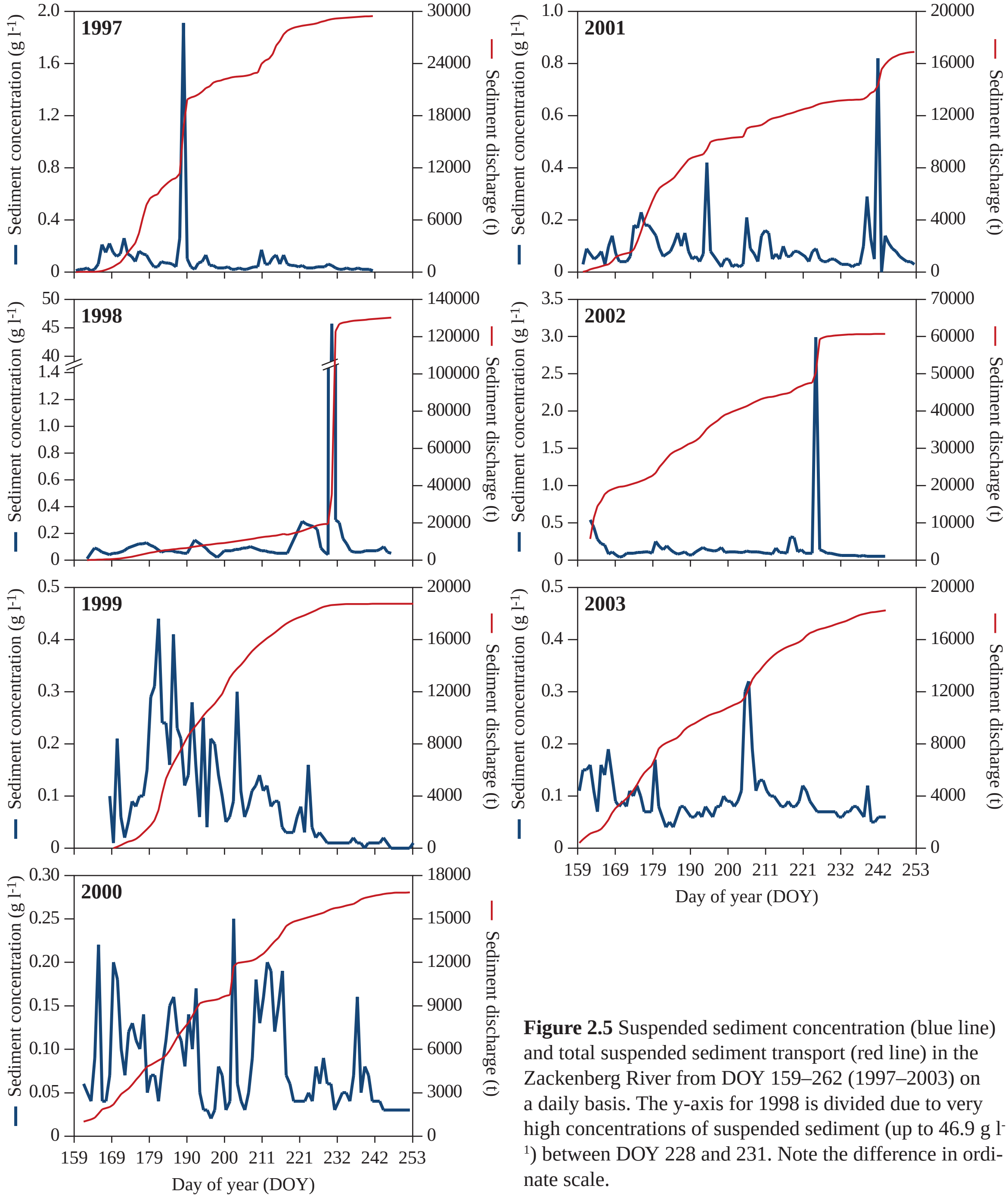


Figure 2.5 Suspended sediment concentration (blue line) and total suspended sediment transport (red line) in the Zackenberg River from DOY 159–262 (1997–2003) on a daily basis. The y-axis for 1998 is divided due to very high concentrations of suspended sediment (up to 46.9 g l^{-1}) between DOY 228 and 231. Note the difference in ordinate scale.

