

# ANALYSES AND REPORTING ON 15 YEARS OF BIOLOGICAL MONITORING FROM BYLOT ISLAND, SIRMILIK NATIONAL PARK OF CANADA



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## ABSTRACT

Our ecological research program has been monitoring the climate and abundance and reproduction of several key species of birds, mammals and plants for the past 15 years on Bylot Island. This report summarizes the climatic and ecological data and examines temporal trends in the data. The neighbouring communities of Pond Inlet and Nanisivik have experienced a strong warming trend in air temperature during the summer, and a weaker one in spring and autumn since 1975. However, no trend in winter temperature was detected, nor in annual or seasonal precipitations. A cooling trend in soil temperature in winter and spring and a decreasing trend in summer wind speed has occurred on Bylot Island over the past decade, which suggest complex feedbacks among various climatic variables. The most significant temporal change that occurred in the terrestrial ecosystem is the large increase in the Greater Snow Goose population, but this probably related to events occurring in the south during winter. The large cyclical fluctuations of lemming populations have a strong influence on the populations of most terrestrial predators, an even on other herbivores like geese due to indirect interactions through shared predators. However, trends in lemming abundance are difficult to detect due the 3 to 4-year periodicity of their population cycle. The strongest links between biological and climatic variables were found between the phenology of reproduction in several bird and plant species and air temperature or snow-melt pattern. Annual plant production in wetlands was also related to summer temperature. Predicting the impacts of climate warming on arctic ecosystems is complex because biological systems may be affected by the climate in several ways, both directly and indirectly (e.g. though effects on higher or lower levels of the food web). Variables related to the phenology of organisms, which are also relatively easy to monitor, should receive most attention because they should allow early detection of the impacts of climate warming on ecosystems.

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# 1 INTRODUCTION

## 1.1 Background

Global climatic change caused in part by the greenhouse gases released due to human activities is a major challenge faced by the earth ecosystems in this century. However, nowhere else on earth are these effects more threatening than in the Arctic. There are two reasons for that. First, because of the harshness of the climate, all physical and biological processes, along with human activities, are strongly dependent on the abiotic conditions in the Arctic. Second, all models predict that warming trends will be strongest in the Polar Regions. Indeed, global climate models predict that, over the course of the XXI<sup>th</sup> century, Arctic summer temperatures could increase by as much as 4° to 8°C (Rowntree et al. 1993, Rowntree 1997). Precipitation is also expected to increase from 10 to 20% as well as daily and seasonal variability in both temperature and precipitation, leading to more frequent climatic extremes (Balling 1997; Balling et al. 1998). Recent analyses indicate that temperatures in the Arctic have been increasing steadily for the last three decades (Moritz et al. 2002). The major thinning of Arctic sea ice recently detected may be another indication of rapid change already affecting the Polar Regions (Vinnikov et al. 1999).

Several long-term studies in different parts of the globe have detected ecological changes due to climate warming, such as alterations in geographical and breeding ranges, flowering dates, breeding dates, and migration schedules (review by McCarty 2001, Berteaux et al. 2004). Impacts of climatic changes on arctic ecosystems are expected to be particularly strong because community structure is increasingly dominated by abiotic factors as we move closer to the poles and the climate becomes harsher (Hansell et al. 1998). Disruption of close ecological linkages, such as trophic interactions among plants-herbivores and herbivores-predators, will affect a significant proportion of the species assemblages in these depauperate communities (Gauthier et al. 2004a). Thus, the simple ecological communities of the arctic may be at great risk. This, in turn, will have a large impact on Inuit societies that are dependent on the exploitation of wildlife species.

Yet, evidences of these changes and of their impacts on biological communities are still scarce in the Arctic, mainly because few sites have adequate long-term data sets to address these questions adequately. Our ongoing, long-term ecological research program on Bylot Island,

Sirmilik national Park, Nunavut, offers an exceptional opportunity to help filling this important knowledge gap. The large colony of Greater Snow Geese (*Chen caerulescens atlantica*) breeding on Bylot Island was the incentive to start the project in 1989. Because the population was growing rapidly during the 1980's, there was fear that this could negatively impact the Arctic tundra (Batt et al. 1998). We thus initiated a study on the demography of the population and the impact of goose grazing on the tundra vegetation. However, over the years, the research program has broadened up considerably and now includes many other components of the terrestrial ecosystem. A central theme of the project is now to study the trophic interactions (interactions between plant, herbivores and predators) in the context of global change. A key question for us is to understand how climate change is impacting the animal and plant communities of the tundra.

The ecological research program of Bylot Island, which has been running for 15 years, has become one of the longest, most comprehensive and rigorous long-term biological monitoring program in Nunavut. Our program is monitoring the abundance and reproduction of several key species of birds, mammals and plants. In addition, the most significant climatic variables have been continuously recorded through a network of automated weather station maintained by us for more than a decade. We think that this monitoring could help elucidate climatic effects on ecological variables, and thus be of utmost importance to predict the consequences of climate change for ecosystems. The identification of key climatologic parameters will also help to improve future ecological monitoring programs at this site and other sites in the Arctic.

## **1.2 Objectives**

The first aim of this report is to summarize in a single document all the climatic and ecological data that have been collected on Bylot Island over 15 years, with an emphasis on the examination of temporal trends in the data. A second aim is to start investigating potential relationships between ecological variables and climatic parameters to gain a better understanding of how these variables interact with each other. Our specific objectives were as follows:

1. Describe the seasonal climatic regime of Bylot Island.
2. Examine the spatial variability in the climatic regime of the North Baffin area by comparing climatic data between Bylot Island, Pond Inlet and Nanisivik

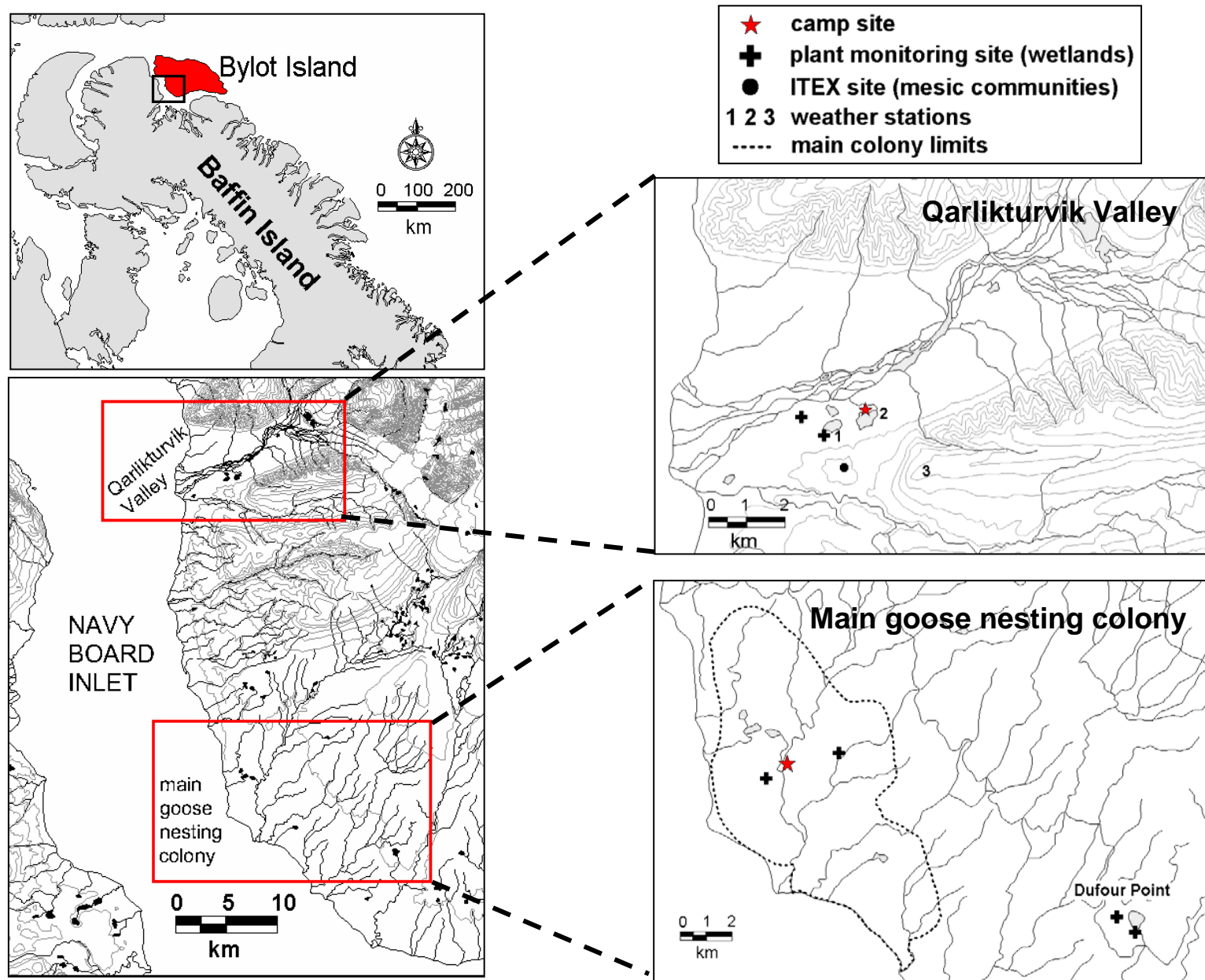
3. Analyse temporal climatic trends at Bylot Island, Pond Inlet, and Nanisivik over the past three decades.
4. Analyse temporal trends in the abundance and reproductive phenology of key species of birds (geese, owls, passerines) mammals (lemmings and foxes) and plants (in wetland and mesic communities) present on Bylot Island.
5. Start investigating relationships between climatic factors and biological variables on Bylot Island.



## 2 STUDY AREA

Our ecological studies have been conducted on the south plain of Bylot Island, Sirmilik National park, Nunavut (73° N, 80° W; Fig. 1). Because of the presence of several large bird colonies (geese and seabirds) and high overall bird diversity, the island is also a Migratory Bird Sanctuary (Lepage et al. 1998). The south plain of Bylot Island (ca 1,600 km<sup>2</sup>) has a lush and productive tundra ecosystem which contrasts with the barren landscape that covers much of North Baffin Island (Gauthier et al. 1996). This exceptional arctic ecosystem became part of the Sirmilik National Park of Canada in 1999 and is included in the North Baffin E-MAN (Ecological Monitoring and Assessment Network) site. Topography of this region is characterized by flat lowlands and upland plateaus dissected by valleys, with elevation generally below 350 m above sea level.

The south plain can be divided into 3 broad types of plant communities. First, wetlands are abundant in low-lying areas that are poorly drained, and include meltwater channels, shallow ponds and lakes, and especially polygons, which result from the formation of ice wedge in the permafrost. Wetlands develop into fens, i.e. peat accumulating systems, and are dominated by sedges such as *Carex aquatilis* var. *stans*, *Eriophorum scheuchzeri*, and *E. angustifolium*, and grasses such as *Dupontia fisheri* and *Pleuropogon sabiniei*. Second, mesic communities, which are the most abundant on the south plain, occur in moist areas with fine soil material such as polygon rims, sloping terrain and hummocky tundra. Mesic communities have a rich and diverse vegetative cover, though plant abundance generally decreases along a decreasing soil moisture gradient. Common plants of this habitat include shrubs (*Salix* spp, *Vaccinium uliginosum*), forbs (*Cassiope tetragona*, *Oxytropis maydelliana*), grasses (*Arctagrostis latifolia*, *Alopecurus alpinus*, *Poa glauca*, *Luzula confusa*) and some mosses. Finally, xeric communities are found in exposed areas with dry, gravel soil such as slopes with a northern exposure and ridges, or at higher elevation (>400 m). The vegetative cover is very sparse and consists of only a few plant species (e.g. *Dryas integrifolia*, *Saxifraga oppositifolia*; Duclos 2002).



**Figure 1.** Location of the main study area, Bylot Island, north of Baffin Island, Nunavut. Also shown is the South plain of Bylot Island where the two main study sites are located. Maps on the right present a fine scale of these study sites, including camp locations, sampling sites and weather stations.

### 3 METHODOLOGY

The ecological studies and environmental monitoring project at Bylot Island is broadly divided into 2 categories: the climate itself and the biological parameters, which include several species of birds, mammals and plants of the tundra. In this section, we present an overview of the methods used to monitor these parameters. Detailed information on our monitoring protocols can be found in Gauthier et al. (2004d).

#### 3.1 Climatic Data

##### 3.1.1 *Recording of Climatic Data*

We installed a first complete automated weather station in the lowlands (polygon tundra, 20 m above sea-level [ASL]) of the Qarlikturvik Valley (73°08'N; 80°00'W) of Bylot Island in 1993 (Bylot-2; Fig. 1). Since March 1994, this fully automated meteorological station has continuously recorded the following climate variables: air and ground temperatures (at 2 and 10 cm belowground), quantum and incident solar radiation, relative humidity, wind speed and direction. In 2001, a snow depth sensor was also added. Average values of these parameters are recorded on an hourly basis and daily minimum and maximum are recorded for several values. Summer precipitation is also recorded manually from late May to late August with the help of a pluviometer since 1995. Details on all the instruments are found in Gauthier et al. (2004d).

In 2001, a second complete meteorological station has been installed at an altitude of 340m ASL in mesic tundra (Bylot-3). This automated station records the same data than the first station and therefore allows a comparison of climatic regimes between wetland tundra (typical of lowlands) and mesic tundra (typical of uplands) through an altitudinal gradient.

A third environmental monitoring station that only records soil temperatures at 2 cm depth also exists on Bylot Island. This automated station was installed in 1992 (Bylot-1) and in the first few years has recorded soil temperature intermittently. In 1996, 5 pairs of sensors were positioned, one sensor of each pair inside a 1×1 m fenced area where goose grazing is permanently excluded (exclosure) and the other one in a nearby area grazed by geese (control). Average, minimum and maximum daily ground temperature is recorded. This set-up allows a comparison of soil temperature regimes between areas grazed and ungrazed by geese.

Snow-melt has been monitored manually in the Qarlikturvik Valley using 2 methods. First, since 1990 we visually estimated the proportion of the valley covered by snow every 2 to 3 days. This estimated is made separately for different portions of the valley from a vantage point near our Base-camp. Second, since 1995 we measure snow depth at 50 stations spaced out at 10-m interval along two 250-m transects every 2 days. The transects are located in lowlands across a variety of terrain (i.e. hummocky terrain, slopes and polygons). Snow-melt is monitored from our arrival (late May) until the snow disappears (around the 3<sup>rd</sup> week of June).

Ten years of data is a short time length for a good evaluation of climate trends. In order to extend temporal and regional climate coverage, we obtained longer data sets from Environment Canada weather stations located at the airports closest to the Bylot Island study site: Pond Inlet (100 km to the east; 72°41' N, 77°59' W) and Nanisivik (150 km to the west; 72°59' N; 84°37' W). We analysed data on air temperature (minimum, average and maximum), precipitation and snow thickness from 1976 to 2002.

### ***3.1.2 Climatic Variables***

From the data on air temperature, variables important for biological processes, such as the number of degree-days above 0°C (or thawing degree-days, TDD) and the number of frost-free days, were calculated. The number of degree-days above 0°C is a sum of all daily temperatures reaching above 0°C. It therefore represents heat accumulation, an important factor influencing plant growth and plant life events (such as flowering).

Solar radiation is an important variable owing to its direct influence on living organisms. Two kinds of solar radiations are recorded by our weather stations. The first one, referred to as incident radiation, represents all visible solar radiation reaching the ground, either directly or indirectly by scattering, reflection or diffusion. It is measured in Joules per square meter per day, which represents how much energy reaches one meter of ground per day.

The second type of solar radiation measured by the station is known as Photosynthetically Active Radiation (PAR). In comparison with incident radiation, PAR can be more easily linked with plant production because it is limited to the spectrum of light used by plants for photosynthetic activity. It is measured as total number of photons (energy particles) reaching one

square meter of ground per day. PAR is measured in number of photons instead of energy units because one photosynthetic reaction occurs each time one photon is absorbed by a plant.

In order to obtain data on wind direction, one random sample per hour was recorded by the weather station. However, because wind direction is a circular measure ( $0^\circ$  to  $360^\circ$ ), it must be analysed differently than other variables. In order to obtain daily and monthly averages for wind direction, the true vector average method was used. Following this method, each observation of wind direction was considered a vector: the vector length was given by the wind speed and its orientation by the wind direction. Each vector was then broken in its meridional (V) and zonal (U) components, using the following formulas:

$$V = -wind\ speed \times \cos(\pi/180 \times \theta)$$

$$U = -wind\ speed \times \sin(\pi/180 \times \theta)$$

where  $\theta$  = wind direction, in degrees.

The V and U components were averaged separately to obtain monthly or daily values and then were converted back to wind direction:

$$\theta = 180/\pi \times \arctan(-U/-V)$$

The U and V values were also used to calculate directional wind speed (*i.e.* average speed of the wind blowing from the average wind direction) using the formula:

$$Average\ directional\ wind\ speed = \sqrt{(U^2 + V^2)}$$

## 3.2 Biological Data

### 3.2.1 Greater Snow Goose Population Survey

A large greater snow goose (*Chen aerculescens atlantica*) breeding colony of several thousand birds is located on Bylot Island. The abundance and distribution of Greater Snow Geese on Bylot Island has been monitored by aerial surveys at five-year intervals since 1983. The survey zone covers the 1 600-km<sup>2</sup> south plain of the island. The area is divided into 400 2x2 km plots grouped into three strata representing suitability of the habitat for brood-rearing geese, and about 20% of the plots are sampled. The survey is conducted well after the hatch (about the 3<sup>rd</sup> week in July) so as not to disturb nesting geese. The surveys are conducted from a helicopter, searching for and photographing all groups of geese encountered within each sample plot. Each flock of geese is counted from projected images later in the lab and classified as breeders or non-breeders based on the presence or absence of young in the flock, respectively. Based on average brood size determined from ground counts, the total number of young present in all flocks where young were detected is estimated, assuming that each brood is accompanied by 2 parents. Data obtained from the sample plots is then extrapolated to the whole study zone. Further details of survey methods can be found in Reed & Chagnon (1987), and Reed et al. (1992). Besides information on the total number of breeders, non-breeders and goslings, the surveys also provide additional information on the distribution of goose families during the summer in relation to the types of habitat.

### 3.2.2 Greater Snow Goose Reproduction

The reproduction of Greater Snow Geese, which is their most important activity during the summer, is monitored annually on Bylot Island. A first monitoring takes place during the nesting period. Since 1989, we search extensively for goose nests in the Qarlikturvik Valley (73° 08' N; 80° 00' W). However, because this area is primarily a brood-rearing area, the reproductive effort of geese at this site is small and highly variable from year to year (between none and a few hundred nests). Therefore, the number of nests monitored there varies between 0 and 200. Since 1992 (except in 1993), our monitoring of nesting activity is concentrated at the main colony where several thousand of geese nest every year (72° 53' N, 79° 55' W). We monitor between 200 and 400 nests annually, split between 2 samples. A first sample is a restricted area of ~1 km<sup>2</sup>

located in the center of the colony and has been monitored every year. A second sample includes a variable number (between 6 and 21) of 40-ha random plots (200 m × 200m) scattered across the colony since 1999. The entire colony covered an area of ~63 km<sup>2</sup> in 2003.

In each nest, we recorded the number of eggs and marked them with a permanent felt pen for individual recognition. The position of all nests was recorded with a GPS receiver. Nests were classified as found during laying if new eggs appeared later. Nests were revisited in the first half of incubation, during hatching and after the goslings had left the nest in order to determine their fate. At hatch, a sample of several hundred goslings is marked with web-tags. Nesting parameters are not biased by our visits (Bêty and Gauthier 2001). From this monitoring, we calculated several parameters. We measured the phenology of nesting using the date at which birds started laying their first egg (egg-laying date) and the date that most eggs hatch in a nest (hatching date; most eggs within a nest hatch within 24 h). We measured the reproductive effort with the density of nests found in the central portion of the colony that is monitored annually and the total number of eggs per nest (clutch size). Finally, we calculated the nesting success as the proportion of nests where at least one egg hatched. More details on the monitoring of goose nests and the calculation of nesting parameters can be found in Annex 1.

A second monitoring of goose reproduction occurs at the end of the summer on the brood-rearing area. During the period that adults have lost flight capability due to wing-molt and young are still unable to fly, several thousand geese are captured for marking since 1990. From 5 to 15 August, several thousands geese are rounded up in nets with the help of personnel on foot, and driven into corral traps. Captured birds are almost exclusively successful nesters and their young of the year, since non-breeders and failed-nesters leave the island to molt elsewhere or have regained flight capacity at the time of banding (Reed et al. 2003). All birds captured for the first time were fitted with a metal U.S. Fish and Wildlife Service leg band, and a number of adult females, chosen haphazardly within each catch, were fitted with individually coded plastic neck bands. All recaptures of previously marked banded birds were noted, as was the presence or absence of a neck band upon recapture. A sample of several hundred goslings is measured (culmen, head, tarsus and 9<sup>th</sup> primary length) and weighed to obtain information on their growth during the summer. All goslings are also checked for the presence of web-tags. More details on the banding of geese can be found in Annex 1. Goose banding causes minimal adverse effects on

geese (Menu et al. 2001). From the goose banding data, we obtain a measure of annual productivity of geese which is the ratio of young: adult (Y: A) in the total catches.

### **3.2.3 Lemming Abundance**

We sampled lemming abundance every year following the protocol of the small-mammal survey coordinated across the Northwest Territories and Nunavut by the Northwest Territories Renewable Resources office, in Yellowknife (Shank 1993). Lemming trapping is carried out in two study plots of the Qarlikturvik Valley (one in the wetlands, one in the dryer uplands) since 1994. Since 1997, trapping is also conducted at a third study plot in an upland habitat at the main goose nesting colony. Although no trapping was conducted in 1993, a quantitative estimate of lemming abundance is nonetheless available based on winter nest surveys, which were conducted on the island in 1993 and 1996 (Olivier Gilg, pers. com.). The ratio nest survey/lemming abundance obtained in 1996 was applied to the 1993 nest survey to estimate lemming abundance that year.

At each study plot, we used traps 50 Museum Special snap-traps baited with peanut butter and rolled oats. Traps were set at stations every 10-m along two 240-m long transect lines, 100 m apart, during a period of 10 or 11 days for a total of ~500 trap-nights (50 traps x 10 nights) per plot. Traps were positioned within 1 m of each station, preferably near a lemming burrow if one was found within this radius, and were checked daily. Lemmings caught were identified (collared, *Dicrostonyx groenlandicus*, or brown, *Lemmus sibiricus*, lemmings) and all sprung traps were reset. The lemming abundance index is determined by calculating the number of lemmings caught per 100 trap-nights. We subtracted 0.5 night for each sprung trap to improve estimates of sampling effort and controlled for site-specific rates of trap-springing as recommended by Beauvais and Buskirk (1999). More details can be found in Gauthier et al. (2004d).