$$\text{POC (mg l}^{-1}\text{)} = 0.02\text{Cs (mg l}^{-1}\text{)} + 0.37 \quad (R^2 = 0.60;\ p<0.01) \qquad (6)$$

Average water conductivity in the Zackenberg River ranges between 16 and 100 µS cm^{-1} (1997–2003), with a maximum conductivity at 302 µS cm^{-1} measured in 1998 during the 17-hour rainstorm (Table 2.8).

Average concentration values for different anions and cations are given in Table 2.9. The input of nitrate (NO_3^-) from the Zackenberg River to Young Sound is estimated at 13 t yr^{-1} in 2003 based on the NO_3^- concentrations in the river water at 8 am. Nitrate concentrations generally vary during the runoff season between 0.08 mg l^{-1} and 0.36 mg l^{-1} (1997–2003;

Table 2.9 Chemical characteristics of the Zackenberg River water. Maximum, average and minimum values for anions and cations measured in water samples collected at 8 am during 1997–2003. Values from the extreme event in 1998 (DOY 288) are not included.

	Cl-	NO_3^{2-}	SO_4	Na^+	Mg^{2+}	K^+	Ca^{2+}	Fe^{2+}	Al^{3+}
Anions and cations (mg l^{-1})									
Maximum	3,02	0,36	29,98	3,73	14,71	0,75	13,31	0,74	0,87
Average	0,59	0,16	6,17	0,80	0,92	0,42	3,51	0,23	0,28
Minimum	0,14	0,08	1,56	0,31	0,40	0,22	1,38	0,06	0,07

Table 2.9). Peak concentrations are found during the first weeks (2–3 weeks) after river break up, reflecting high river discharge. This results in a peak input of NO_3^- to Young Sound in June.

2.5.4 Total river discharge, suspended sediment yield, suspended organic matter yield and organic/inorganic carbon to Young Sound/Tyrolerfjord

The annual river discharge from the Zackenberg River (Zackenberg River drainage basin), varies between 122 million m^3 yr^{-1} (239 mm yr^{-1}) and 306 million m^3 yr^{-1} (598 mm yr^{-1}) (Table 2.7). To estimate the river discharge from the total Young Sound/Tyrolerfjord drainage basin it seemed reasonable to upscale from the Zackenberg River drainage basin (512 km^2) to the Young Sound/Tyrolerfjord drainage basin (2,620 km^2), because the Zackenberg River drainage basin, due to its intermediate position in the east-west running drainage basin of Young Sound/Tyrolerfjord, probably represents an average in terms of climate. Consequently, the contribution of river discharge to the Young Sound/Tyrolerfjord system is estimated to vary between 630 and 1,570 million m^3 yr^{-1} with an average of 970 million m^3 yr^{-1} (1996–2003; Table 2.10).

Based on the same assumptions it is suggested that the annual contribution of suspended sediment to the Young Sound/Tyrolerfjord system varies between 77,000 and 670,000 t yr^{-1} with an average of 210,000 t yr^{-1} (1997–2003; Table 2.10). The annual contribution of suspended organic matter is estimated to vary between 6,000 and 59,000 t yr^{-1} with an average of 17,000 t yr^{-1} (1997–2003). The total carbon discharge (POC, DOC and DIC) is 6,033 t yr^{-1} (2003) and the total NO_3^- discharge is 66.5 t yr^{-1} (2003; Table 2.10).