### **3.2.4 Breeding Activity of Arctic and Red Foxes**

The breeding activity of Arctic (*Alopex lagopus*) and Red fox (*Vulpes vulpes*) has been monitored at dens annually since 1993. Until 2002, monitoring of dens only occurred in the Qarlikturvik Valley and in the vicinity of the main goose nesting colony (about 100 km<sup>2</sup>). Dens were found while walking throughout the study area for other activities and their position



recorded with a GPS receiver. The number of dens found gradually increased from 1993 to 2002. In 2003, we expanded the covered area to about 600 km<sup>2</sup> by conducting a systematic survey of fox dens, which considerably increased the number of known fox dens. All known dens are visited at once or more in June or early July and all traces of fox activity is noted (e.g. fresh digging, new hairs, fresh prey. Dens showing signs of activity are re-visited later in the summer to determine the presence of litter and the number of pups in each litter. Litter size data presented here are the minimum number of pups observed at dens, which may sometimes be lower than the true number of pups present at dens. All observations of adults near dens are also noted, and the species of fox identified. More details can be found in Gauthier et al. (2004d).

### **3.2.5 Reproduction of Other Bird Species**

The reproduction of other avian species is monitored besides geese, especially Snowy Owls (*Nyctea scandiaca*) and Lapland Longspurs (*Calcarius lapponicus*). Since 1993, we search systematically for owl nests in our two study areas (Qarlikturvik Valley and at the main goose nesting colony). However, owls only nest on Bylot Island in years of high lemming abundance. Longspur nests are found in the Qarlikturvik Valley while walking throughout the study area for other activities since 1995, often when females are flushed from their nest. The position of all nests is recorded with a GPS receiver and nests are revisited periodically to determine their fate. For both owl and longspur nests, we determine laying and hatching dates, clutch size and nesting success (see under Goose reproduction for definition of these parameters). Information on the reproductive activity of other bird species has also been collected sporadically, i.e. when time allowed. These species include loons (*Gavia* spp.), Canada Geese (*Branta canadensis*) Ross Geese (*Chen Rossii*), King Eider (*Somateria spectabilis*), Long-tailed Ducks (*Clangula hyemalis*), Sandhill Crane (*Grus canadensis*), Glaucous Gull (*Larus hyperboreus*), Jaegers (*Stercorarius* spp.), plovers (*Pluvialis* spp.), sandpiper (*Calidris* spp.), and Rough-legged Hawk (*Buteo lagopus*).

### **3.2.6 Plant Monitoring in Wetlands**

The annual production of plants in wetlands and the impact of goose grazing on graminoid plants is evaluated each year at the 3 sites on the island: the Qarlikturvik Valley (monitored since 1990), the main goose nesting colony (monitored since 1998), and north of

Pointe Dufour (monitored since 1998). At each site, 12 exclosures (1 × 1 m fenced areas built with chicken wire to keep geese off the geese) were installed in late June. At the end of the plant-growing season (i.e. between 12 and 15 August), we sampled the vegetation inside and outside the exclosures. All live above-ground plant biomass was cut, sorted out into sedges (*Eriophorum scheuchzeri* or *Carex aquatilis*) and grasses (mostly *Dupontia fisheri*), dried, and weighed. Above-ground biomass of vascular plants included all green material and white basal stems buried in mosses. The biomass of vegetation inside the exclosure (ungrazed) gives a measure of plant production for the year (Gauthier et al. 1995). In comparison, the difference between the amount of vegetation inside and outside the exclosure (ungazed vs grazed) gives an indication of the proportion of vegetation grazed by geese during the summer (i.e. grazing impact). Use of the area by geese was monitored by counting faeces on 1 x 10 m transects located near each exclosure every 2-weeks in the Base-camp Valley and once at the end of the season at the other sites. More details can be found in Gauthier et al. (2004d).

### **3.2.7 Plant Monitoring in Mesic Communities**

The monitoring of flowering parameters of four vascular species was initiated at Bylot Island in 1998. This environmental monitoring is part of the International Tundra Experiment (ITEX, [www.itex-science.net](http://www.itex-science.net)) program that evaluates the impact of environmental change on tundra communities around the world. In 1998, a site was selected on top of a low hill in the vicinity of the base camp. The site was chosen because it had four of the ITEX species in sufficient abundance. The four plant species were: the evergreen shrub *Dryas integrifolia*, the cushion plant *Saxifraga oppositifolia*, the deciduous shrub *Salix arctica* (males and females) and the graminoid *Luzula nivalis*. To facilitate monitoring, reduce trampling and allow to add treatments in future years if desired, 30 quadrats (70cm x 70cm) were established throughout the site. One individual of each of the four selected plant species were marked within - or in close proximity of - each quadrat, following standard ITEX protocols (Molau and Mølgaard, 1996). For *S. arctica* both male and female ramets were marked, however, since it was not always possible to determine the sex of the ramet early in season, two ramets were marked and their sex will be confirmed over the years when flowering occurs. Each year since 1999, the number of flowers and phenological phases of the marked individuals are monitored in order to elucidate relationships between plant phenology and climate variables. In 1999 and 2003 plant abundance

was measured using the point sampling approach in order to monitor community changes. The community data are not presented here.

### **3.3 Data Analysis**

Data were analysed with the SAS Institute Inc software, Version 8.0. For climatic data, when data were analysed on a monthly basis, the following grouping of months was used: spring: March to May, summer: June to August, autumn: September to November, and winter: December to February. Comparisons between climatic stations were done with factorial ANOVA (usually using site and months or seasons as fixed factors). Temporal trends were examined using simple regression analyses. All results are reported with their standard error, unless mentioned otherwise.

## 4 RESULTS

### 4.1 Climate Description

In this section, we will present a brief overview of the climate on Bylot Island, Pond Inlet and Nanisivik, and we will compare the climatic regime between these 3 sites

#### 4.1.1 Bylot Island

Data for the climate on Bylot Island comes from the 10-year database accumulated from the automated weather station Bylot-2.

##### 4.1.1.1 Air Temperature

For the entire year, the average air temperature in the Qarlikturvik Valley of Bylot Island was  $-14.8^{\circ}\text{C}$ . The warmest month of the year was July, with an average of  $6.3^{\circ}\text{C}$  and the coldest month was February with an average of  $-39.2^{\circ}\text{C}$  (Fig. 2). On a seasonal basis, average temperature was  $4.5^{\circ}\text{C}$  in summer,  $-11.2^{\circ}\text{C}$  in autumn,  $-32.6^{\circ}\text{C}$  in winter and  $-19.4^{\circ}\text{C}$  in spring.

The annual number of thawing degree-days averaged  $437 \pm 16$  with most of them accumulated during the summer months. For the month of July only, a crucial period for plant growth, the average number of thawing degree-days was  $199 \pm 12$ , or 46% of the annual total (Fig. 3). Each year, organisms living on Bylot Island experienced an average of  $98.9 \pm 3.3$  days where the air temperature was above  $0^{\circ}\text{C}$ . The majority of these days occurred during the summer months ( $86.9 \pm 1.5$  days above  $0^{\circ}\text{C}$  or 88% of annual total; Fig. 4).

##### 4.1.1.2 Soil Temperature

At a depth of 2 cm, the average annual soil temperature was  $-10.2^{\circ}\text{C}$ , or  $4.6^{\circ}\text{C}$  warmer than air temperature. The coldest month for soil temperatures was February with an average of  $-24.2^{\circ}\text{C}$  and the warmest month was July with an average of  $7.3^{\circ}\text{C}$  (Fig. 5). On a seasonal basis, average temperature was  $4.6^{\circ}\text{C}$  in summer,  $-4.2^{\circ}\text{C}$  in autumn,  $-20.5^{\circ}\text{C}$  in winter and  $-20.2^{\circ}\text{C}$  in spring. Because the soil acts as an insulator, especially in winter, soil temperatures were generally more tempered than the surrounding air temperature. Indeed, the amplitude in temperature between the warmest and the coldest month was  $31.5^{\circ}\text{C}$  at 2 cm in the soil compared to  $45.5^{\circ}\text{C}$  in

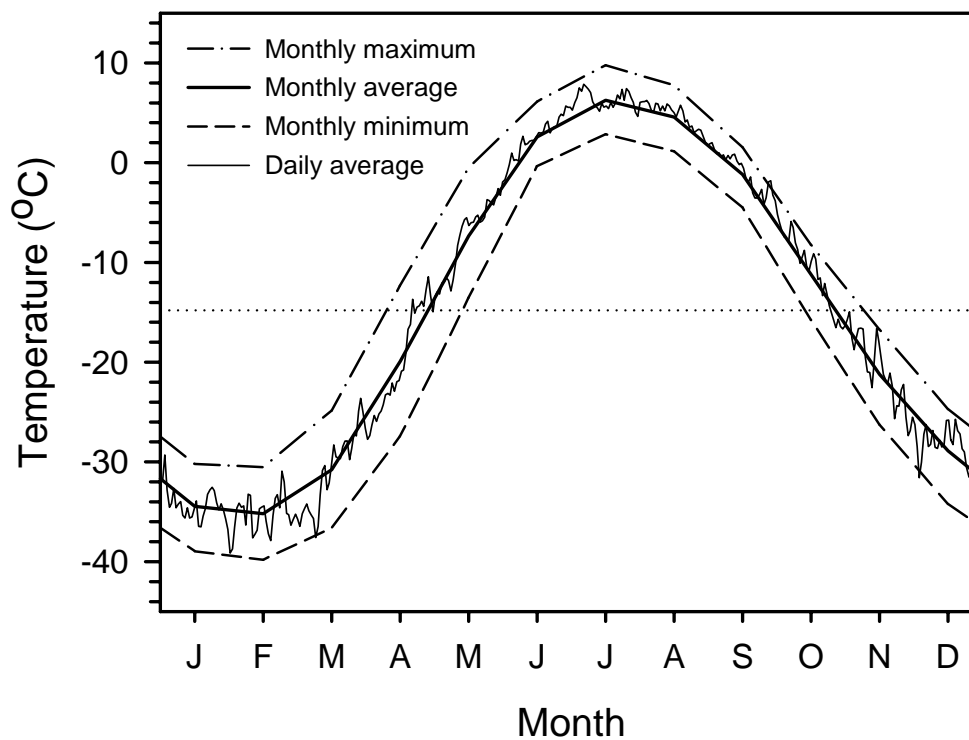
the air. Soil temperature also warms up and cools down later than air temperature in spring and autumn, respectively.

At a 10 cm depth, the annual soil temperature was slightly colder than at 2 cm, with an annual average of  $-11.1^{\circ}\text{C}$ . It is, however, during the summer that the soil temperature at 10 cm was much colder than at 2 cm (Fig. 5). July was the warmest month at both soil depths, but the July average at 10 cm ( $2.8^{\circ}\text{C}$ ) was  $4.5^{\circ}\text{C}$  colder than at 2 cm. The coldest month for soil temperatures at 10 cm was March, with an average of  $-24.2^{\circ}\text{C}$ . The Seasonal averages were  $0.7^{\circ}\text{C}$  in summer ( $4^{\circ}\text{C}$  less than at 2 cm),  $-4.8$  in autumn,  $-20.2^{\circ}\text{C}$  in winter and  $-20.7$  in spring. Because temperatures at 10 cm are more tempered than at 2 cm, the amplitude between the warmest and the coldest month was only  $27.0^{\circ}\text{C}$  at 10 cm compared to  $31.5^{\circ}\text{C}$  at a 2 cm-depth.

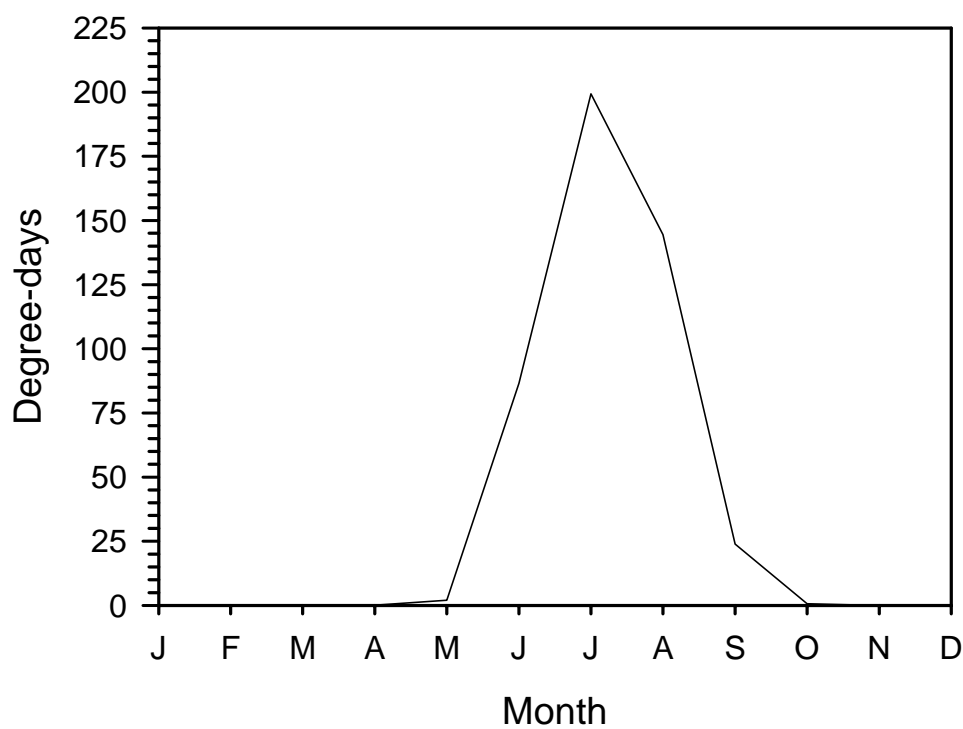
#### 4.1.1.3 Solar Radiation

On Bylot Island, the average incident radiation was  $8.32 \text{ MJ (Mega Joules) m}^{-2} \text{ day}^{-1}$  and the accumulated annual input of incident radiation reached a sum of  $3052 \text{ MJ m}^{-2} \text{ year}^{-1}$  (from 1994 to 2003). In the Arctic, the amount of solar energy input presents large seasonal variations. Effectively, solar radiation ranged from zero input during the winter darkness to very high inputs during times of continuous summer daylight (Fig. 6). Indeed, May and June showed the highest inputs of incident radiation, with monthly averages of  $22.81 \pm 0.79 \text{ MJ m}^{-2} \text{ day}^{-1}$  and  $22.22 \pm 0.40 \text{ MJ m}^{-2} \text{ day}^{-1}$ , respectively. May and June also presented the highest cumulative inputs, with averages of  $689 \pm 12 \text{ MJ m}^{-2} \text{ month}^{-1}$  and  $685 \pm 27 \text{ MJ m}^{-2} \text{ month}^{-1}$ , respectively. In contrast, the cumulative input of incident radiation was null for the month of December. On a seasonal basis, average incident radiation was  $18.03 \pm 0.45 \text{ MJ m}^{-2} \text{ day}^{-1}$  in summer,  $2.37 \pm 0.07 \text{ MJ m}^{-2} \text{ day}^{-1}$  in autumn,  $0.12 \text{ MJ m}^{-2} \text{ day}^{-1}$  in winter and  $12.97 \pm 0.36 \text{ MJ m}^{-2} \text{ day}^{-1}$  in spring.

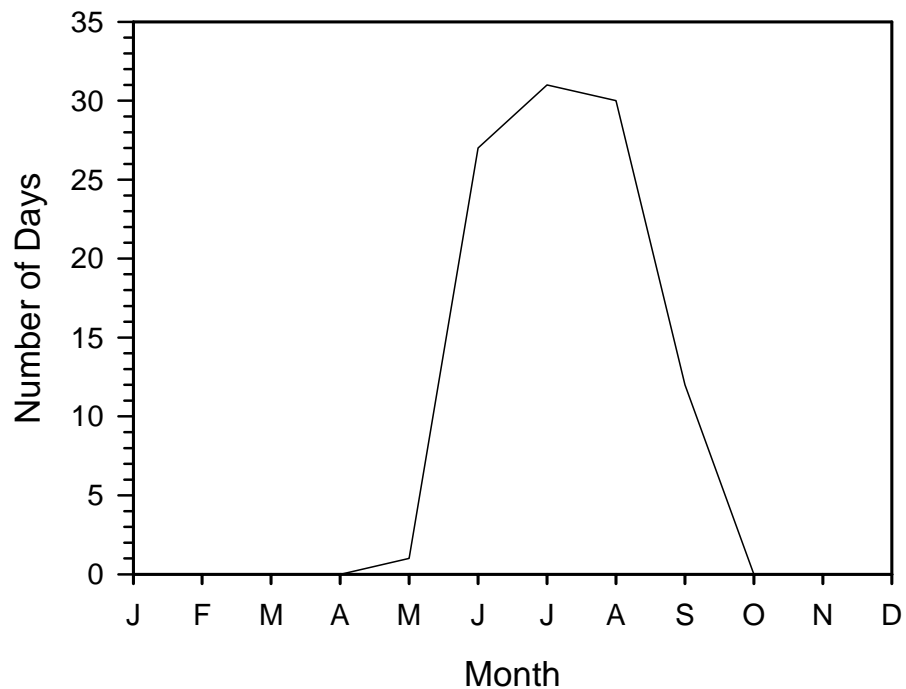
On Bylot Island, photosynthetically Active Radiation (PAR) followed the same pattern as incident radiation. From 1994 to 2003, the average yearly PAR input was  $17.17 \pm 0.49$  moles of photons  $\text{m}^{-2} \text{ day}^{-1}$  and the accumulated annual input of PAR averaged  $6509 \text{ mol m}^{-2}$ . As for incident radiation, May and June were the months with the highest PAR input, showing averages of  $47.03 \pm 1.38 \text{ mol m}^{-2} \text{ day}^{-1}$  and  $45.99 \pm 3.09 \text{ mol m}^{-2} \text{ day}^{-1}$ , respectively (Fig 7). The cumulative PAR inputs for these months averaged  $1477 \pm 44 \text{ mol m}^{-2} \text{ month}^{-1}$  for May and  $1469 \pm 31 \text{ mol m}^{-2} \text{ month}^{-1}$  for June (Fig 7).



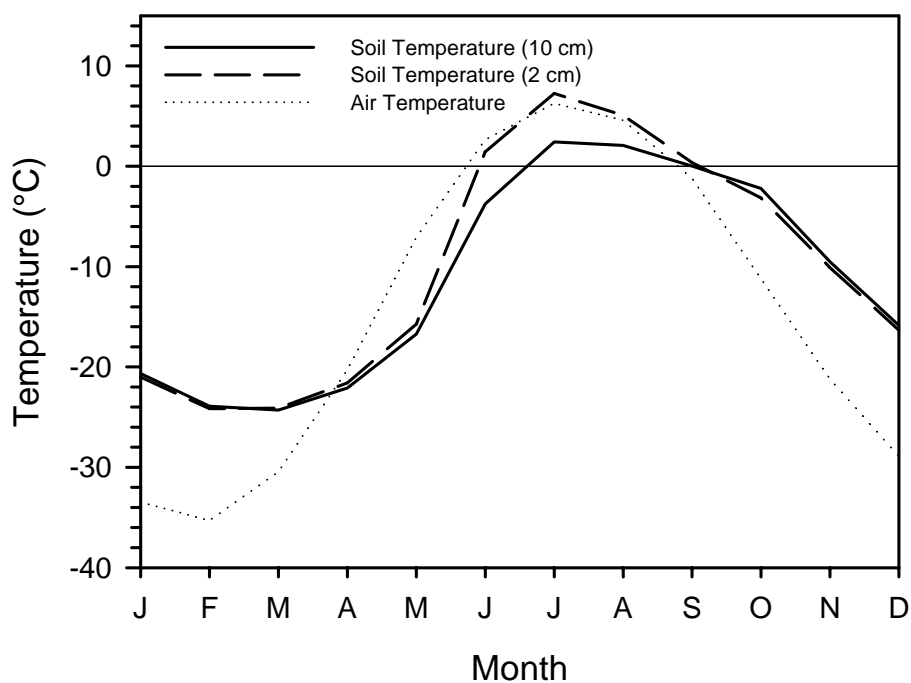
**Figure 2.** Average monthly and daily air temperature on Bylot Island (1994-2003) at 2 m above the ground. The dotted line represents the yearly average.



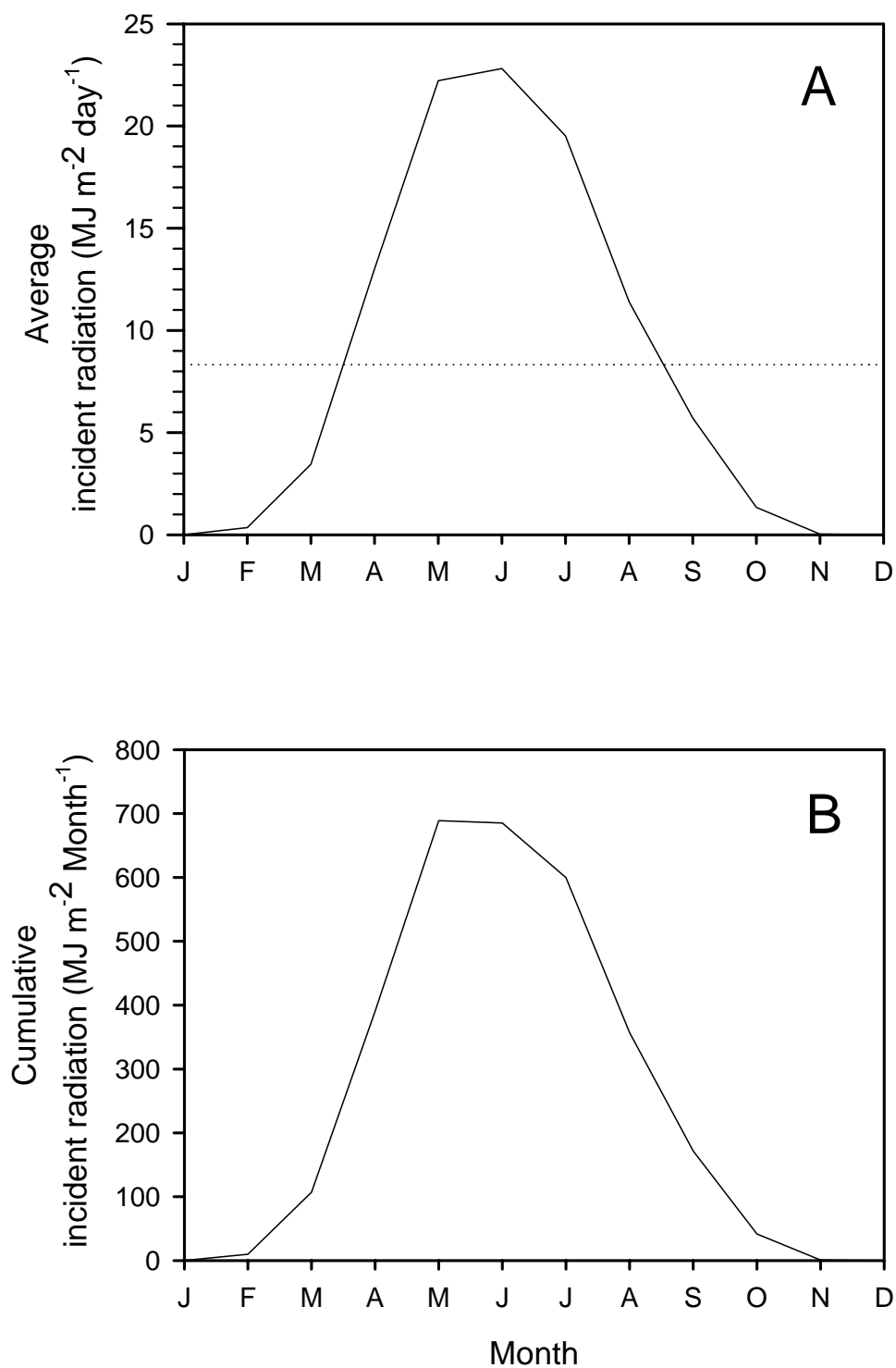
**Figure 3.** Average monthly thawing degree-days (> 0°C) on Bylot Island (1994-2003).