2.6 Discussion

Early in the runoff season, runoff is controlled mainly by the Zackenberg lowland snow melt (R_{snow}) (phase change from solids to liquids) (Rasch et al., 2000), which in turn depends on (1) the amount of available energy fluxes for melting, and (2) the available snow cover in the lowland, quantified by snow depth and snow depletion (Fig. 2.2; Table 2.6). Table 2.6 shows the snow depth and the snow depletion for the valley Zackenbergdalen (lowland), indicating that 10–20% of the snow cover melts before river break-up, which occurs within the first 10 days of June. The meltwater is probably stored as internal accumulation in the remaining snow before the river breaks up. From mid June to the end of June (2–3 weeks) 50% of the lowland snow melts, and by the end of July at least 90% of the snow cover disappeared. This results in a year-

Table 2.10 Rough estimate of the river discharge, suspended sediment yield, organic matter yield and organic/inorganic carbon from the Young Sound/Tyrolerfjord drainage basin.

	1996	1997	1998	1999	2000	2001	2002	2003	Average
Rough estimate of annual river discharge from the Young Sound/Tyrolerfjord drainage basin (million m^3)	630	960	1,180	930	800	700	1,570	950	970
Rough estimate of annual suspended sediment yield from the Young Sound/Tyrolerfjord drainage basin (thousand t)	No data	150	670	100	80	90	310	90	210
Rough estimate of annual organic matter yield from the Young Sound/Tyrolerfjord drainage basin (thousand t)	No data	8	59	12	7	6	17	7	17
Rough estimate of annual carbon yield from the Young Sound/Tyrolerfjord drainage basin (thousand t)	No data	No data	No data	No data	No data	No data	No data	6	6

View from the digital camera set up 477 m ASL (16 July 2005). Looking SE at the Zackenberg river delta and Young Sound.

to-year variation in runoff variability through June and July (Fig. 2.4), controlled mainly by snow melt in the lowland, and in part by precipitation events. Multiple regression shows significant correlation ($R^2 = 0.84$; $p<0.01$) between the total June-July discharge and winter average snow depth, and a less significant correlation ($R^2 = 0.33$; $p<0.10$) between the total June-July discharge and the total June-July precipitation, confirming the effect of snow melt in the early part of the runoff season. Maximum peak discharge (47–159 $m^3 s^{-1}$) is observed in June during the first 1/3 of the runoff period due to the lowland snow melt, except for the extreme 17-hour rainstorm in August 1998 (Fig. 2.4; Table 2.7).

In years with relatively high average snow depth 1999 (0.56 m) and 2002 (0.72 m) snow depletion is delayed compared with other years with lower average snow depth. The date for river break-up does not, however, change significantly in relation to average snow depth (no trend observed). River break-up occurs from DOY 154 to 161 (1996–2003; Table 2.7), approximately 16 to 20 days after the first continuous melting of snow has started at the Zackenberg Meteorological Station (Fig. 2.2; Table 2.6). In the investigation period 1996–2003 the two highest runoff peaks, 141.6 $m^3 s^{-1}$ (1999) and 158.9 $m^3 s^{-1}$ (2002), both in the early part of the melt season, correlate strongly with the lowland snow melt and the average snow depth.

Later in the runoff season when drainage from the lowland areas ceases, the runoff distribution is controlled by melting of the active layer (R_{ground}), by rainfall (R_{rain}), by melting of glaciers ($R_{glacier}$) and snow patches (R_{snow}) on the high-lying plateaus, above 1,000 m ASL (Rasch et al., 2000). Glaciers cover approximately 20% (101 km^2) of the drainage basin and, therefore, glacier meltwater will probably constitute an increasing part of the discharge throughout the runoff season as the snow cover decreases in the drainage basin, causing a more pronounced glacier runoff regime due to the melt rate from the glaciers located in the western part of the drainage basin (Fig. 2.1b). The form and size of the pronounced glacier runoff regime will probably be diminished and delayed through lake Store Sø on its way to Young Sound/Tyrolerfjord. This indicates a meltwater travel time of minimum 12 hours through the catchment (Rasch, 1999).

During the investigation period from 1996–2003, Thawing Degree Days (TDD) increased 46% while Thawing Days (TD) increased 12% (Table 2.6; Fig. 2.3b) mainly due to the increasing air temperature in autumn (0.4°C yr^{-1}; $p<0.05$) (Fig. 2.3a). This results in an intensified thawing rate, a prolonged thawing period in autumn (16 days) and a shorter snow cover period in spring (12 days) and autumn (39 days) (Table 2.6). This probably does not result in better growing conditions for vegetation due to the limited

Table 2.11 Annual water balance estimates (from September to August) from the Zackenberg drainage basin (1997–2003). Precipitation (P): winter precipitation is calculated from rise in the accumulation curves of recorded snow depth and summer precipitation from tipping-bucket measurements. Evapotranspiration (ET) (1998/1999 to 2002/2003) is calculated from linear regression based on evapotranspiration (ET) (1995/1996 to 1997/1998) and Thawing Degree Days (TDD) (1995/1996 to 1997/1998). Sublimation from snow is included in ET. Runoff (R) is measured at the hydrometric station, and storage (ΔS) is calculated as a residual term ($\Delta S = P - ET - R$) in the water balance. Snow drifting within the catchment and from nearby catchments is not included in the water balance.

	Precipitation (P) (mm w.eq.)	**Evaporation (ET) (mm w.eq.)**	**Runoff (R) (mm w.eq.)**	**Storage (ΔS) (mm w.eq.)**
1997–1998	259	68	448	-277
1998–1999	403	80	361	-58
1999–2000	199	85	304	-210
2000–2001	225	113	263	-171
2001–2002	370	129	604	-383
2002–2003	183	169	361	-367
Average	273	107	390	-244

amount of solar radiation in the beginning of October (Table 2.4). The longer autumn thawing period and the shorter autumn snow cover period indicate a longer period of meltwater release from exposed glacier surfaces, and, furthermore, an increase in runoff during the investigation period (Table 2.7). Precipitation (P) in the investigation period (1997–2003) is almost constant, 180–260 mm, except for two outliers 370 mm (2001/2002) and 403 mm (1998/1999) (Table 2.10) and the evapotranspiration (ET) during the investigation period varies between 68 mm (1997/1998) and 169 mm (2002/2003) (Table 2.11). Therefore, the increasing trend in annual runoff during the period (1996–2003) is likely not controlled by changes in precipitation or evapotranspiration but rather by increasing meltwater release from glacier storage (ΔS) (Table 2.11). This suggests a negative glacier mass balance.

Extensive glacier cover occurs in the western part of the Zackenberg River drainage basin (Fig. 2.1b). Subglacial erosion, which depends on the bedrock and the glacier dynamics, is probably a significant sediment contributor to the Zackenberg River. On the other hand, the lake Store Sø (Fig. 2.1b) acts as a reservoir where bed load and suspended sediment from the western part of the drainage basin is trapped. The retained sediment depends on the volume of the lake relative to the inflow (Hasholt, 2003). The trap efficiency of Store Sø has not been measured, but the lake undoubtedly lowers the suspended sediment transport from the Zackenberg drainage basin.

For the entire Zackenberg River drainage basin (512 km^2), the specific annual suspended sediment load is 29 to 253 t km^{-2} yr^{-1} (1997–2003; Table 2.8) during the investigation period. Results from reconnaissance along the Zackenberg River indicate that a major part of the suspended sediment in the river originates from the areas with Cretaceous and Tertiary sandstone in the eastern part of the catchment (Fig. 2.1b), indicating that the main contribution area is less than 512 km^2, and, furthermore, that specific yields are higher than 253 t km^{-2} yr^{-1}. River water from this part of the drainage basin does not pass through Lake Store Sø.