**Figure 4.** Average monthly number of days with mean temperature above 0°C on Bylot Island (1994-2003).

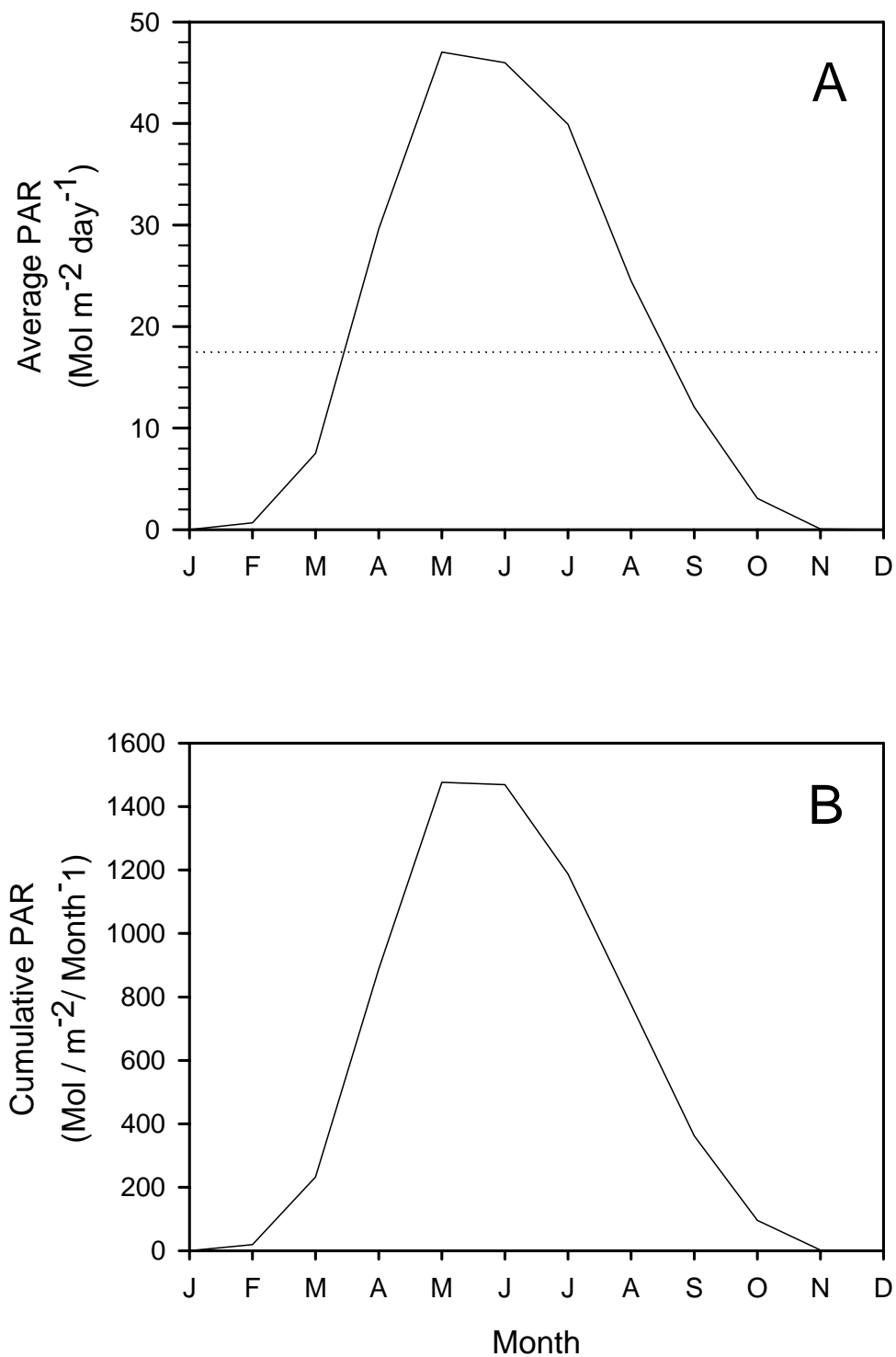


**Figure 5.** Average monthly air and soil temperatures (2-cm and 10-cm depths) on Bylot Island (1994-2003).



**Figure 6.** (A) Monthly average and (B) monthly cumulative incident radiation on Bylot Island (1994-2003). The dotted line represents the yearly average.





**Figure 7.** (A) Monthly average and (B) monthly cumulative Photosynthetically Active Radiation (PAR) on Bylot Island (1994-2003). The dotted line represents the yearly average.

Seasonal averages of PAR inputs were  $34.08 \text{ mol} \pm 1.44 \text{ m}^{-2} \text{ day}^{-1}$  for the summer,  $5.07 \pm 0.23 \text{ m}^{-2} \text{ day}^{-1}$  for the autumn,  $0.23 \pm 0.03 \text{ mol m}^{-2} \text{ day}^{-1}$  for the winter and  $28.05 \pm 0.61 \text{ m}^{-2} \text{ day}^{-1}$  for spring.

#### 4.1.1.4 Precipitations

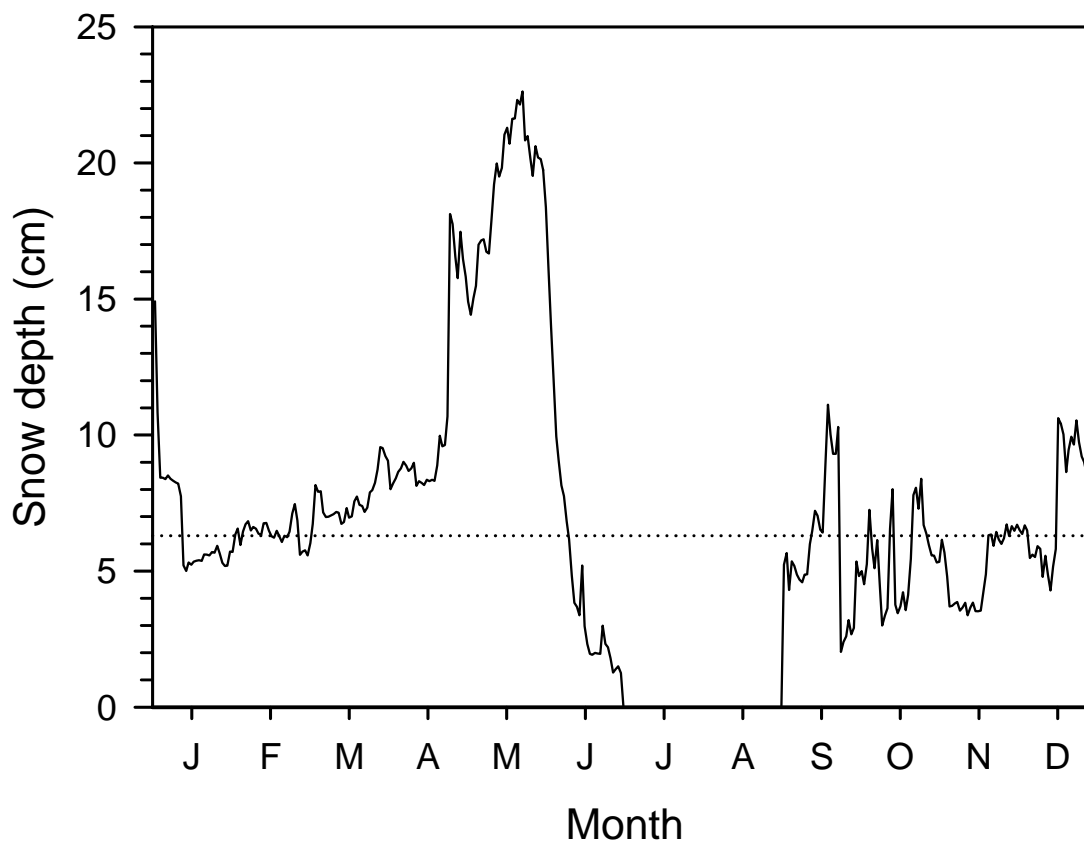
Because summer rainfall was recorded manually, data were available only from 1 June to 17 August, the period of field season. For this time period, rainfall averaged  $80.6 \pm 7.8 \text{ mm}$ . On a monthly basis, 25 % of the total fell in June ( $19.8 \pm 4.4 \text{ mm}$ ), 44 % in July ( $35.0 \pm 3.5 \text{ mm}$ ) and 31% from the 1 to 17 August ( $24.9 \pm 5.4 \text{ mm}$ ).

#### 4.1.1.5 Snow depth and snow cover

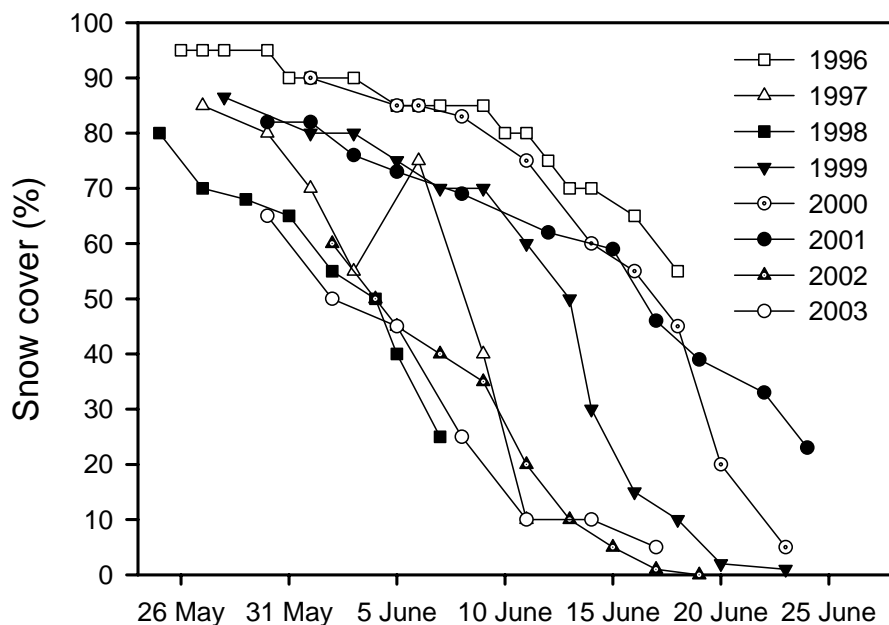
Data on snow depth at one location in lowlands of the Qarlikturvik Valley are automatically recorded at the meteorological station only since 2001, which is a very short period of time. Snow on the ground appeared in September and fluctuated greatly during the autumn (average snow depth for this season, 4.1 cm; Fig. 8). Snow depth increased very slowly during the winter months (from December to February, average snow depth is 7.0 cm). Snow depth increased rapidly in May (monthly average: 19.1 cm) and peaked at the end of this month at 22.6 cm. Snow-melt proceeded rapidly in June.

Data collected manually in the field provided more detailed information on snow cover and snow depth during snow-melt in spring. At the start of the field season in late May, snow cover in the Qarlikturvik Valley is around 90% (Fig. 9). Snow-melt usually progressed rapidly in early June: date of 50% snow cover is around 10 June and in most year, the ground is snow-free (<5 % snow cover) between 20 and 25 June. On average 62% of the valley is still covered by snow on 5 June (period 1989-2003), the date that Snow Geese usually start to nest.

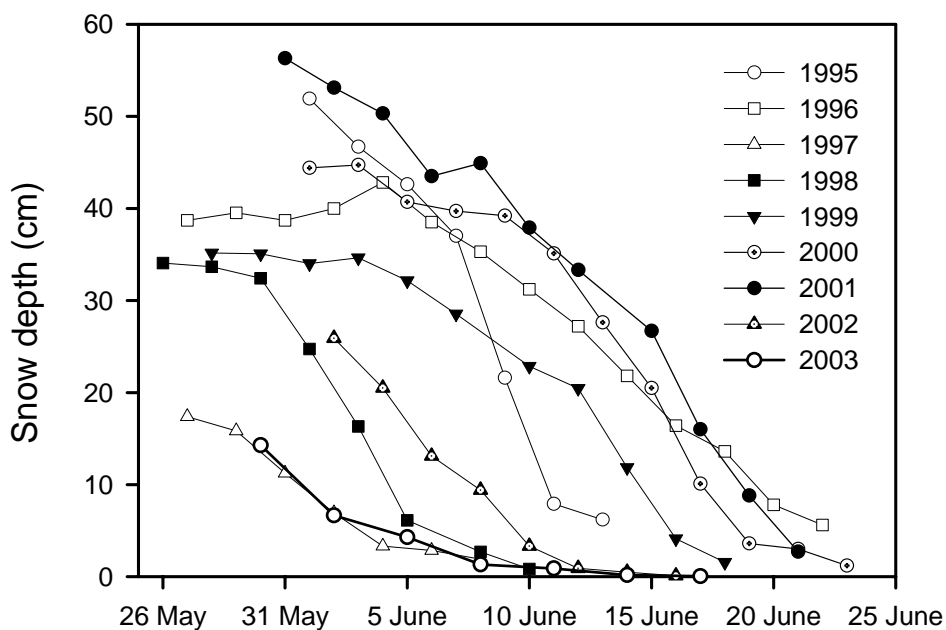
Data from the snow transects provided additional information on the phenology of snowmelt in the Qarlikturvik Valley. On 2 June, snow depth averaged  $31.6 \pm 5.9 \text{ cm}$  across a range of landscapes (Fig. 10). Snow-melt generally followed a sigmoidal pattern in early June, being most rapid between 2 June and the date where average snow depth had reached approximately 10% of its initial value (usually between 10 and 20 June). During this period, the speed of snowmelt averaged  $2.1 \pm 0.3 \text{ cm day}^{-1}$ .



**Figure 8.** Average snow depth as recorded in the lowlands of the Qarlikturvik Valley, Bylot Island (2001-2003). The dotted line shows the average for the period with snow on the ground.



**Figure 9.** Visual estimates of snow cover on the ground in the Qarlikturvik Valley of Bylot Island at 2-3 day intervals from the end of May to the end of June, 1996 to 2003. The dotted line shows the mean snow cover on 5 June.

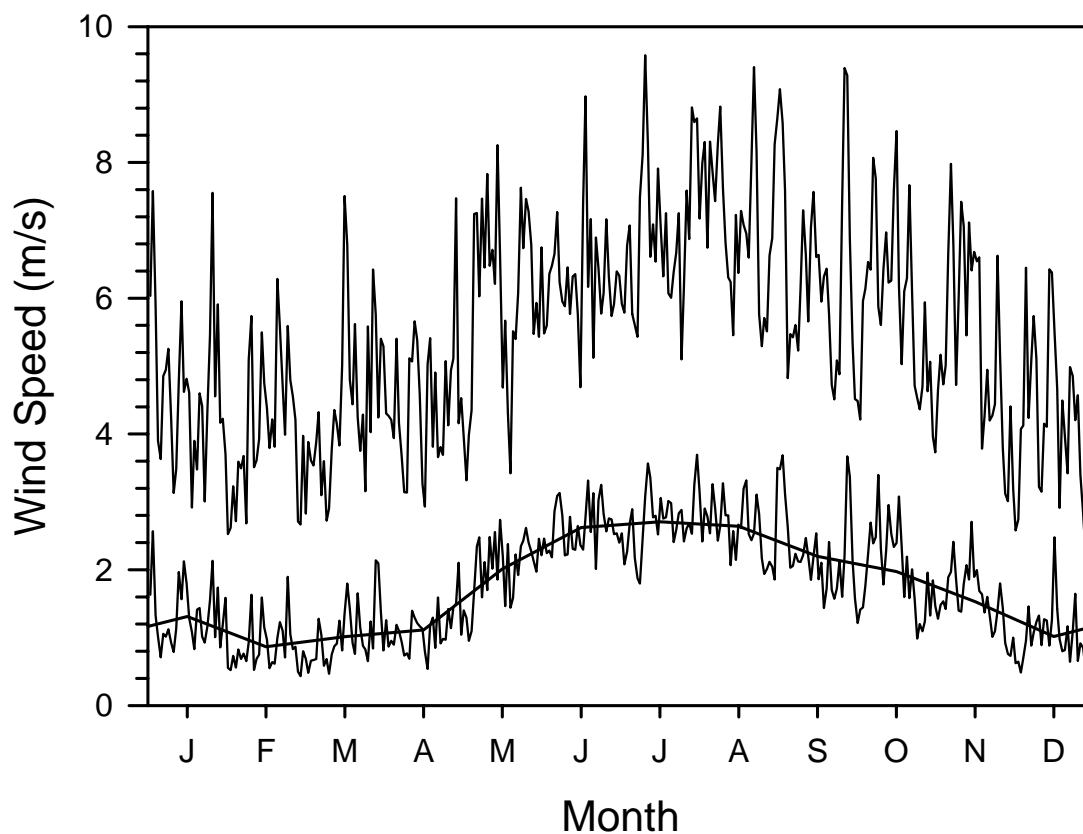


**Figure 10.** Average snow depth along 2 transects ( $n = 50$  stations) in the lowlands of the Qarlikturvik Valley, Bylot Island, at 2-3 day intervals from from the end of May to the end of June, 1995 to 2003. The dotted line shows the mean snow depth on 2 June.

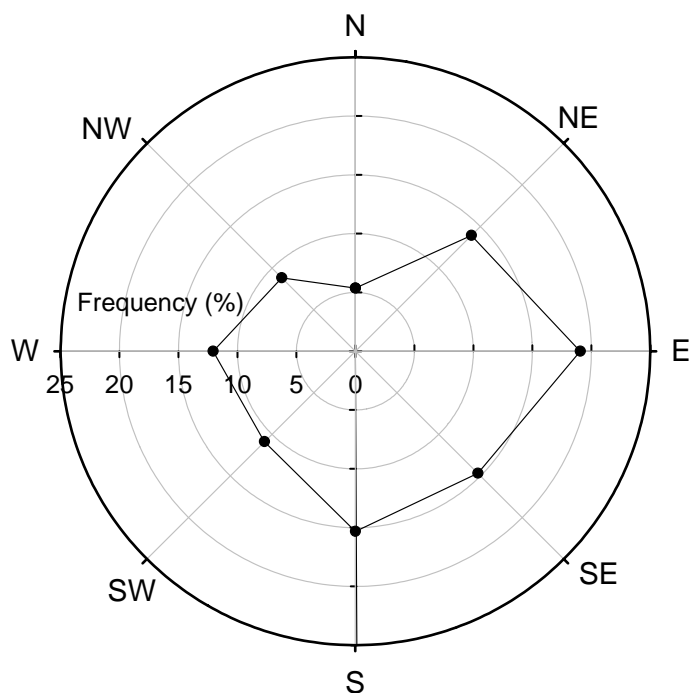
#### 4.1.1.6 Wind Speed and Direction

For the entire year, the average wind speed at 3-m above the ground in lowlands of the Qarlikturvik Valley was  $1.7 \pm 0.2 \text{ m s}^{-1}$ . Wind speed was highest in July, with average daily wind speeds ranging from 1.8 to  $3.7 \text{ m s}^{-1}$  (Fig. 11). The highest maximum wind speed (recorded on an hourly basis) was also recorded in July, with values as high as  $9.6 \text{ m s}^{-1}$ . High maximum daily wind speeds were also frequent in August and September. In contrast, February presented the lowest wind speed with daily averages ranging from 0.4 to  $1.9 \text{ m s}^{-1}$ . On a seasonal basis, wind speed averaged  $2.6 \pm 0.2 \text{ m s}^{-1}$  in summer,  $1.4 \pm 0.2 \text{ m s}^{-1}$  in spring,  $1.1 \pm 0.2 \text{ m s}^{-1}$  in winter and  $1.9 \pm 0.2 \text{ m s}^{-1}$  in autumn.

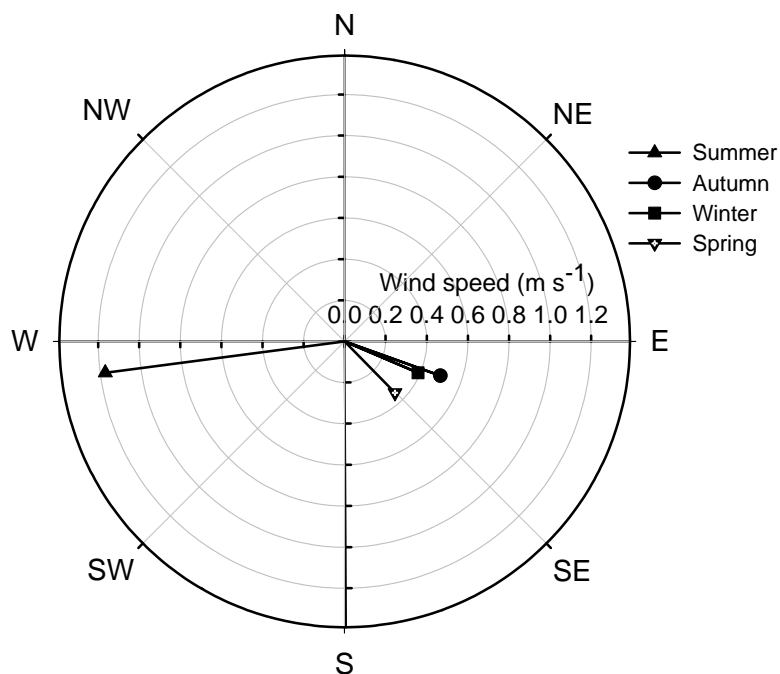
On an annual basis, the wind in lowlands of the Qarlikturvik Valley was blowing most often from the E (19 %), and almost as frequently from the S (15%), SE (15%) and NE (14 %; Fig. 12). However, there were marked seasonal differences in wind direction. During the summer, the average wind direction was actually from the W ( $262^\circ$ ; Fig 13). Indeed, summer winds blew most frequently from the W (30%), the SW (17%) or the NW (16%) and rarely from the other directions ( $\leq 10\%$  each; Fig 14). This was in sharp contrast with the other seasons when average wind direction was almost diametrically opposite, being from the SE ( $110^\circ$  to  $136^\circ$ ; Fig. 13). From the autumn through spring, wind direction was most frequently from the E (21 to 25 % of the time), the S (16 to 18 %), the SE (15 to 18 %) and the NE (15 to 16%), but was rarely from the N, NW, W or SW ( $\leq 11\%$  each; Fig. 14). For all seasons, the wind almost never blew directly from the N ( $\leq 6\%$ ; Fig. 13, 14).