Recent studies on sediment transport to the Arctic Oceans (e.g. Borgen, 1996; Hasholt, 1996; Hasholt, 2003; Borgen & Bønsnes, 2003; pers. comm. Hasholt, 2005) suggest a specific sediment transport from glaciated basins in Greenland of c. 1,000 t km^{-2} yr^{-1} while non-glaciated basins have specific yields of c. 5 t km^{-2} yr^{-1}, and, in Svalbard, 586 t km^{-2} yr^{-1} from glaciated basins and 82.5 t km^{-2} yr^{-1} from non-glaciated basins. The lower values of specific annual suspended sediment load in the Zackenberg River drainage basin (29 to 253 t km^{-2} yr^{-1}) compared with other Arctic drainage basins might be due to the physical settings in Zackenberg, where glaciers are located in less erodable bedrock of Caledonian gneiss

Water discharge measurement in the Zackenberg River.

and granite, resulting in a smaller suspended sediment load compared with other Arctic catchments. It might also be a result of the method used in Zackenberg, where sediment transport is based on the sediment concentration in water sampled at 8 am. In order to evaluate how representative the concentration at 8 am is compared with the average diurnal concentration, fluctuations in sediment concentrations throughout the day must be obtained. In periods with no significant rainfall events, a regular diurnal variation in discharge is observed, with a maximum discharge close to midnight and a minimum discharge around midday. Consequently, a similar diurnal variation in suspended matter is to be expected. Corresponding discharge and sediment concentrations at 8 am and 6 pm measured in 1997, show that the correlation in samples collected at 8 am and samples collected at 6 pm is not the same. There is a tendency towards the river carrying more sediment in the evening than in the morning at equal discharges, presumably due to differences in the river's capacity for carrying suspended material in the rising and falling stages. This indicates that the total sediment concentration based on the 8 am concentrations may be underestimated to some extent.

The variation in dissolved load is reflected in the conductivity of the water. Maximum conductivity in Zackenberg River (66–118 µS cm^{-1}) (1997–2003; Table 2.8) is usually measured during the first days of water discharge. This phenomenon has been ascribed to solutes being washed out of the snow during the first snowmelt (Rasch et al., 2000). After a runoff period of 3–5 days, the conductivity decreases to a level of c. 10–25 µS cm^{-1}, and remains fairly constant over the season, except for a peak observed after a period with rain, e.g. 302 µS cm^{-1} after the extreme event in 1998 (DOY 228; Table 2.8). During and after rain, active layer interflow contributes soil water to the river, and soil water is relatively rich in solutes compared with other sources. An estimate of the dissolved load based on the conductivity measurements is approximately 5,000 t yr^{-1} for the Zackenberg River drainage basin, suggesting that the suspended sediment load constitutes approximately 80% of the total load while bed load and dissolved load constitute the remaining load. This seems reasonable, as the river bed and banks at the cross section near the hydrometric station consist mainly of coarse material like cobbles and boulders, resulting in a stable profile without significant bed-load transport. A rough estimate of the dissolved yield to Young Sound/Tyrolerfjord based on conductivity measurements from Zackenberg River gives approximately 26,000 t yr^{-1}.

2.7 Conclusions

The study explored the meteorological conditions, river discharge, suspended sediment transport, suspended organic matter transport and river water conductivity in the Zackenberg River drainage basin (1995–2003). The data set indicates:

- An increase in mean annual air temperature of c. 0.1°C yr^{-1} (non-significant), and a seasonal warming in all seasons (highest in autumn; 0.4°C yr^{-1} ;$p<0.05$, except in spring, when air temperature decreased 0.7°C yr^{-1} ($p<0.01$).
- An increase in thawing period in autumn (16 days longer) and a decreasing thawing period in spring (2 days shorter), corresponding to a net increase in the thawing period of 14 days (1996–2003).
- A decrease in number of days (approximately 50 days less) with continuous snow cover from 304 days in season 1997/1998 to 253 days in 2002/2003, due to an increasing number of thawing degree days.
- An increasing annual trend in river discharge from Zackenberg River in the range of 122–306 million m^3 yr^{-1} and a river discharge (roughly estimated) from the entire catchment area of the Young Sound/Tyrolerfjord system in the range of 630–1,570 million m^3 yr^{-1}.
- Annual transport of suspended sediment from the Zackenberg River in the range of 15,000 to 130,000 t yr^{-1}, corresponding to a specific load between 29 and 253 t km^{-2} yr^{-1}.
- Annual transport of carbon and nitrate, respectively, from the Zackenberg River of 1,179 t yr^{-1} and 13 t yr^{-1} in 2003.
- Roughly estimated total annual suspended sediment yield from the entire catchment area of Young Sound/Tyrolerfjord to the sea of between 77,000 and 670,000 t yr^{-1}.
- Annual transport of suspended organic matter from the Zackenberg River in the range of 1,100 to 11,500 t yr^{-1}, corresponding to a specific load between 2 and 22 t km^{-2} yr^{-1}.
- Roughly estimated total annual suspended organic matter yield from the entire catchment of the Young Sound/Tyrolerfjord system of between 6,000 and 59,000 t yr^{-1}.
- Roughly estimated total annual carbon yield (POC, DOC and DIC) from the entire catchment of the Young Sound/Tyrolerfjord system of 6,033 t yr^{-1} and a nitrate yield of 66.5 t yr^{-1} for 2003.
- Maximum water conductivity (c. 100 µS cm^{-1}) during the first days of water discharge, indicating high dissolved load concentrations in the first meltwater being washed out of the snow. After a runoff period of 3–5 days the conductivity decreases to a level of c. 10–25 µS cm^{-1}, and stays more or less constant during the rest of the season. Based on conductivity measurements, the dissolved load from the Zackenberg River is c. 5,000 t yr^{-1}. A roughly estimated annual dissolved yield from the entire catchment of the Young Sound/Tyrolerfjord system gives c. 26,000 t yr^{-1}.

2.8 Acknowledgements

The Zackenberg Ecological Research Operations is acknowledged for providing access to ecosystem monitoring data from the Zackenberg Station. Ph.D. Student Jørgen Hinkler, Institute of Geography, University of Copenhagen, is acknowledged for quality control of data sets and for establishing the applied climate database. Furthermore, ASIAQ (Greenland

The hydrometric station where water level is measured every 15 min.

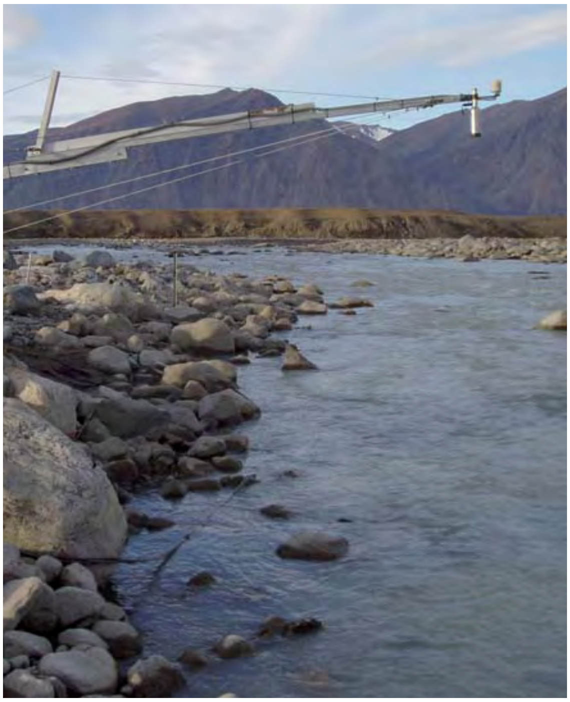


Photo: Charlotte Sigsgaard

Field Investigations) is acknowledged for quality control of data sets. Professor Søren Rysgaard, Greenland Institute of Natural Resources, is thanked for a critical review of the manuscript. We thank the two anonymous referees for their valuable comments.

2.9 References

Anderson, E. A. 1976. A point energy balance model of a snow cover. Office of Hydrology, National Weather Service, NOAA Tech. Rep. NWS 19, 150 pp.

Bay, C. 1992. A phytogeographical study of the vascular plants of northern Greenland – north of 74° northern latitude. Meddr. Grønland, Biosci., 36, 52 pp.

Bay, C. 1999. Teknisk rapport 27. Pinngortitaleriffik, Grønlands Naturinstitut: 23–27. (In Danish).

Bogen, J. 1996. Erosion and Sediment yield in Norwegian rivers. In: Walling, D. E. & Webb, B. W., (eds.). Erosion and Sediment Yield: Global and regional perspectives. Proc. of the Exeter Symposium, July. IAHS Publ. 236: 73–84.

Bogen, J. & Bønsnes, T. E. 2003. Erosion and sediment transport in High Arctic rivers, Svalbard. Polar Res. 22(2): 175–189.

Box, J. E. 2002. Survey of Greenland instrumental temperature records: 1973–2001. Int. J. Clim. 22: 1829–1847.

Broecker, W.S., Peteet, D.M. & Rind, D. 1985. Does the ocean-atmosphere system have more than one stable mode of operation. Nature 315: 21–26.

Broecker, W.S. & Denton, G.H. 1990. The role of ocean-atmosphere reorganization in glacial cycles. Quat. Sci. Rev. 9: 305–341.

Brown, R. D., Brasnett, B. & Robinson, D. 2003. Gridded North American monthly snow depth and snow water equivalent for GCM evaluation. Atm.-Ocean 41(1): 1–14.

Cappelen, J., Jørgensen, B. V., Laursen, E. V., Stannius, L. S. & Thomsen, R. S. 2001. The Observed Climate of Greenland, 1958–99 – with Climatological Standard Normals, 1961–90. Technical Report 00–18, Danish Meteorological Institute, Ministry of Transport, Copenhagen, 150 pp.

Church, M. 1974. Hydrology and permafrost with reference to northern North America. Proceedings, Workshop on Permafrost Hydrology, Canadian National Committee for IHD. Ottawa: 7–20.

Crowely, T. J. 2000. Causes of climate change over the past 1000 years. Science 289: 270–277.

Flato, G. M. & Boer, G. J. 2001. Warming asymmetry in climate change simulations. Geophys. Res. Lett. 28: 195–198.

Hansen, B. U., Humlum, O. & Nielsen, N. 2003. Meteorological Observations 2002 at the Arctic Station, Quqertarsuaq (69°15’N), Central West Greenland. Geografisk Tidsskrift/Danish J. Geogr. 103(2): 93–97.

Hasholt, B. 1996. Sediment transport in Greenland. In: Walling, D. E. & Webb, B. W., (eds.). Erosion and Sediment Yield: Global and regional perspectives. Proc. of the Exeter Symposium, July. IAHS Publ. 236: 105–114.

Hasholt, B. 2003. Method for estimation of the delivery of sediments and solutes from Greenland to the ocean. IAHS publication no. 279. Erosion Prediction in ungauged basins: Integrating Methods and Techniques. Proceedings of symposium HS01, IUGG 2003 at Sapporo: 84–92.

Hinkler. J., Pedersen, S. B., Rasch, M. & Hansen, B. U. 2002. Automatic snow cover monitoring at high temporal and spatial resolution, using images taken by a standard digital camera. Int. J. Rem. Sens. 23: 4669–4682.

Hinkler. J., Hansen, B. U. & Tamstorf, M. 2003. Sea-ice and snow accumulation in High Arctic Greenland. Proceedings of Northern Research Basins 14th International Symposium and Workshop, 25-29th August 2003. Kangerlussuaq/Sdr. Strømfjord, Greenland: 59–66.

Kane, D. 1997. The impact of hydrologic perturbation on Arctic ecosystems induced by climate change. In: Oechel, W.C., Callaghan, T., Gilmanov, T., Holten, J.I., Maxwell, B., Molau, U. & Sveinbjörnsson, B. (eds.). Global Change and Arctic Terrestrial Ecosystems. Ecological Studies 124: 63–81. Springer, New York.

Killingtveit, Å., Pettersson, L-E. & Sand, K. 2003. Water balance investigations in Svalbard. Polar Res. 22: 161–174.

Koch, L. & Haller, J. 1971. Geological map of East Greenland 72°-76° N. Lat. (1:250.000). Meddr. Grønland, 183: Plate 2.