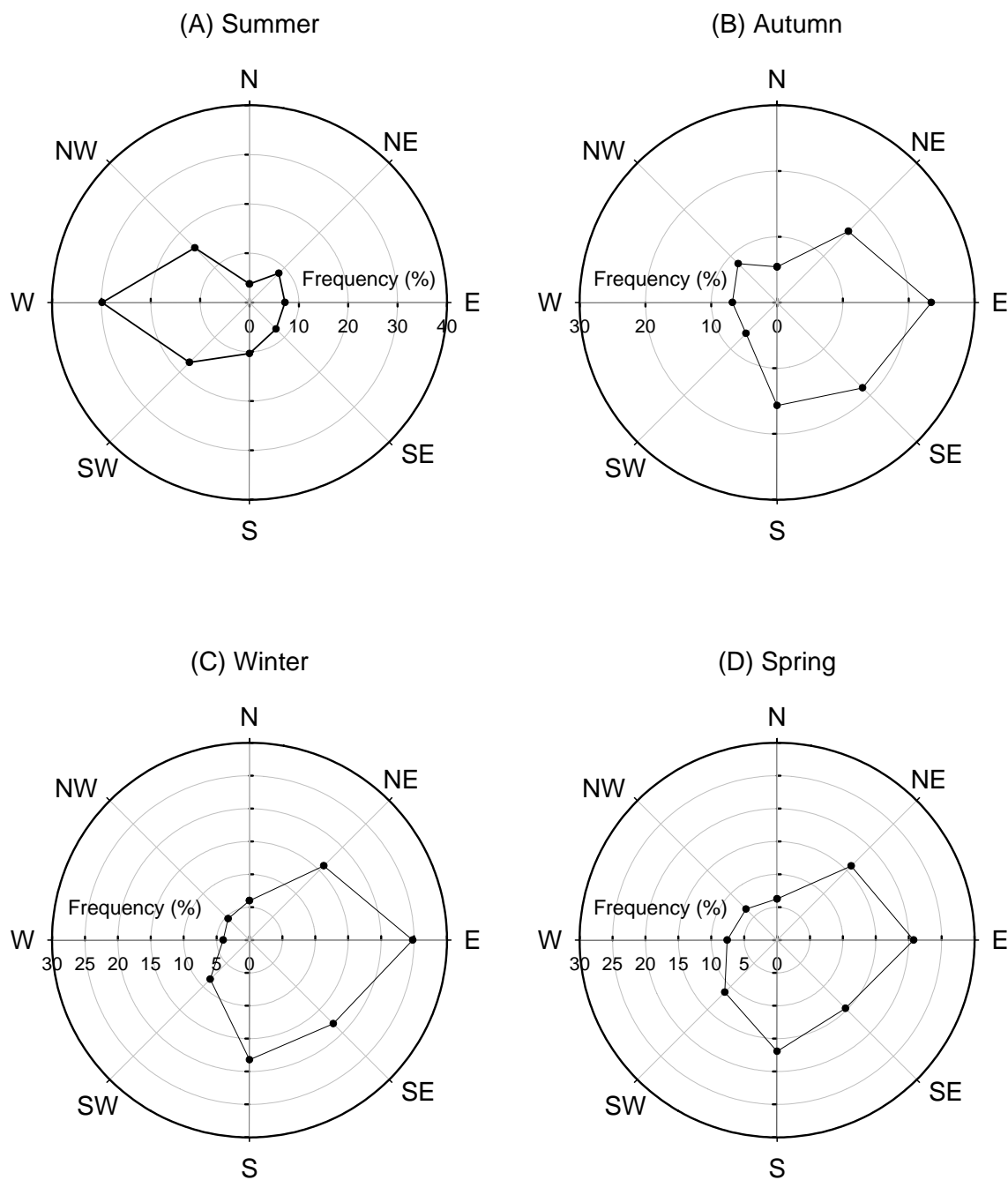
**Figure 11.** Daily average (lower thin line) and maximum (higher thin line) wind speeds at 3-m above the ground in lowlands of the Qarlikturvik Valley, Bylot Island (1994-2003). The thick line shows the monthly average wind speed.



**Figure 12.** Annual wind direction frequency distribution at 3-m above the ground in lowlands of the Qarlikturvik Valley, Bylot Island (1994-2003).



**Figure 13.** Average seasonal wind direction at 3-m above the ground in lowlands of the Qarlikturvik Valley, Bylot Island (1994-2003). The vector length represents the average directional wind speed.



**Figure 14.** Wind direction frequency distribution at 3-m above the ground in lowlands of the Qarlikturvik Valley, Bylot Island for (A) summer, (B) autumn, (C) spring and (D) winter (1994-2003).



## **4.1.2 Pond Inlet**

### **4.1.2.1 Air Temperature**

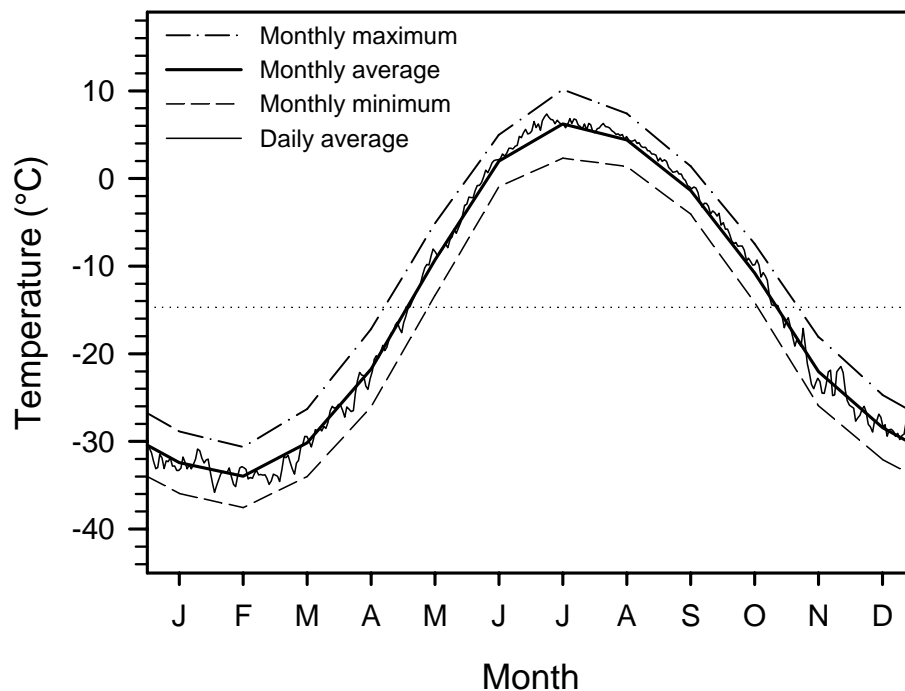
Annual average air temperature in Pond Inlet was  $-14.7 \pm 0.3$  °C. The warmest month of the year was July, with an average of  $6.2 \pm 0.3$  °C, and the coldest month was February, with an average  $-34.0 \pm 0.7$  °C (Fig. 15). During the summer, average air temperature was  $4.1 \pm 0.2$  °C, while it cooled down to an average of  $-11.6 \pm 0.5$  °C in autumn,  $-31.5 \pm 0.5$  °C in winter and  $-20.3 \pm 0.4$  °C in spring.

### **4.1.2.2 Precipitations**

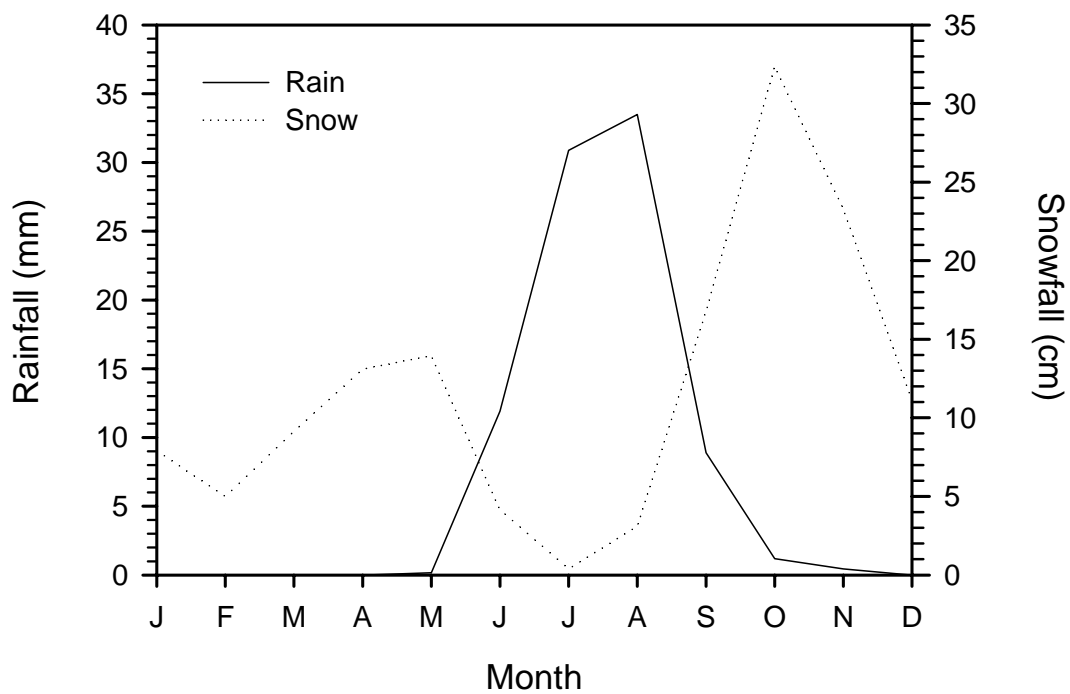
Pond Inlet received an average of  $82.3 \pm 7.2$  mm of rain annually, the majority of which falling during the summer months ( $76.3 \pm 7.2$  mm in summer or 93 % of the annual total) (Fig. 16). The wettest month of the year was August, with an average rainfall of  $33.5 \pm 4.8$  mm. The annual snowfall averaged  $141 \pm 11$  cm annually. There was 2 annual peaks in snowfall: in October, which was the snowiest month ( $32.4 \pm 3.6$  cm), and in May ( $14.0 \pm 1.6$  cm; Fig. 16). On a seasonal basis, the autumn was the snowiest season, with an average snowfall of  $71.9 \pm 6.2$  cm (51 % of the annual total), followed by spring with  $36.4 \pm 3.3$  cm (26%). In comparison, snowfall averaged  $25.2 \pm 2.6$  in winter (18%) and  $8.6 \pm 1.8$  cm in summer (6%).

### **4.1.2.3 Snow depth**

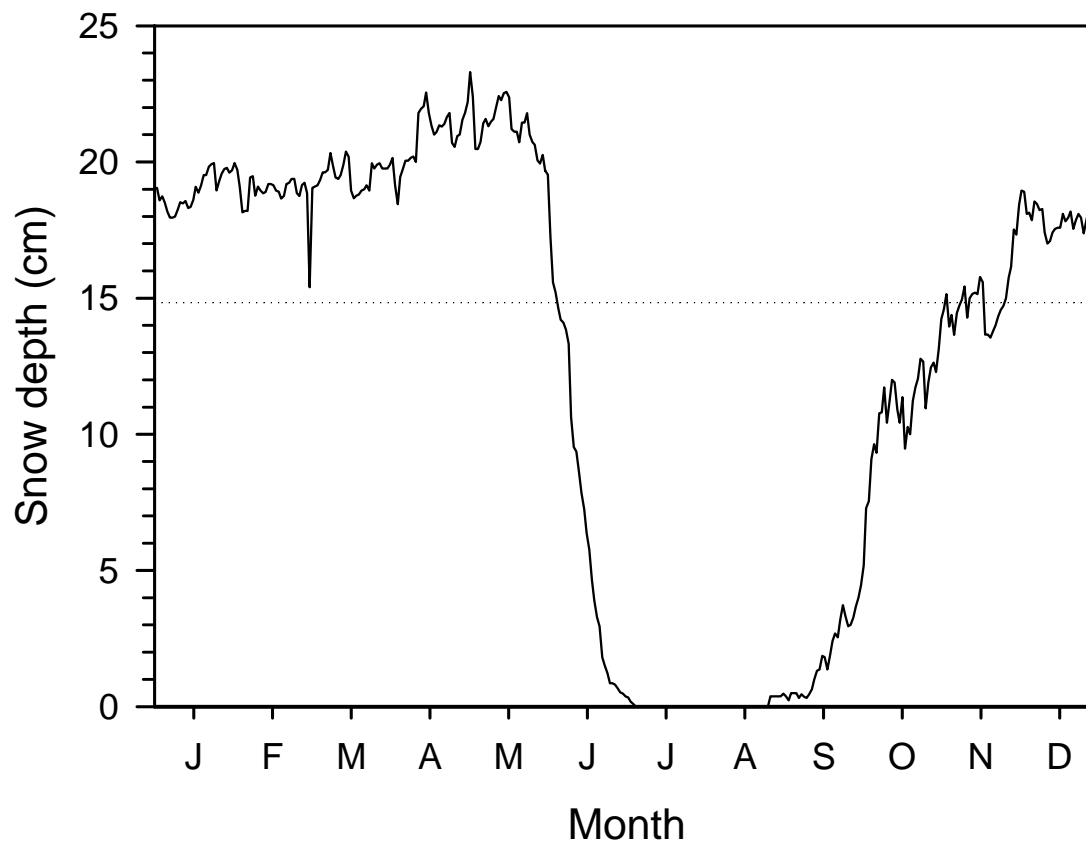
Data on snow depth at Pond Inlet have been available for most years since 1976, except for a short period between 1995 and 2001. Snow on the ground appeared in September and increased rapidly until December (average snow depth for the autumn was 9.5 cm; Fig. 17). Snow depth increased very little during the winter months (average winter snow depth was 18.5 cm). As on Bylot Island, snow depth increased during spring to reach its highest level in May ( $21.3$  cm, monthly average), followed by a rapid snow melt during the month of June.



**Figure 15.** Average monthly and daily air temperatures at the Pond Inlet airport (1976-2002). The dotted line represents the yearly average.



**Figure 16.** Average monthly precipitation at the Pond Inlet airport (1976-2002).



**Figure 17.** Average daily snow depth at the Pond Inlet airport (1976-1995 and 2001-2002). The dotted line represents the average for the period with snow on the ground.

### **4.1.3 Nanisivik**

#### **4.1.3.1 Air Temperature**

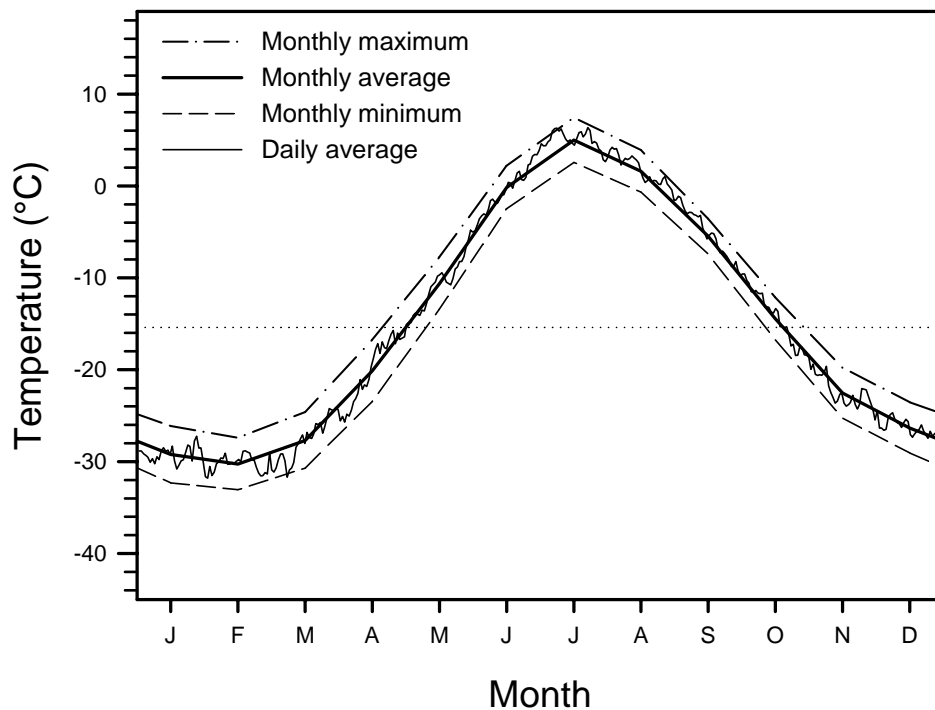
The yearly average temperature at Nanisivik was  $-15.4 \pm 0.3$  °C. As for Pond Inlet and Bylot Island, the warmest month of the year was July, with an average air temperature of  $5.0 \pm 0.4$  °C, and the coldest month of the year was February, with an average  $-30.3 \pm 0.8$  °C (Fig. 18). The seasonal average was  $2.0 \pm 0.3$  °C in summer,  $-14.2 \pm 0.4$  in autumn,  $-28.8 \pm 0.5$  °C in winter and  $-19.6 \pm 0.4$  in spring.

#### **4.1.3.2 Precipitations**

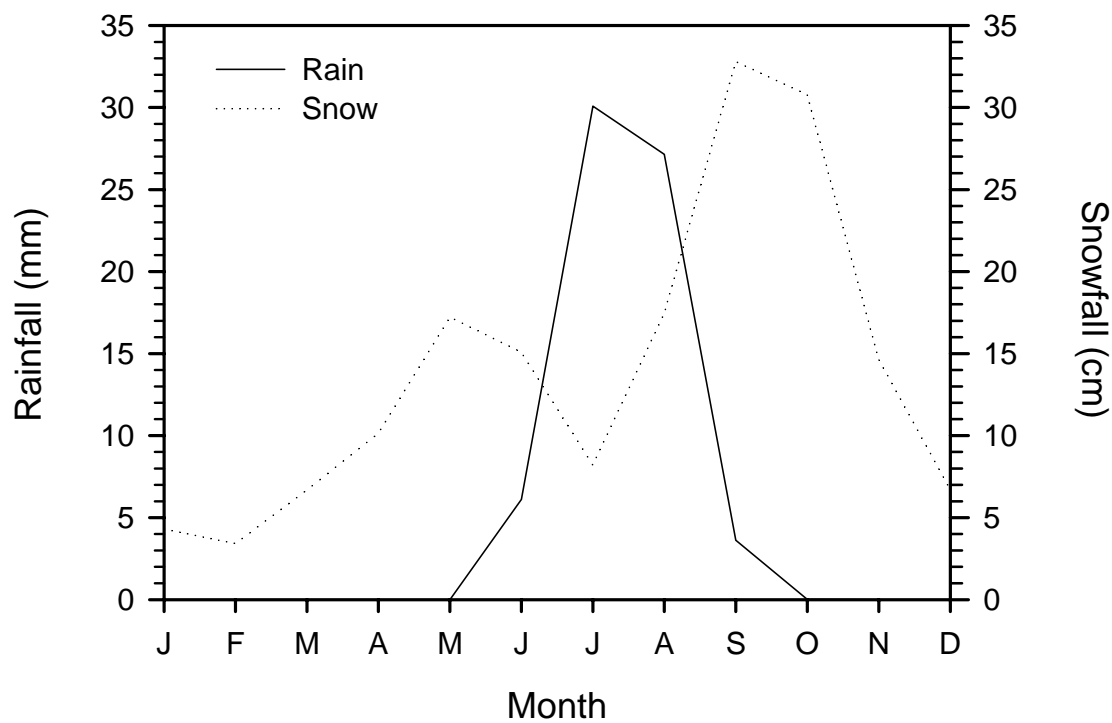
On average, Nanisivik received  $68.2 \pm 7.3$  mm of rain and  $174.7 \pm 15.5$  cm of snow annually. Most of the rain fell during the summer ( $61.7 \pm 6.8$  mm of rain or 91 % of the annual total) and the wettest month of the year was July with  $30.1 \pm 2.9$  mm of rain (Fig. 19). In terms of snowfall, September was the snowiest month of the year, with an average snowfall of  $32.8 \pm 4.5$  cm. On a seasonal basis, the average snowfall was highest in autumn ( $81.7 \pm 7.8$  cm or 47 % of the annual total), followed by summer ( $43.2 \pm 4.9$  or 25%) spring ( $34.1 \pm 3.9$  or 20%). Snowfall was lowest in winter ( $14.4 \pm 1.8$  cm or 8%).

#### **4.1.3.3 Snow depth**

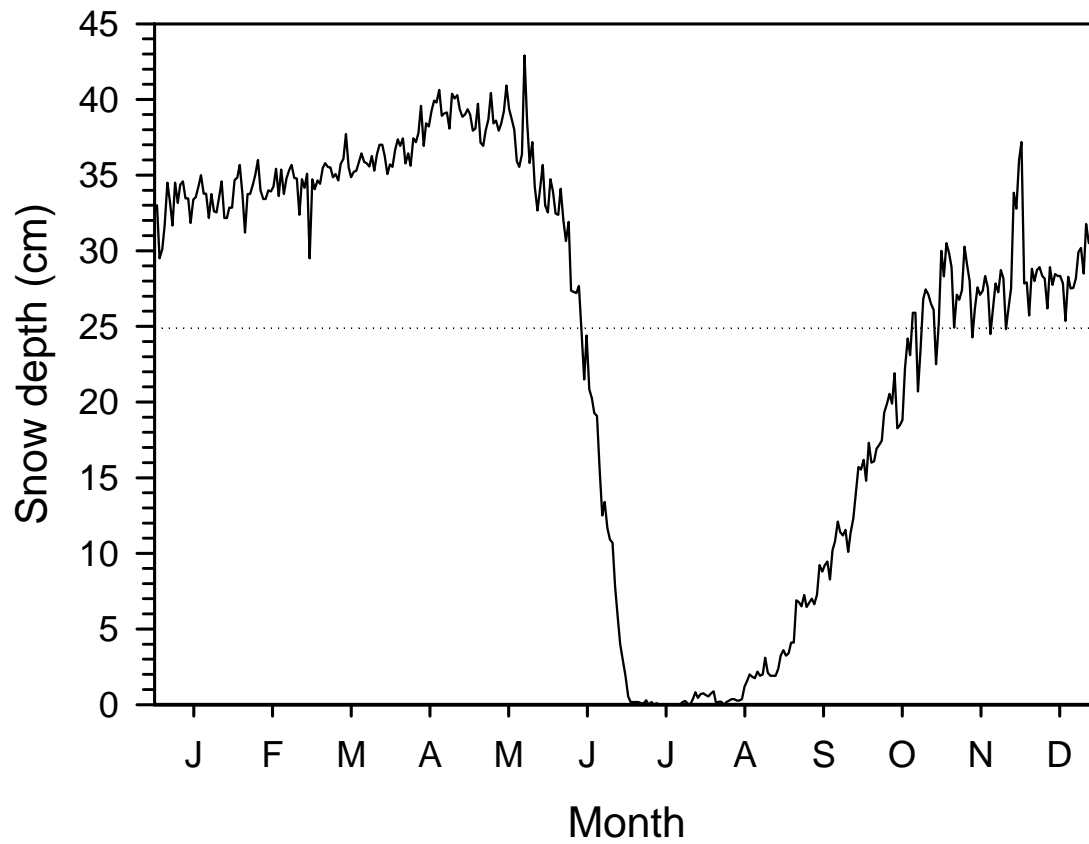
Data on snow depth at Nanisivik have been available only for the years 1981 to 1996. Snow on the ground appeared earlier than in Pond Inlet and Nanisivik and started to accumulate in August. Snow depth increased quickly from August to October (average autumn snow depth was 20.9 cm; Fig. 20), but remained relatively stable for the rest of autumn (Fig. 20). Snow accumulation continued slowly but steadily during the winter months (seasonal average: 32.1 cm) and early spring. Snow depth peaked in May (monthly average: 37.8 cm), and declined dramatically throughout the month of June (Fig. 20). On average, both annual and peak snow depths were higher in Nanisivik (24.9 and 42.9 cm) than at Pond Inlet (14.8 and 23.3 cm, respectively).



**Figure 18.** Average monthly and daily air temperatures at the Nanisivik airport (1977-2002). The dotted line represents the yearly average.



**Figure 19.** Average monthly precipitation at the Nanisivik airport (1977-2002).



**Figure 20.** Average daily snow depth at the Nanisivik airport (1981-1996). The dotted line represents the average for the period with snow on the ground.

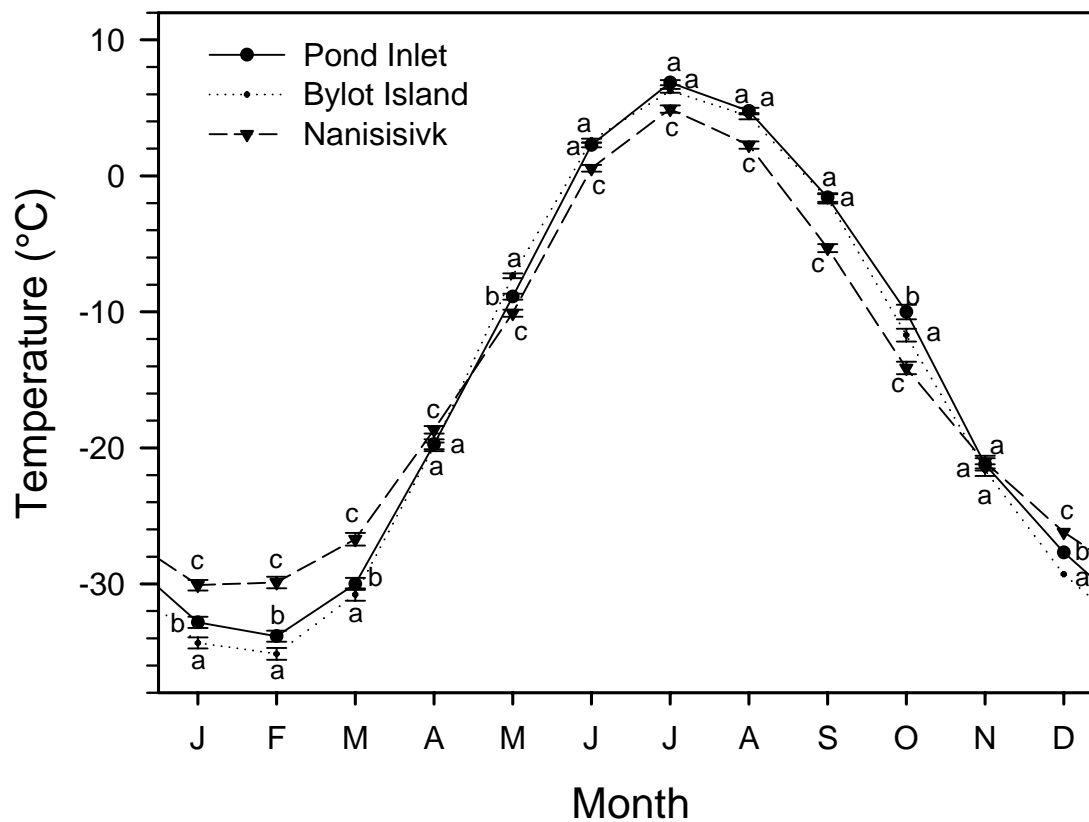
#### ***4.1.4 Comparison of Bylot Island vs. Pond Inlet and Nanisivik***

Weather data from Pond Inlet, Nanisivik and Bylot Island were compared statistically to examine regional variability in climate. The comparison covered the period where climatic data were recorded at the 3 sites simultaneously, that is from 1994 to 2002 for air temperature and 1995 to 2002 for precipitation.

##### **4.1.4.1 Air Temperature**

Statistical analyses revealed some differences in air temperature between the 3 sites, but these differences were not the same throughout the year (interaction site  $\times$  month  $F = 23.7$ ,  $df = 22$ , 7849,  $P < 0.0001$ ). Temperatures were most similar between Pond Inlet and Bylot Island (Fig. 21). These two sites experienced similar temperatures during the summer (months of June to September) but winter temperatures on Bylot Island were significantly colder than those of Pond Inlet (months of December to March). In spring, temperatures tended to be slightly warmer on Bylot Island than Pond Inlet (difference significant in May only) whereas the reverse was true in fall (difference significant in October only). Nevertheless, differences in monthly air temperatures between Bylot Island and Pond Inlet were very small and never exceeded 1.7°C (Fig. 21).

There were more differences in air temperature between Bylot Island and Nanisivik than between Bylot Island and Pond Inlet. From May to October, monthly temperatures at Bylot Island were significantly warmer than compared to those of Nanisivik (Fig. 21), whereas temperatures from December through April were significantly colder at Bylot Island (no significant differences were found in November). Given the great similarity in air temperatures between Pond Inlet and Bylot Island, the exact same pattern of significant differences were found between monthly air temperatures of Pond Inlet and Nanisivik (Fig. 21).



**Figure 21.** Comparison of monthly air temperatures (Mean  $\pm$  SE) at Bylot Island, Pond Inlet and Nanisivik (1994-2002). Means with different letters differ ( $P < 0.05$ ) within months.



#### 4.1.4.2 Summer Rainfall

Statistical analyses revealed that overall, there was no difference in summer rainfall between Bylot Island, Pond Inlet and Nanisivik ( $F = 1.25$ ,  $df = 2$ ,  $41$ ,  $P = 0.299$ ). However, analyses on a monthly basis revealed that June rainfall at Bylot Island was more abundant than at Nanisivik ( $F = 4.95$ ,  $df = 1$ ,  $41$ ,  $P = 0.032$ ). Otherwise, rainfalls were very similar across sites in July and August (Fig. 22). At all sites, rainfall increased from June to August ( $F = 7.37$ ,  $df = 2$ ,  $41$ ,  $P = 0.0018$ ).

#### 4.1.5 Soil Temperatures in Grazed vs. Ungrazed Areas

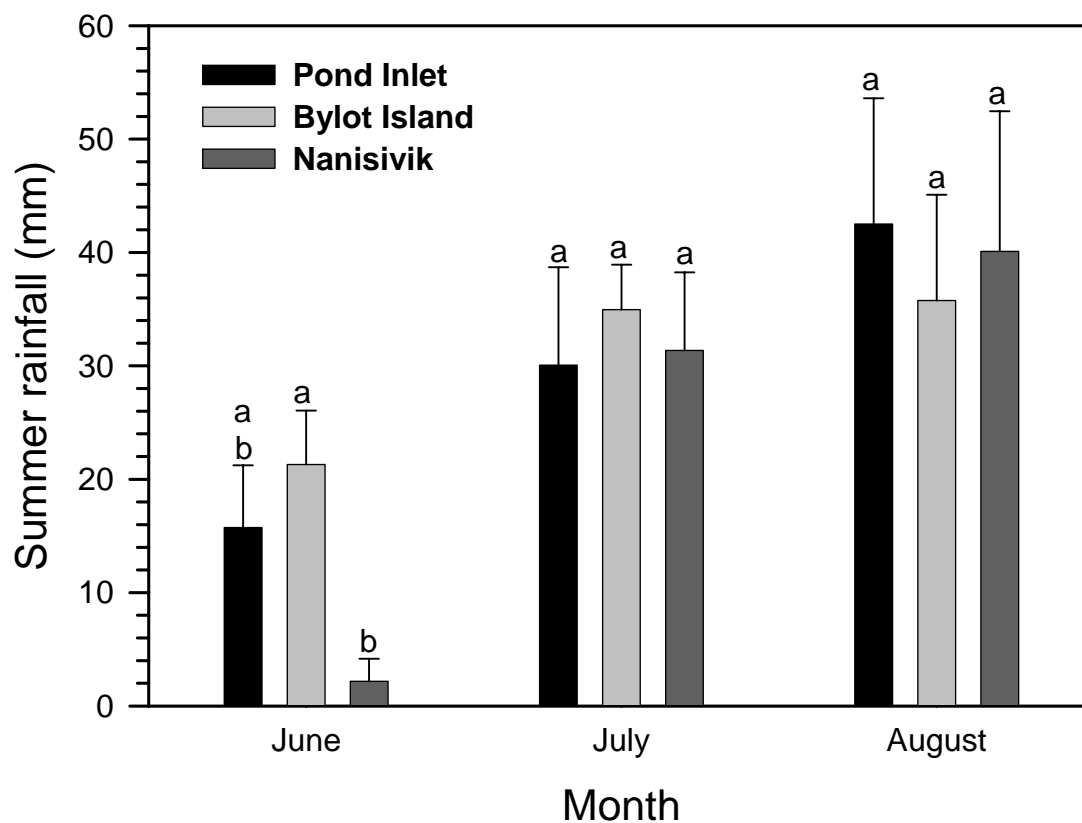
Because goose grazing is intense in wetland of Bylot Islands, we monitored difference in soil temperature between grazed and permanently ungrazed (i.e. within exclosures) areas. Statistical analyses revealed differences in soil temperature (2-cm depth) during the summer between areas grazed and ungrazed by geese. For the 3 summer months, the average soil temperatures in ungrazed areas were  $1.3^{\circ}\text{C}$  warmer than in grazed areas ( $F = 68.8$ ,  $df = 1$ ,  $4419$ ,  $P < 0.0001$ ; Fig. 23). This difference, however, was not the same across summer months (interaction treatment $\times$ month:  $F = 14.4$ ,  $df = 2$ ,  $4419$   $P < 0.0001$ ). The greatest monthly temperature difference was recorded in June ( $2.3^{\circ}\text{C}$ ) and the smallest in September ( $0.7^{\circ}\text{C}$ ).

## 4.2 Climate Trends

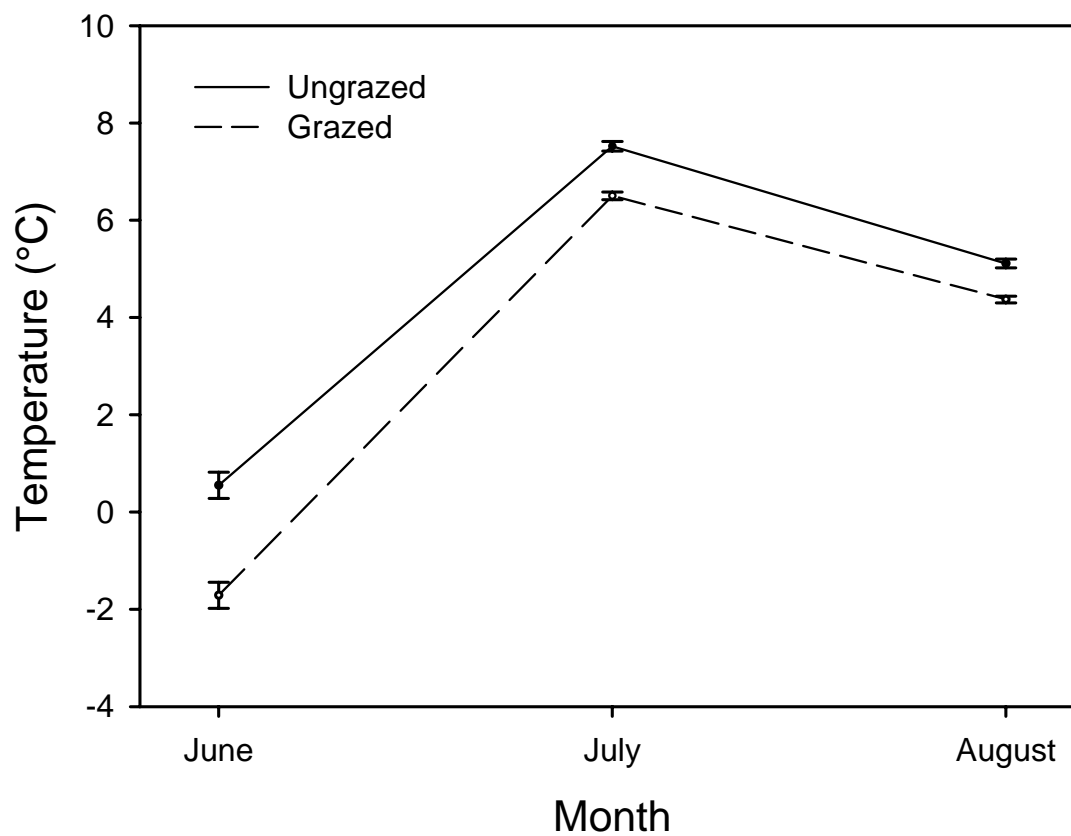
### 4.2.1 Pond Inlet

#### 4.2.1.1 Air Temperature

From 1976 to 2002, the average annual air temperature in Pond Inlet has shown a weak, statistically non significant warming trend. Over this period, air temperature increased by an average of  $0.47^{\circ}\text{C}$  per decade (Fig. 24). However, when considering summer temperatures only, a statistically significant warming trend was detected. Since 1976, summer temperatures in Pond Inlet have increased by  $0.7^{\circ}\text{C}$  per decade for a total gain of  $1.82^{\circ}\text{C}$  over the last 26 years (Fig. 25). For spring and autumn, air temperatures have also shown weak warming trends, though statistically non significant. Autumn air temperatures have increased by  $1.02^{\circ}\text{C}$  every 10 years



**Figure 22.** Summer monthly rainfall (Mean  $\pm$  SE) at Bylot Island, Pond Inlet and Nanisivik (1995-2002). Rainfall for the entire month of August at Bylot Island was extrapolated based on the ratio of rainfall 1-17:18-31 August at Pond Inlet. Statistical analyses, however, were limited to the period 1-17 August. Means with different letters differ ( $P < 0.05$ ) within months.



**Figure 23.** Monthly soil temperatures (2-cm depth; mean  $\pm$  SE) between areas grazed and ungrazed by geese, Bylot Island (1996-2003).

whereas the spring temperatures have shown an increase of  $0.66^{\circ}\text{C}$  every 10 years. For the winter, there was no noticeable trend in air temperature (Fig. 25).

#### 4.2.1.2 Precipitations

There was a great variability in the amount of precipitation, either rain or snow, received every year at Pond Inlet. Over the last 26 years, there was no detectable trend in total annual rainfall or snowfall. However, it is interesting to note that with 171.6 mm of rainfall, the summer 2002 was the wettest one in 26 years. On a seasonal basis, the amount of snow falling on Pond Inlet during autumn has shown weak decreasing trends, although statistically non significant. Autumn snowfalls have decreased by an average of 15.8 cm per decade (Fig. 26). No other trends were detected in other seasons for precipitations.

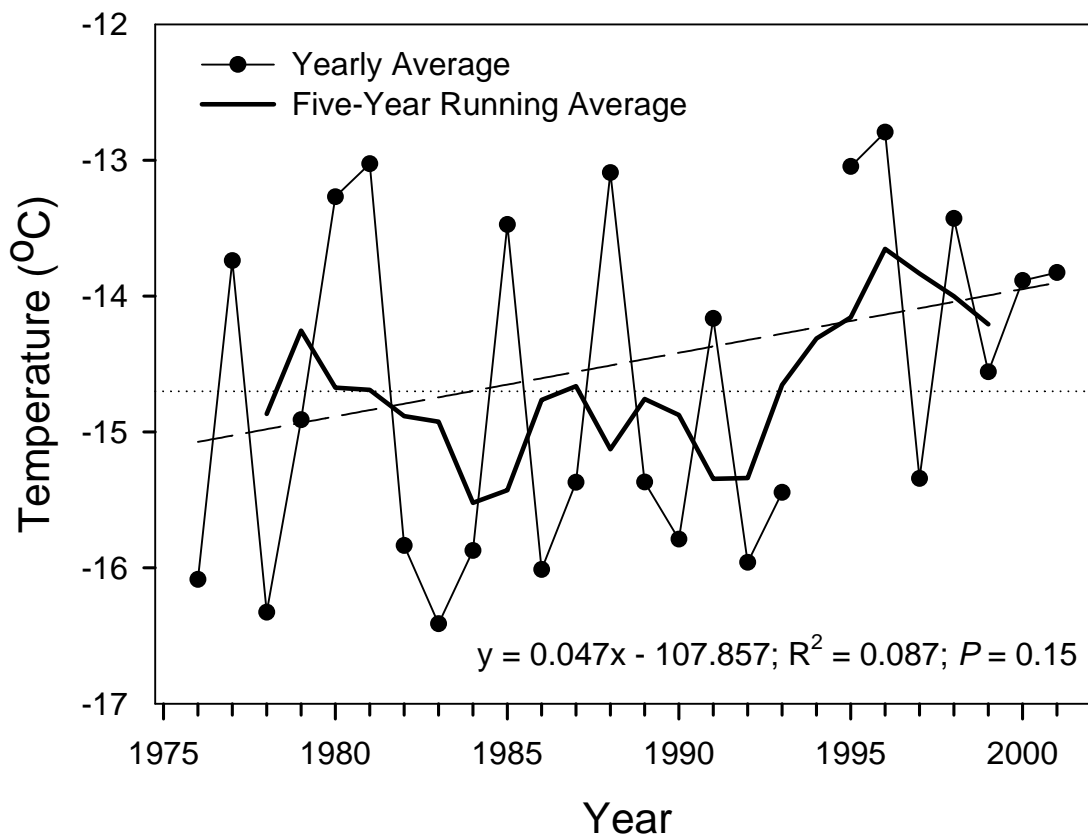
#### 4.2.1.3 Snow Depth

The annual average snow depth at Pond Inlet did not reveal evidence of temporal trends since 1976 (Fig. 27), but presented considerable variability from year to year. However, average snow depth during winter presented a weak increasing trend over the years, increasing by an average of 4.92 cm every 10 years, although this trend was not statistically significant (Fig. 28). No trends were found at other seasons.

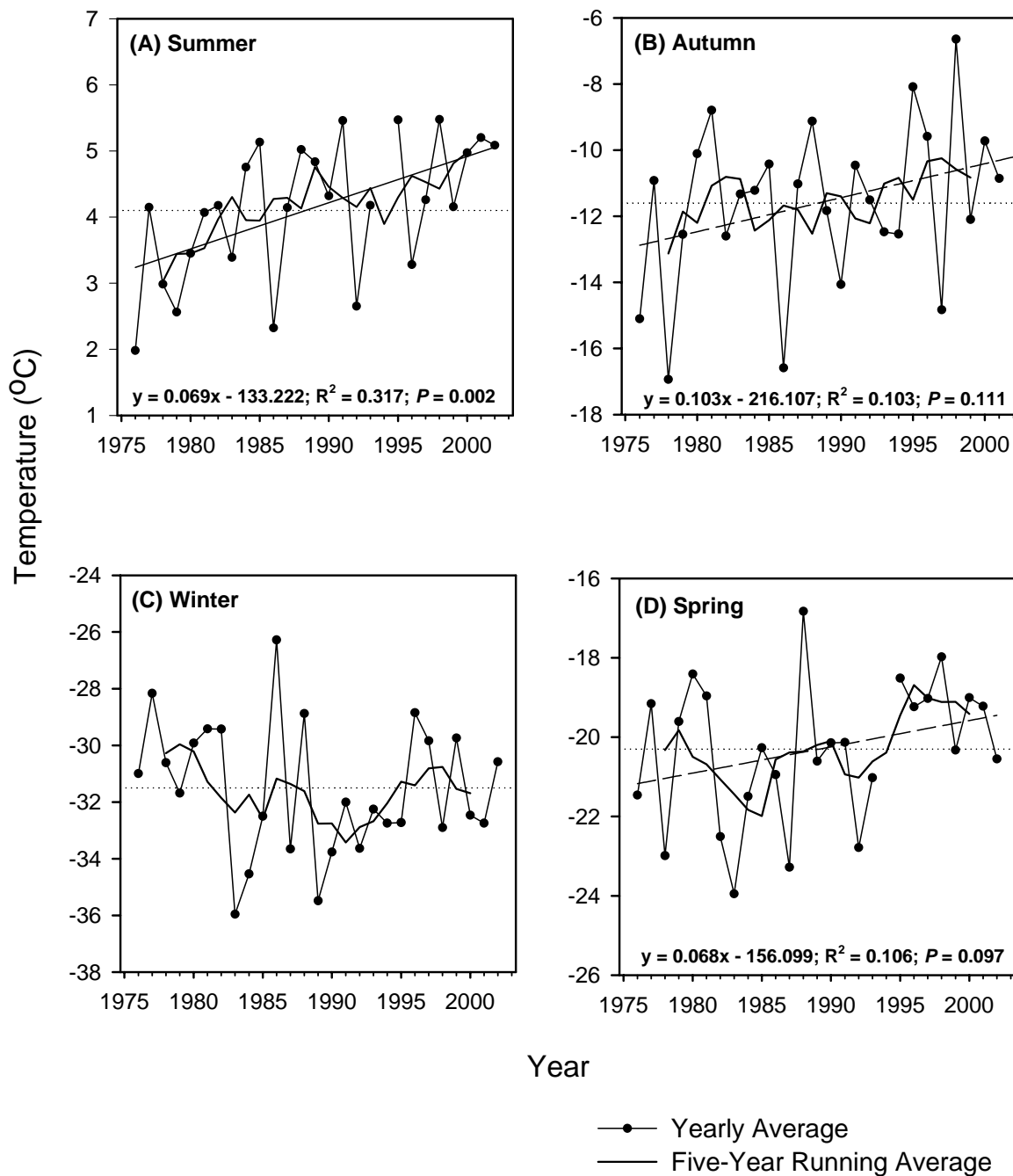
### **4.2.2 *Nanisivik***

#### 4.2.2.1 Air Temperature

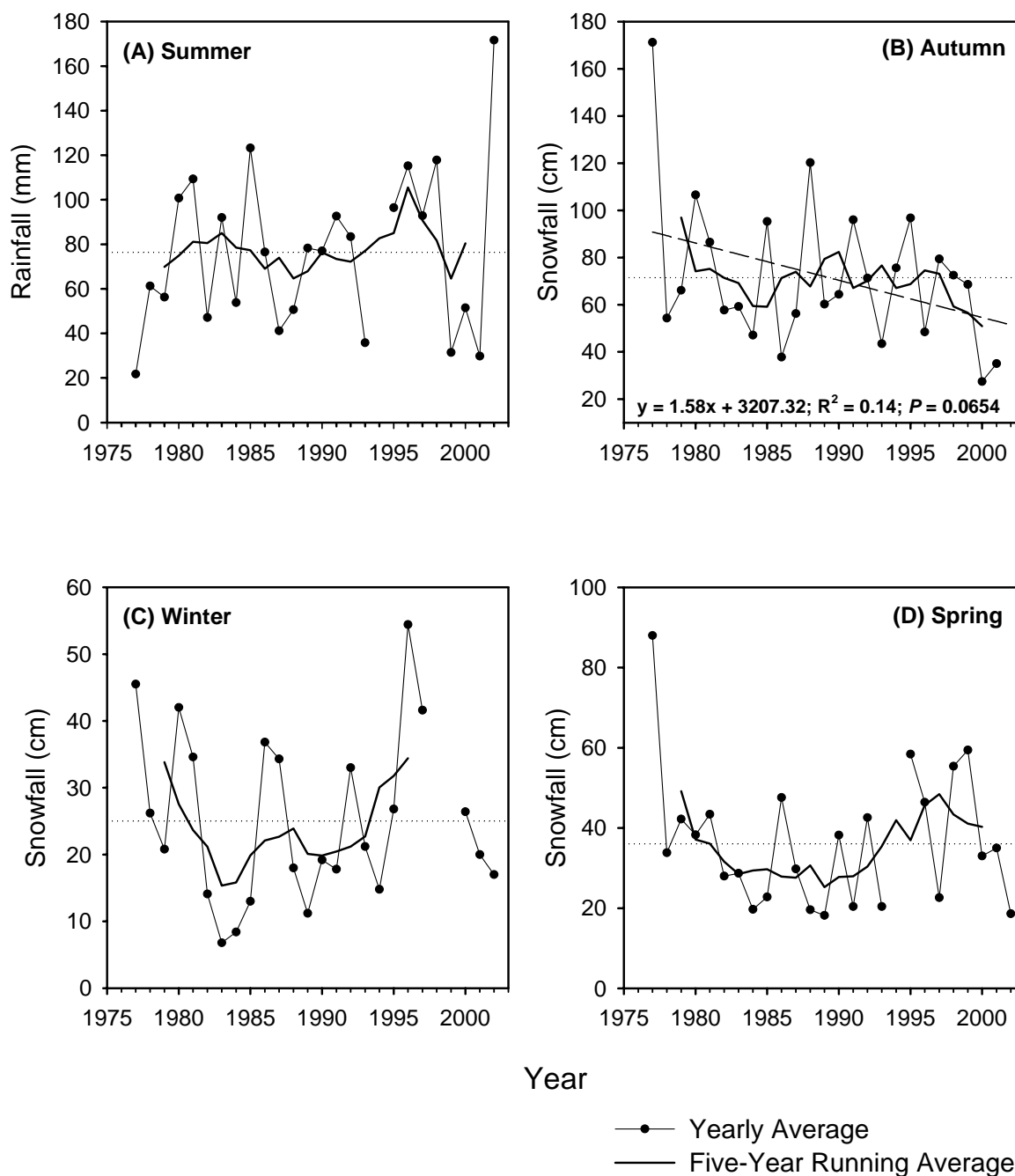
In contrast to Pond Inlet, there was no detectable trend in annual air temperature at Nanisivik from 1977 to 2002 (Fig. 29). However, Nanisivik showed the same statistically significant trend in summer temperature. Summer temperatures have increased by an average of  $0.79^{\circ}\text{C}$  per decade, for a total of  $1.98^{\circ}\text{C}$  over the last 25 years (Fig. 30). Spring temperatures in Nanisivik have also shown a weak but statistically non significant warming trend, increasing at a rate of  $0.9^{\circ}\text{C}$  per decade, for a total of  $2.3^{\circ}\text{C}$  over the last 25 years (Fig. 30). However, there were no detectable trends for autumn and winter temperatures.