Maxwell, B. 1997. Recent climate patterns in the Arctic. In: Oechel, W.C., Callaghan, T., Gilmanov, T., Holten, J.I., Maxwell, B., Molau, U. & Sveinbjörnsson, B. (eds.). Global Change and Arctic Terrestrial Ecosystems. Ecological Studies 124: 21–47. Springer, New York.

Meltofte, H. & Thing, H. (eds.) 1996. ZERO – Zackenberg Ecological Research Operations. 1st Annual Report, 1995. Danish Polar Center. Ministry of research and information technology, Copenhagen. 64 pp.

Meltofte, H. & Thing, H. (eds.) 1997. ZERO – Zackenberg Ecological Research Operations. 2nd Annual Report, 1996, Danish Polar Center. Ministry of research and information technology. 80 pp.

Meltofte, H. & Rasch, M. (eds.) 1998. ZERO – Zackenberg Ecological Research Operations. 3rd Annual Report, 1997. Danish Polar Center. Ministry of Research and Information Technology, Copenhagen. 68 pp.

Nielsson, B. 1969. Development of a depth-integrating water sampler, UNGI Report 2, Uppsala University, Sweden. 74 pp.

Rasch, M. (eds.) 1999. ZERO – Zackenberg Ecological Research Operations. 4th Annual report, 1998. Danish Polar Center. Ministry of Research and Information Technology. 62 pp.

Rasch, M. (ed.) 2000. Zackenberg Station – en platform for højarktisk økologisk forskning i Nordøstgrønland. Kaskelot 127. 32 pp. (In Danish).

Rasch, M. & Caning, K. (eds.) 2003. ZERO – Zackenberg Ecological Research Operations. 9th Annual report, 2003. Danish Polar Center. Ministry of research and information technology, Copenhagen. 91 pp.

Rasch, M., Elberling, B., Jakobsen, B. H. & Hasholt, B. 2000. High-resolution measurements of water discharge, sediment, and solute transport in the River Zackenbergelven, Northeast Greenland. Arct. Antarct. Alp. Res. 32: 336–345.

Rysgaard, S., Vang, T., Stjernholm, M., Rasmussen, B., Windelin, A. & Kiilsholm, S. 2003. Physical conditions, carbon transport, and climate change impacts in a Northeast Greenland fjord. Arct. Anarct. Alp. Res. 35: 301–312.

Serreze, M.C., Maslanik,J., Scambos, T. A., Fetterer F., Stroeve, J., Knowles, K., Fowler, C., Drobot, S., Barry, R. & Haran, T. M. 2002. A record minimum Arctic sea ice extent and area in 2002. Geophys. Res. Lett. 30(3): 1110, doi:10.1029/2002GL016406.

Soegaard, H., Hasholt, B., Friborg, T. & Nordstroem, C. 2001. Surface energy- and water balance in a High-Arctic environment in NE Greenland. Theor. Appl. Climatol. 70: 35–51.

Soil Survey Staff 1999. Soil Taxonomy. U.S. Government Printing Office, Washington D.C. 869 pp.

Sturm, M., Schimel, J., Michaelson, G., Welker, J. M., Oberbauer, S. F., Liston, G. E., Fahnestock, J. & Romanovsky, V. E. 2005. Winter biological processes could help convert Arctic tundra to shrubland. BioScience, 55: 17–26.

Sykes, J. M., Lane, A. M. J. & George, D. G. 1999. The United Kingdom environmental change network: Protocols for standard measurements at freshwater sites. Center for Ecology and Hydrology, Dorset, 131 pp.

Sælthun, N. R. & Barkved, L. J. 2003. Climate changes scenarios for the SCANNET region. Norwegian Institute for Water Research, Report no. 4663–2003: 1–70.

Walkers, D. A., Gould, H. A., Maier, H. A. & Reynolds, M. K. 2002. The circumpolar Arctic vegetation map: AVHRR-derived base map, environmental controls and integrated mapping procedures. Int. J. Rem. Sens. 23: 2552–2570.

WHO, 2001. WHO statement on the status of the global climate in 2001. WHO#670. World Meteorological Organization, Geneva, Switzerland, 84 pp.