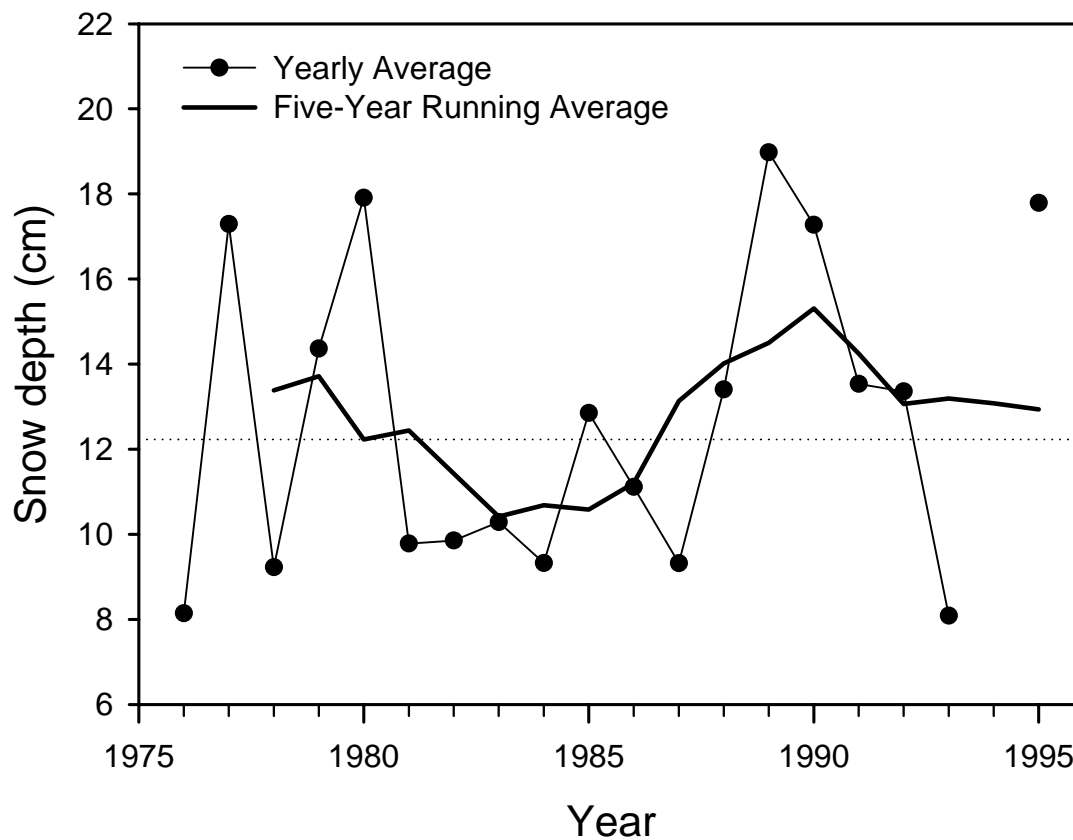
**Figure 24.** Mean annual air temperature and 5-year running mean from 1976 to 2002 at Pond Inlet. The non-significant temporal trend is represented by a dashed line ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.



**Figure 25** Mean air temperature and 5-year running mean from 1976 to 2002 at Pond Inlet for (A) summer, (B) autumn, (C) spring and (D) winter. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.

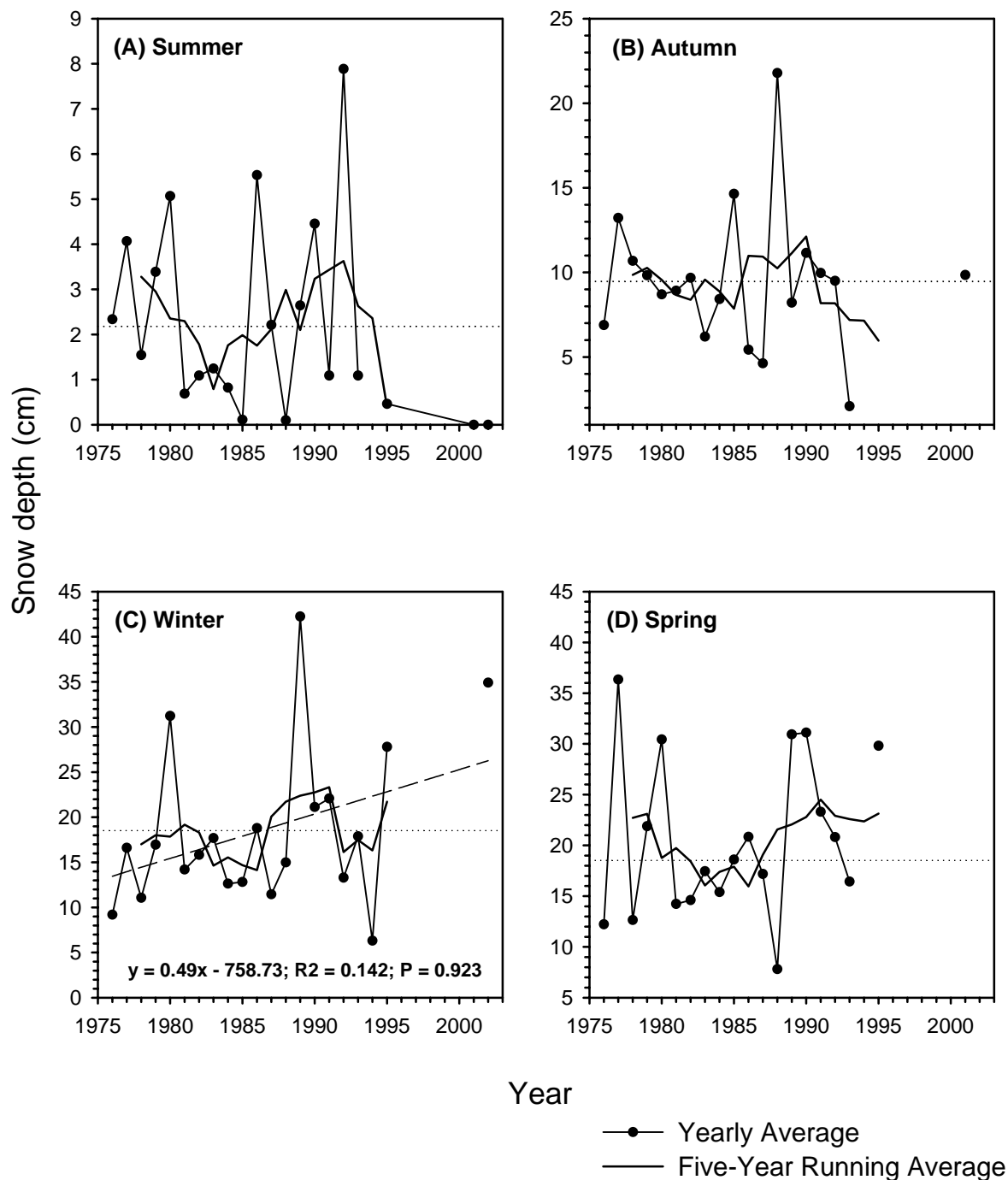


**Figure 26.** Mean precipitation and 5-year running mean from 1976 to 2002 at Pond Inlet for (A) summer rainfall, (B) autumn snowfall, (C) spring snowfall and (D) winter snowfall. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.

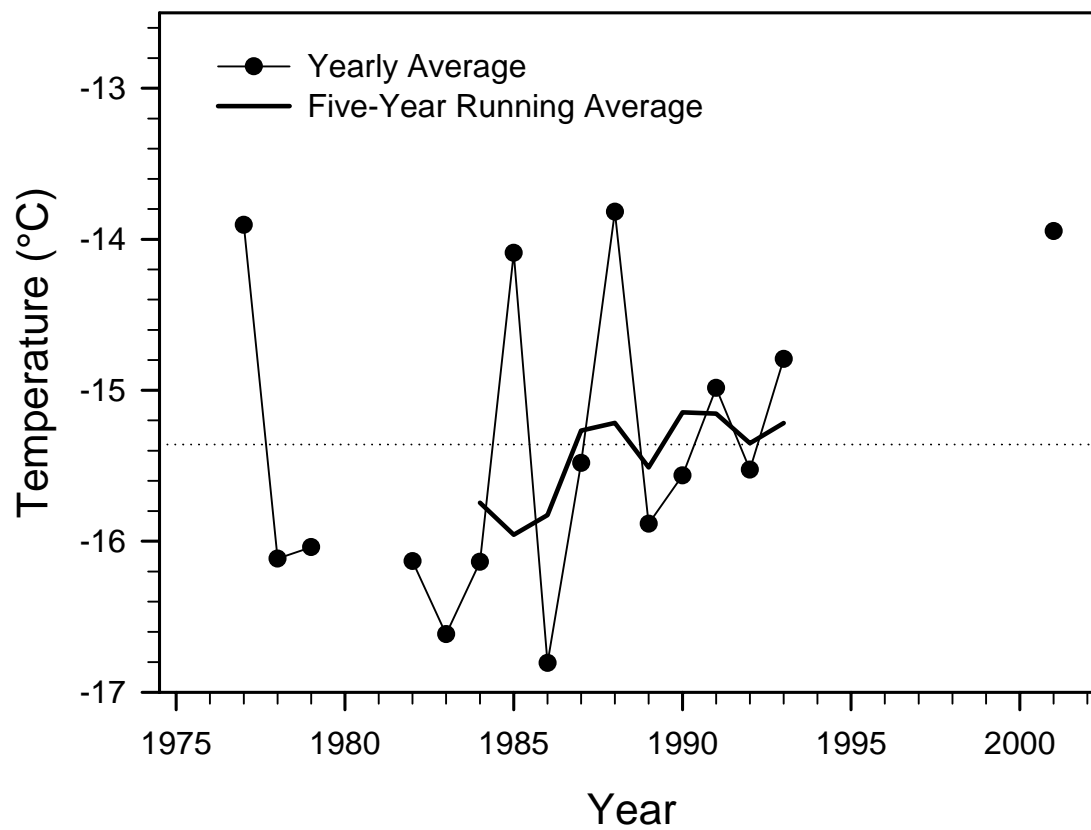


**Figure 27.** Mean annual snow depth and 5-year running mean from 1976 to 1995 at Pond Inlet. The dotted line shows the mean for the whole period.

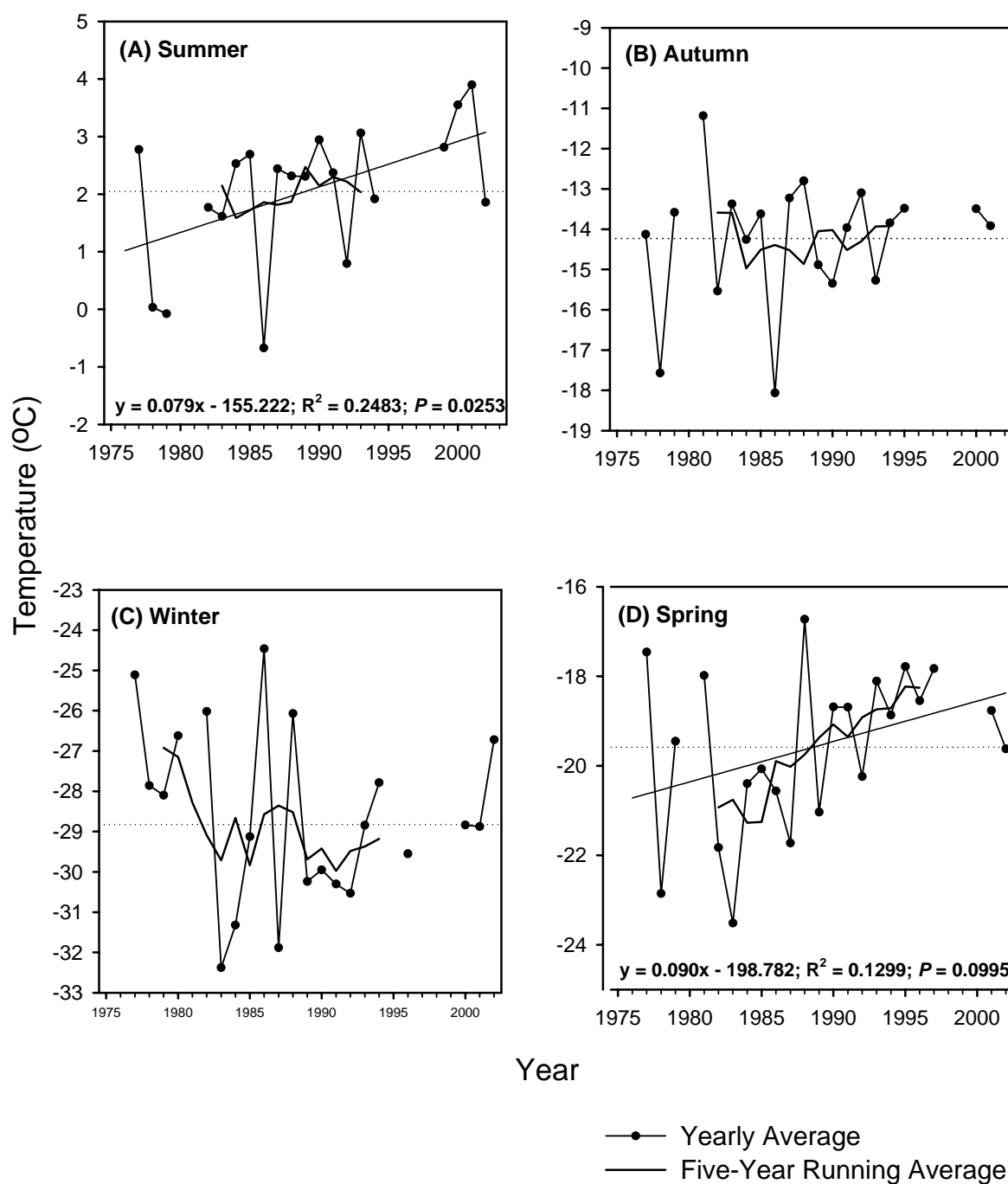




**Figure 28.** Mean snow depth and 5-year running mean from 1976 to 1995 and 2001 at Pond Inlet for (A) summer, (B) autumn, (C) spring and (D) winter. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.



**Figure29.** Mean annual air temperature and 5-year running mean from 1977 to 2002 at Nanisivik. The dotted line shows the mean for the whole period.



**Figure 30.** Mean air temperature and 5-year running mean from 1977 to 2002 at Nanisivik for (A) summer, (B) autumn, (C) spring and (D) winter. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.

#### 4.2.2.2 Precipitations

A weak increasing trend in summer rainfall was noticed at Nanisivik between 1977 and 2002. This statistically non-significant trend showed a rate of increase of 13.7 mm of summer rainfall per decade, for a total of 34.3 mm over the last 25 years (Fig. 31). Finally, there were no detectable trends in total annual snowfall or snowfall in other seasons at Nanisivik (Fig. 31).

#### 4.2.2.3 Snow depth

There were no detectable temporal trends in annual snow depth at Nanisivik (Fig. 32). When examined on a seasonal basis, there was no trend in winter (as found in Pond Inlet) or for any other season (Fig. 33). The inter-annual variability in snow depth was however important.

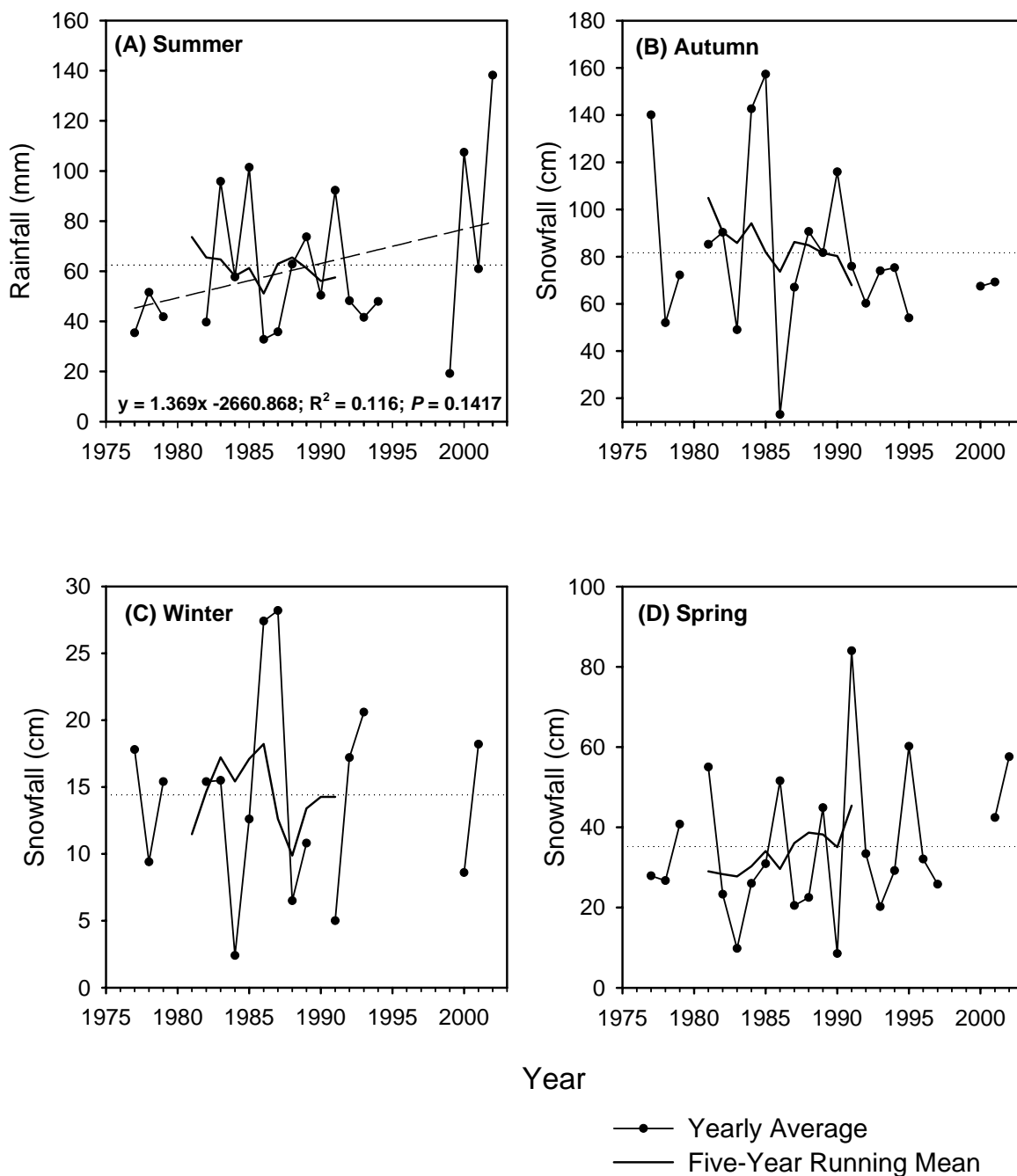
### **4.2.3 Bylot Island**

Even though 10 years is still a relatively short time period for studying climate changes, data from Bylot Island have been analyzed for temporal trends, and some have been found.

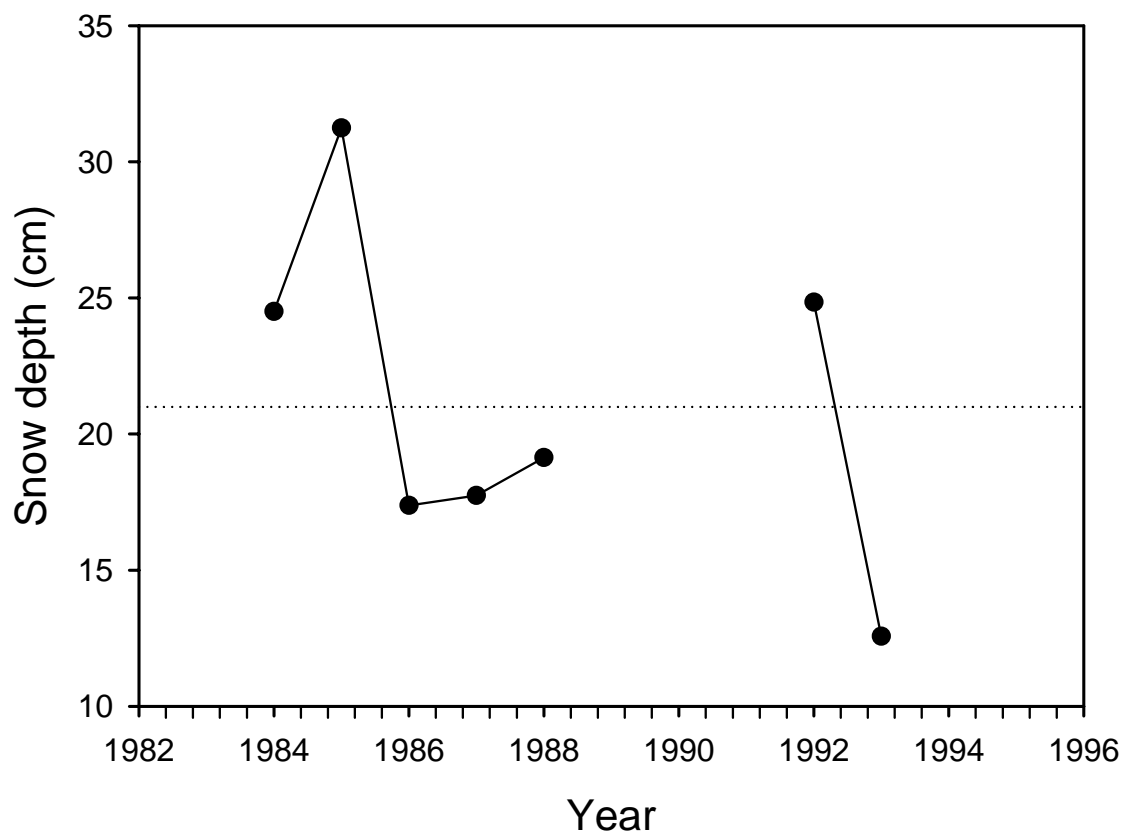
#### 4.2.3.1 Air Temperature

There was no detectable trend in annual air temperature at Bylot Island (Fig. 34). However, on a seasonal basis, a weak warming trend approaching statistical significance was observed in winter with an average gain of 4.2°C over 10 years (Fig. 35). This trend is strongly influenced by the warm winter of 2002-2003, which showed an average temperature of -29.3°C (more than 3 degrees above the -32.6°C average). There were no trends in temperature for the other seasons at Bylot Island (Fig. 35).

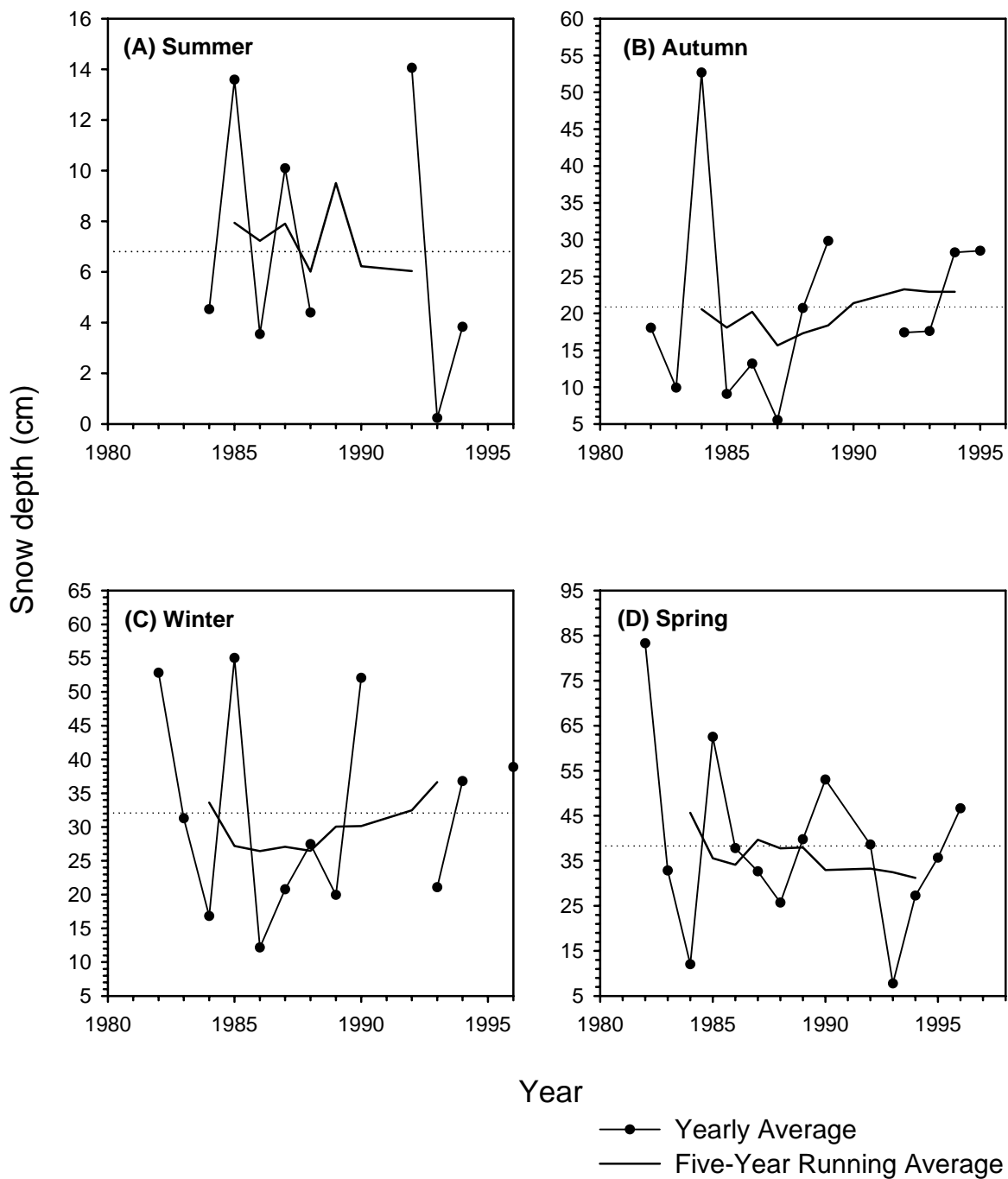
We found no evidence of temporal trends in the yearly and seasonal number of thawing degree-days, except for a weak, non statistically significant decrease in spring TDD (Fig. 36). However, this decreasing trend was influenced by the extremely high TDD value recorded in 1994 (14.4), which contrasted with the spring TDD from 1995 to 2003 (ranging from 0 to 3.3). A similar effect was found in the number of days above 0°C, with an unusually high value in spring 1994 (8) compared to other years (values ranging from 0 to 2), which accounted for the weak decreasing trend in the number of spring days above 0°C from 1994 to 2003 (Fig. 37). In contrast, data showed a weak increasing trend in the number of days above 0°C in autumn. The



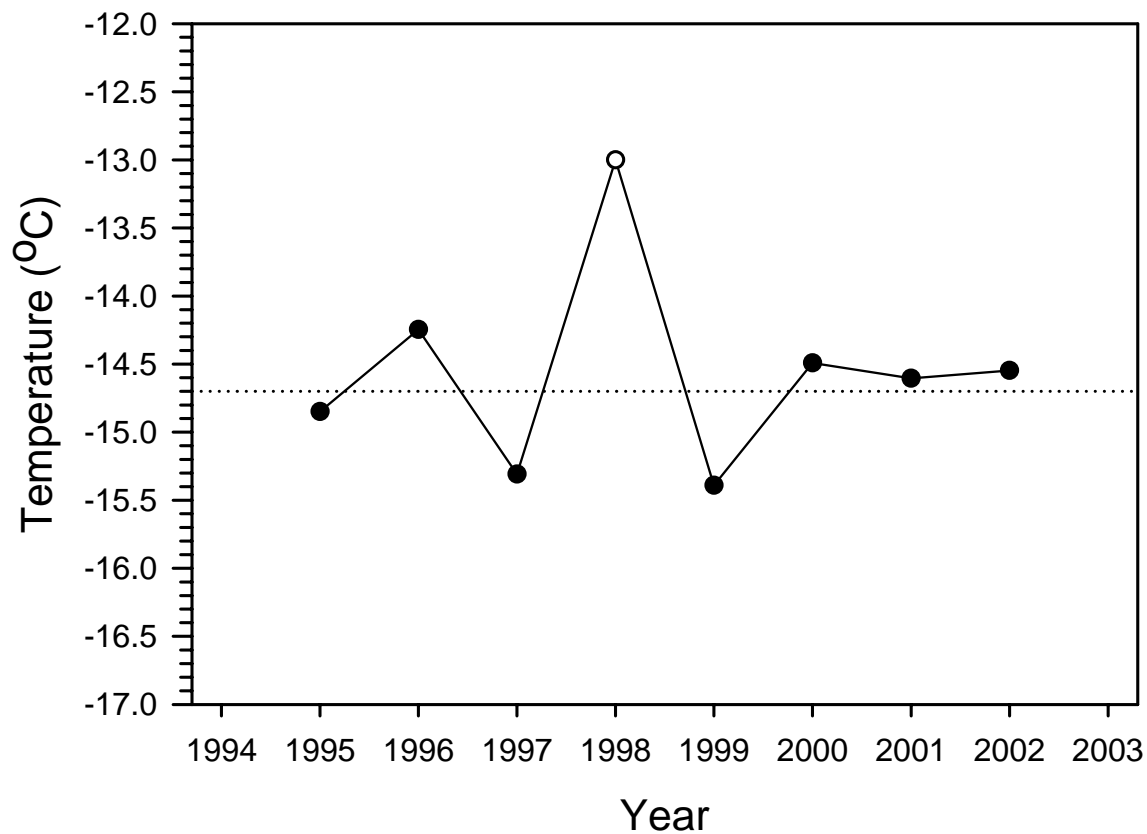
**Figure 31.** Mean precipitation and 5-year running mean from 1977 to 2002 at Nanisivik for (A) summer rainfall, (B) autumn snowfall, (C) spring snowfall, (D) winter snowfall. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.



**Figure 32** Mean annual snow depth from 1981 to 1997 at Nanisivik. The dotted line shows the mean for the entire period.

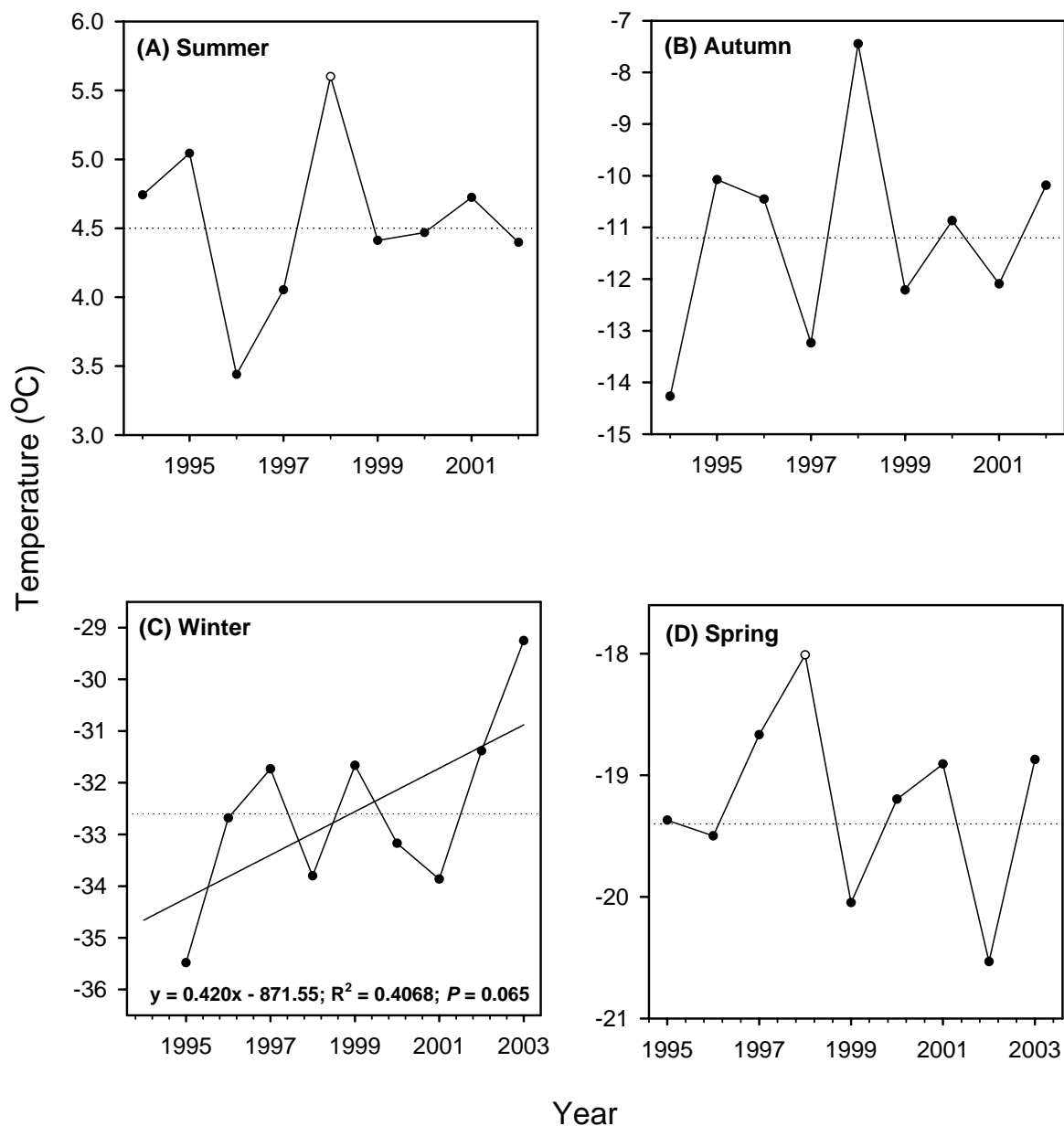


**Figure 33.** Mean snow depth and 5-year running mean from 1981 to 1997 at Nanisivik for (A) summer, (B) autumn, (C) spring and (D) winter. The dotted line shows the mean for the whole period.



**Figure 34.** Mean annual air temperature from 1995 to 2002 in the Qarlikturvik Valley lowlands, Bylot Island. The dotted line shows the mean for the whole period. Air temperature for 1998 is represented by a white circle and was extrapolated for part of the year from the relation between the air temperatures at Bylot Island and Pond Inlet due to missing values. Statistical analyses, however, excluded the 1998 value.





**Figure 35.** Mean air temperature from 1994 to 2003 in the Qarlikturvik Valley lowlands, Bylot Island for (A) summer, (B) autumn, (C) spring and (D) winter. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ). The dotted line shows the mean for the whole period. Air temperature for the spring and summer 1998 is represented by a white circle and was extrapolated from the relation between the air temperatures at Bylot Island and Pond Inlet. Statistical analyses, however, excluded the 1998 value.

very high number of TDD and number of days above 0°C in autumn 1998 compared to other years (Fig. 36 and 37) indicated that a very unusual warm spell occurred that year. For the summer as well as for the yearly number of days above 0°C, there was no temporal trend.

#### 4.2.3.2 Soil Temperature

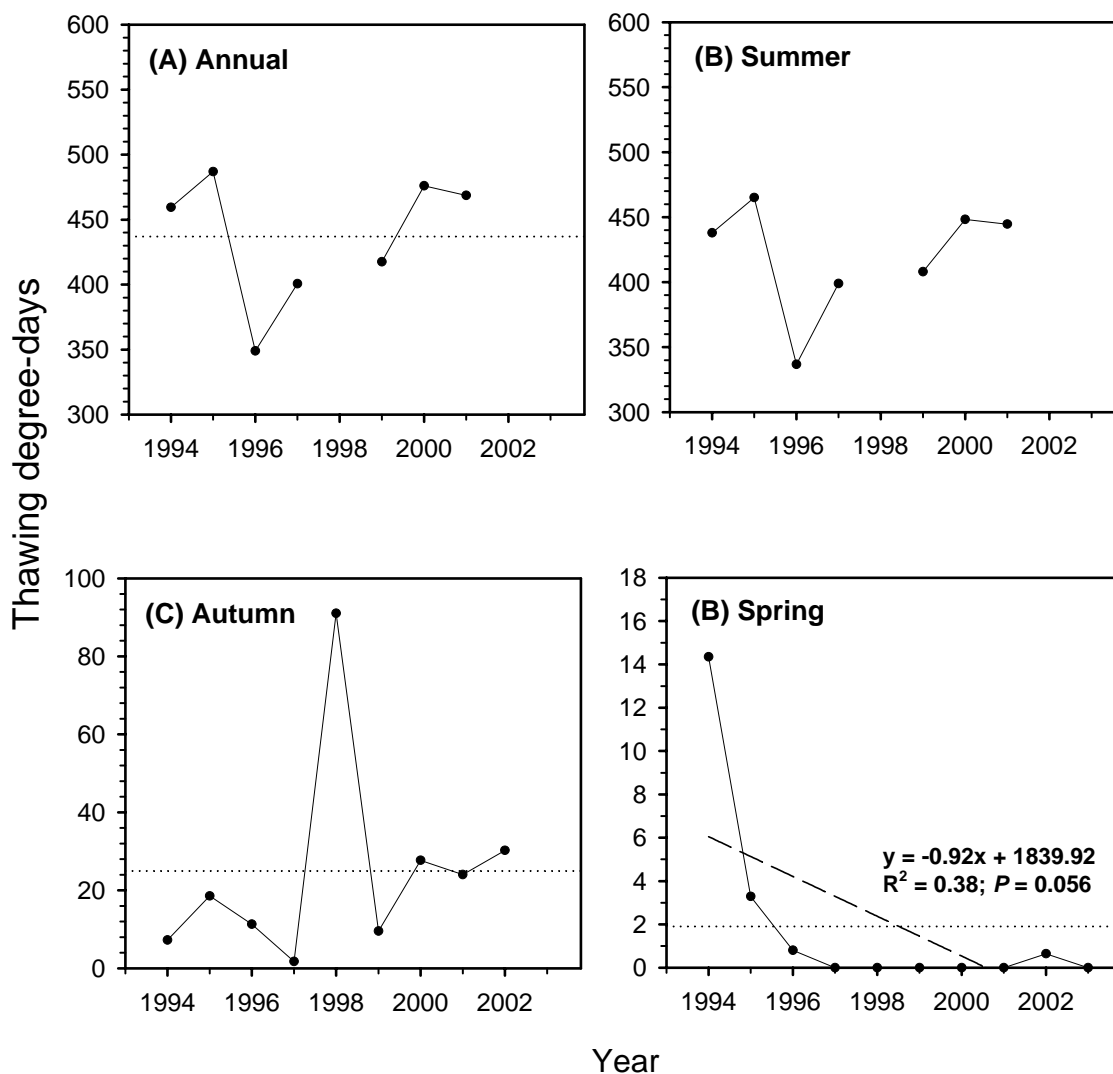
Data on soil temperatures at 10-cm depth showed surprisingly strong cooling trends over the last 10 years. These trends reached significance in spring, winter, and for the whole year. The annual soil temperature at 10 cm has cooled by -4.83°C over 10 years (Fig. 38), with cooling trends in spring and winter averaging -4.01°C and -6.10°C over 10 years, respectively (Fig. 39). In summer and autumn, soil temperature at 10 cm also showed cooling trends, although they were weaker than at other seasons and statistically non significant (Fig. 39). Soil temperatures at 10 cm decreased by -2.54°C over 10 years in summer and -3.62°C in autumn.

Soil temperatures at 2-cm depth generally showed the same cooling trends, with annual soil temperatures decreasing by -5.71°C over 10 years (Fig. 38). On a seasonal basis, winter temperature at 2 cm decreased significantly by -5.56°C over 10 years, but there were no detectable trends in other seasons (Fig. 39).

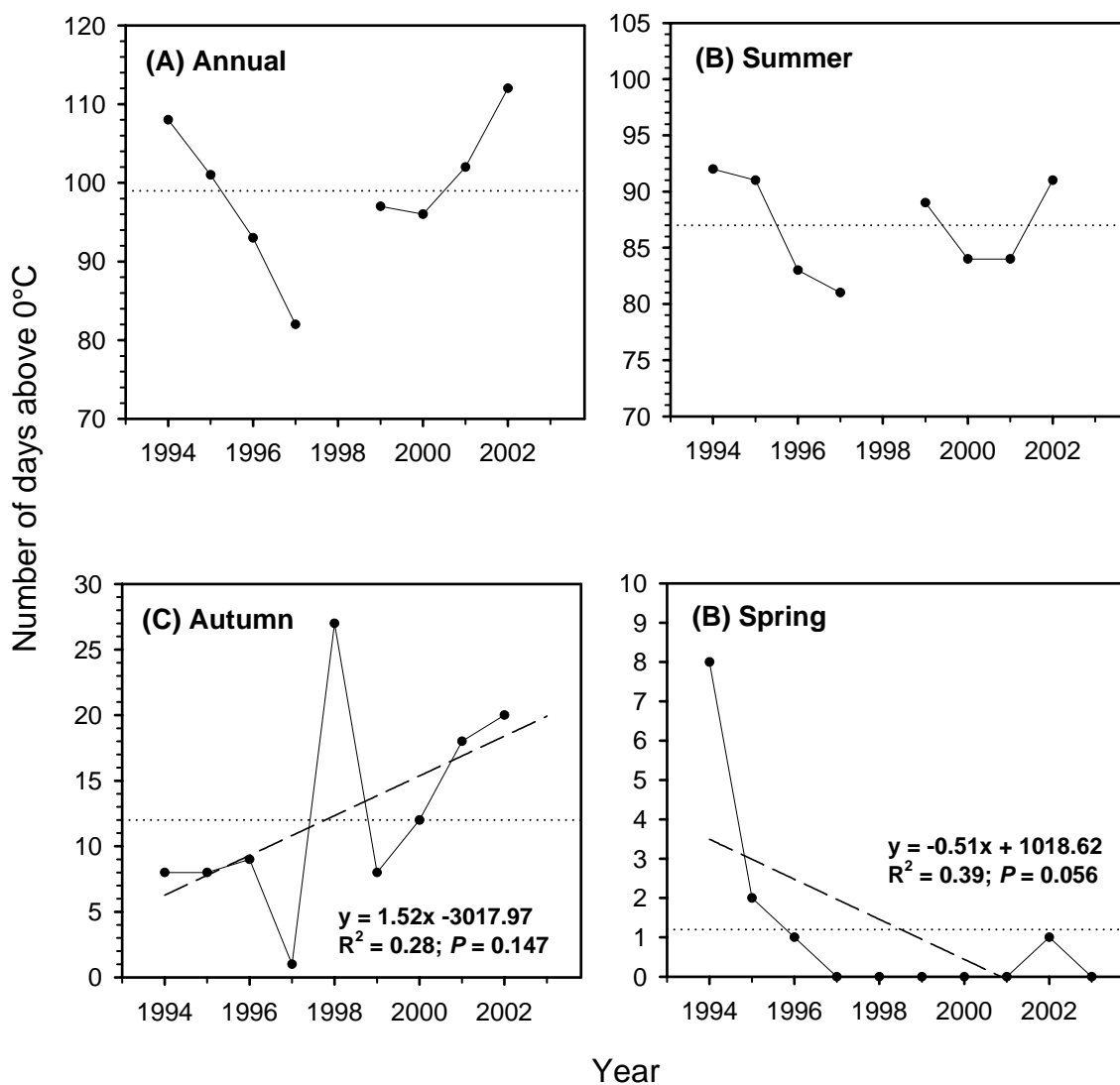
#### 4.2.3.3 Precipitations

We found no evidence of temporal trends in summer rainfall at Bylot Island but there was a weak, statistically non significant decreasing trend in rainfall for the month of June. Average June rainfall decreased by 25.5 mm over 10 years (Fig. 40). This trend was influenced by the absence of rainfall during the month of June of 2000.

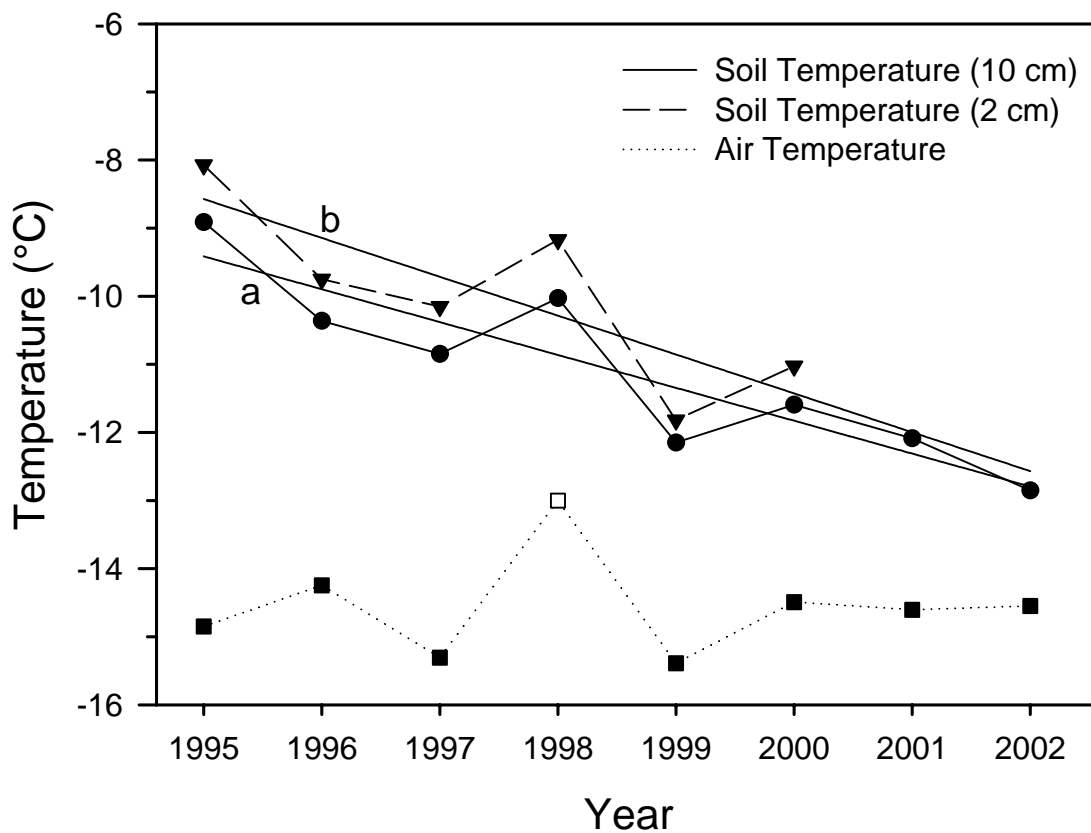
The percentage of snow cover recorded in lowlands of Bylot Island on 5 June greatly varied among years, ranging from 40 % to 85 % in recent years. However, there was no evidence of a temporal trend in the percentage of snow covered area on 5 June ( $R^2 = 0.244$ ,  $df = 8$ ,  $P = 0.177$ ; Fig. 41). Similarly, there was large inter-annual differences in the speed of snowmelt, but no temporal trend was found ( $R^2 = 0.039$ ,  $df = 8$ ,  $P = 0.610$ ; Fig. 42).



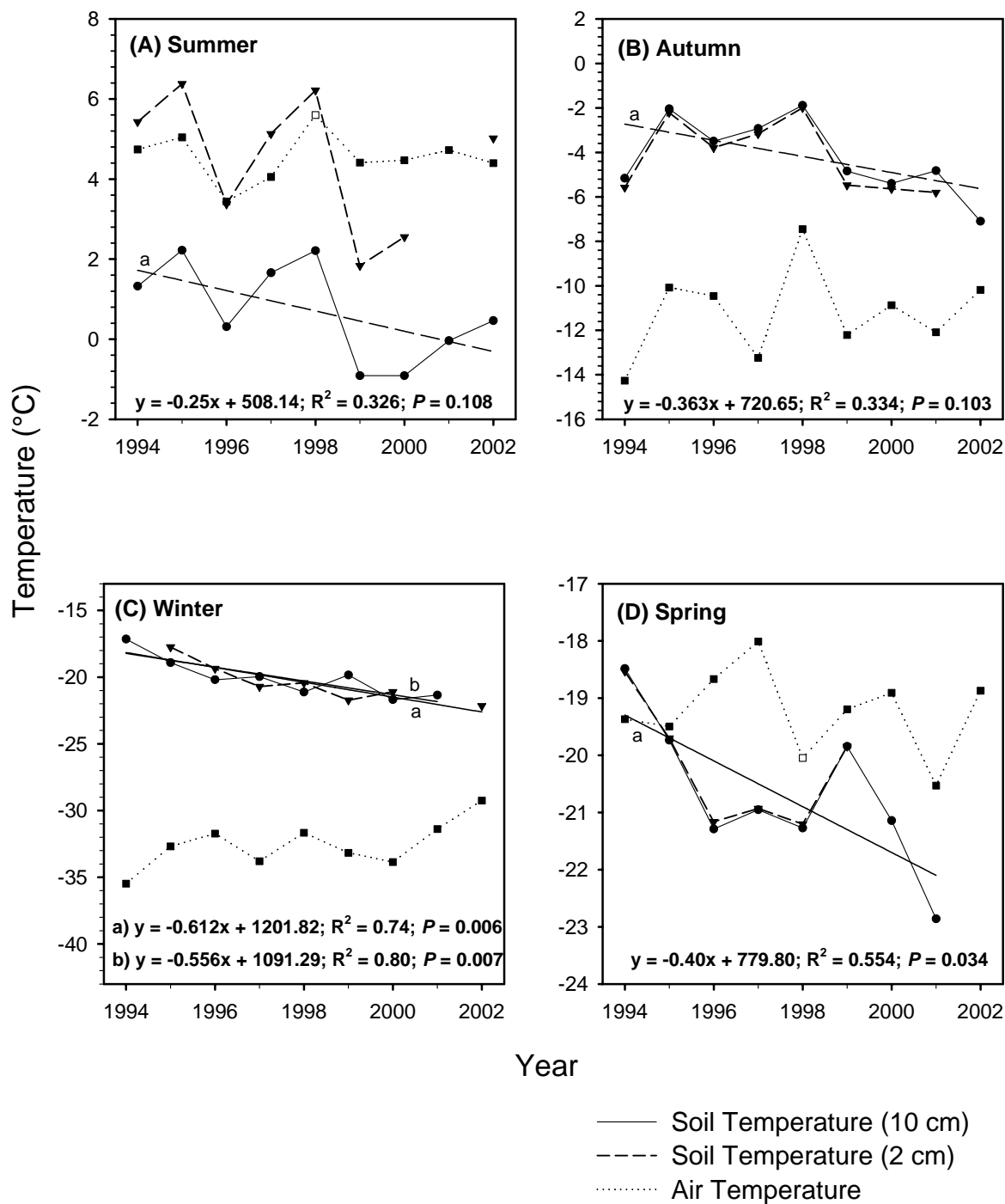
**Figure 36.** Number of thawing degree-days from 1994 to 2002 in the Qarlikturvik Valley lowlands, Bylot Island for (A) entire year, (B) summer, (C), autumn and (D) spring. Temporal trends are represented by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.



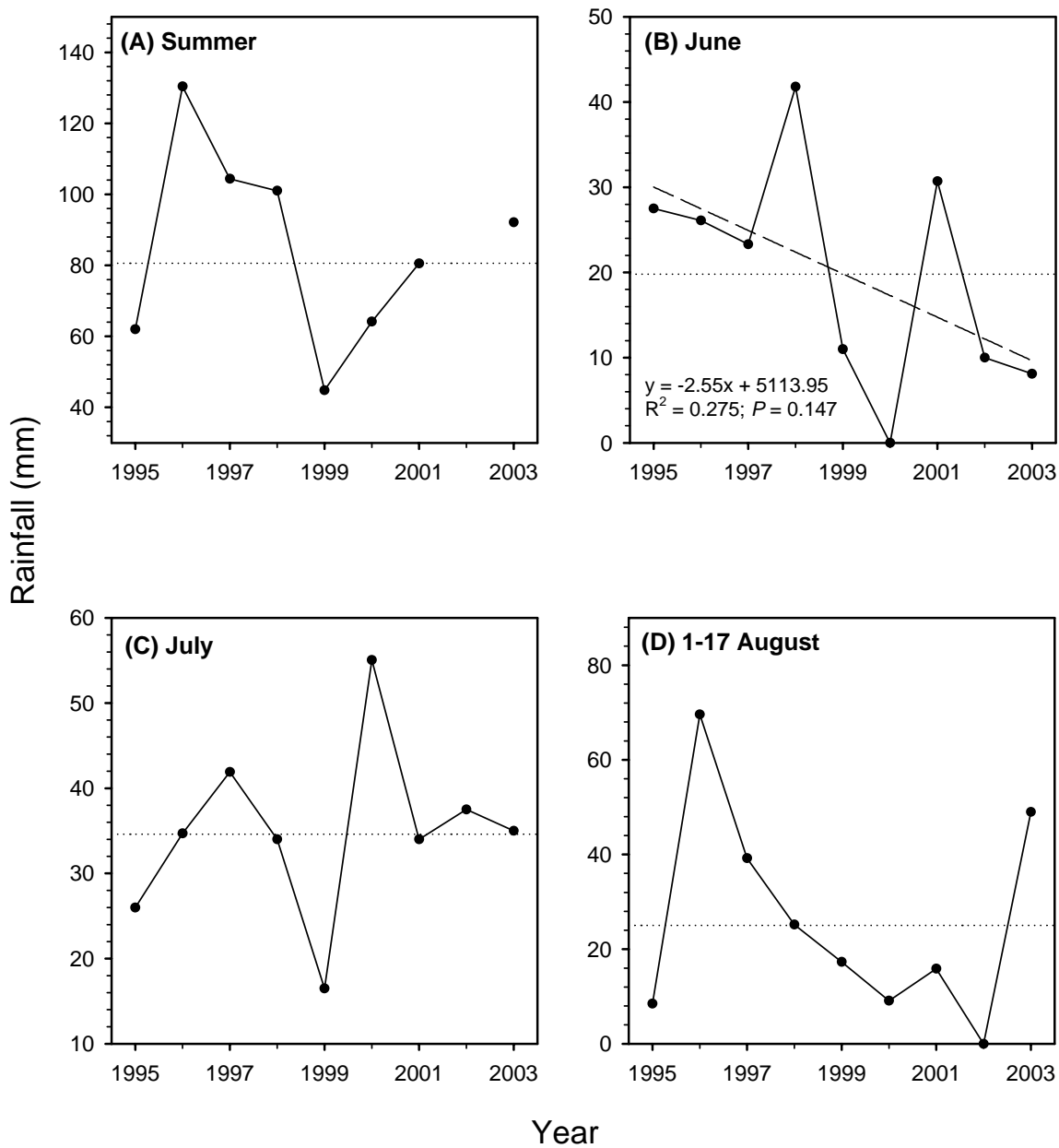
**Figure 37.** Number of days above 0°C from 1994 to 2002 in the Qarlikturvik Valley lowlands, Bylot Island for (A) entire year, (B) summer, (C), autumn and (D) spring. Temporal trends are represented by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.



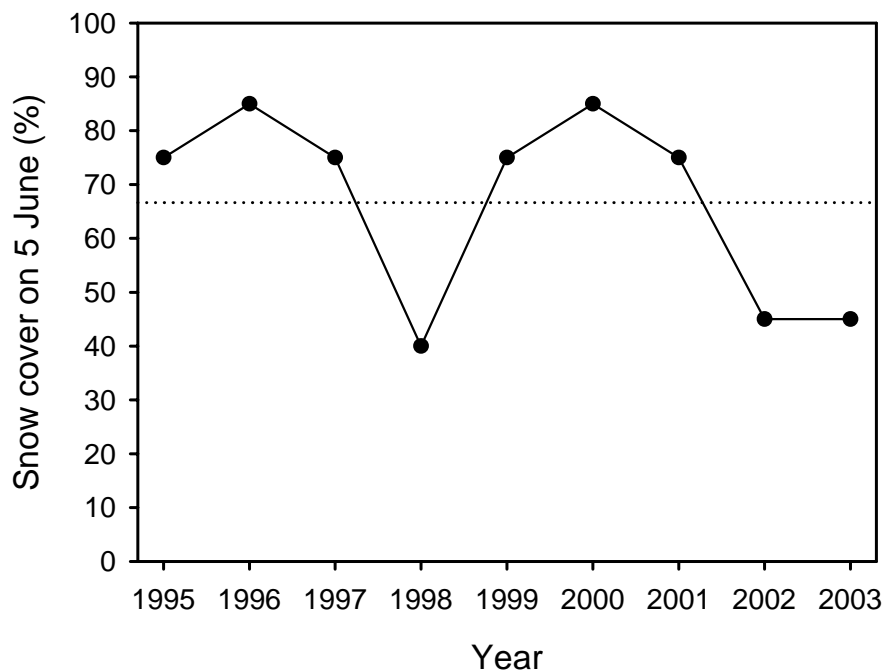
**Figure 38.** Mean annual air and soil temperatures (at 2-cm and 10-cm depths) from 1995 to 2002 in the Qarlikturvik Valley lowlands, Bylot Island. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ). (a) 10-cm:  $y = -0.483x + 953.914$ ,  $R^2 = 0.82$ ,  $P = 0.002$ ; (b) 2-cm:  $y = -0.571x + 1130.37$ ,  $R^2 = 0.645$ ,  $P = 0.054$ . The air temperature for the year 1998 is represented by a white circle and was extrapolated for part of the year from the relation between the air temperatures at Bylot Island and Pond Inlet.



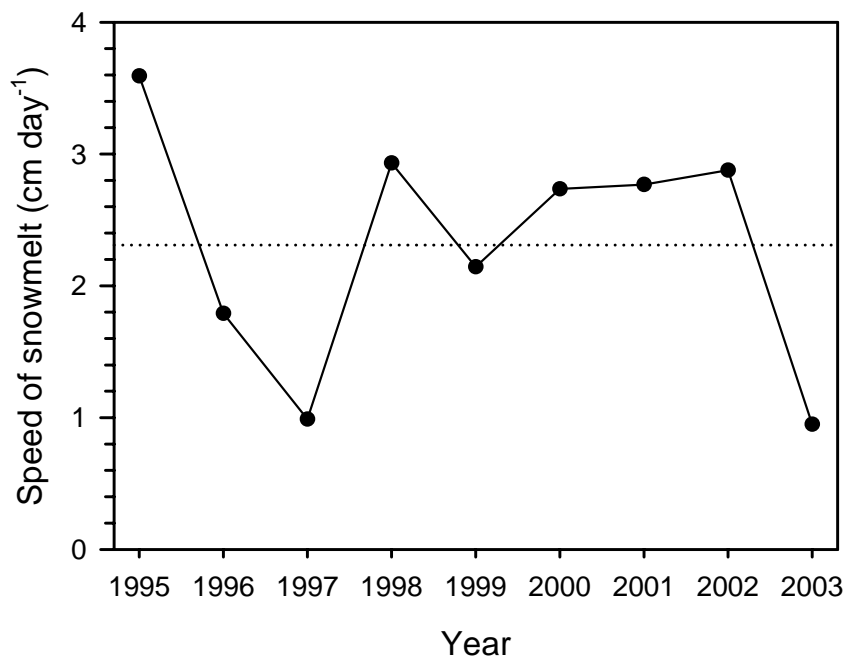
**Figure 39.** Mean air and soil temperatures (at 2-cm and 10-cm depths) from 1994 to 2002 in the Qarlikturvik Valley lowlands, Bylot Island for (A) summer, (B) autumn, (C) winter and (D) spring. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ); 10-cm (a), 2-cm (b). Air temperature for the spring and summer 1998 is represented by a white circle and was extrapolated from the relation between the air temperatures at Bylot Island and Pond Inlet.



**Figure 40.** Mean summer and monthly rainfall from 1995 to 2003 in the Qarlikturvik Valley lowlands, Bylot Island. Temporal trends are represented by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.



**Figure 41.** Mean percentage of snow cover on the ground on 5 June from 1995 to 2003 in the Qarlikturvik Valley lowlands, Bylot Island. The dotted line shows the mean for the whole period.

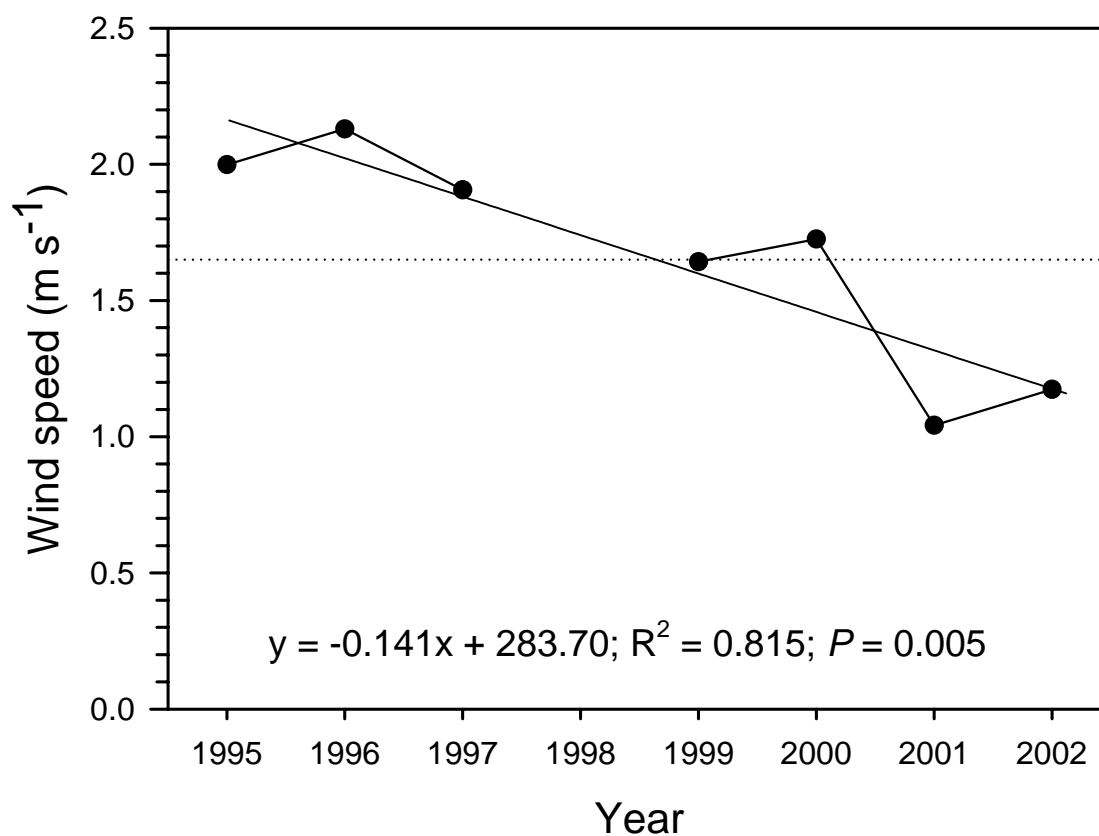


**Figure 42.** Mean speed of snowmelt during the month of June from 1995 to 2003 in the Qarlikturvik Valley lowlands of Bylot Island. The dotted line shows the mean for the whole period.

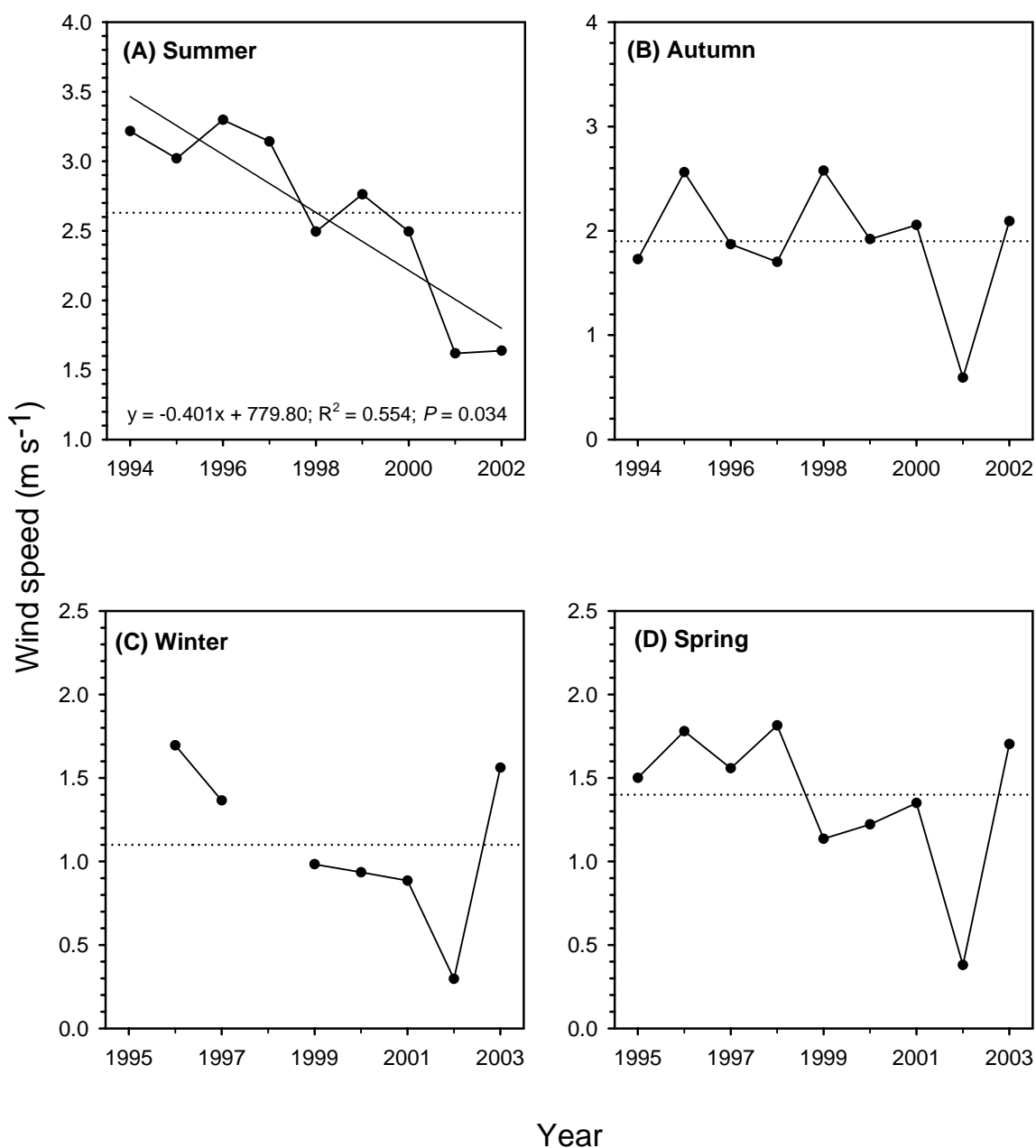


#### 4.2.3.4 Wind Speed

Average annual wind speeds decreased significantly by  $1.4 \text{ m s}^{-1}$  over the last 10 years on Bylot Island, a 59 % reduction (Fig. 43). This annual decrease was entirely due to the summer, the season with the strongest winds, because no detectable trend was found in other seasons. In summer, wind speed decreased by  $2.1 \text{ m s}^{-1}$  over 10 years (Fig. 44).



**Figure 43.** Mean annual wind speed from 1995 to 2003 in the Qarlikturvik Valley lowlands, Bylot Island. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ). The dotted line shows the mean for the whole period.



**Figure 44.** Mean wind speed from 1994 to 2003 in the Qarlikturvik Valley lowlands, Bylot Island, for (A) summer, (B) autumn, (C) winter and (D) spring. Temporal trends are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ). The dotted line shows the mean for the whole period.

## 4.3 Biological Monitoring

### 4.3.1 Greater Snow Geese

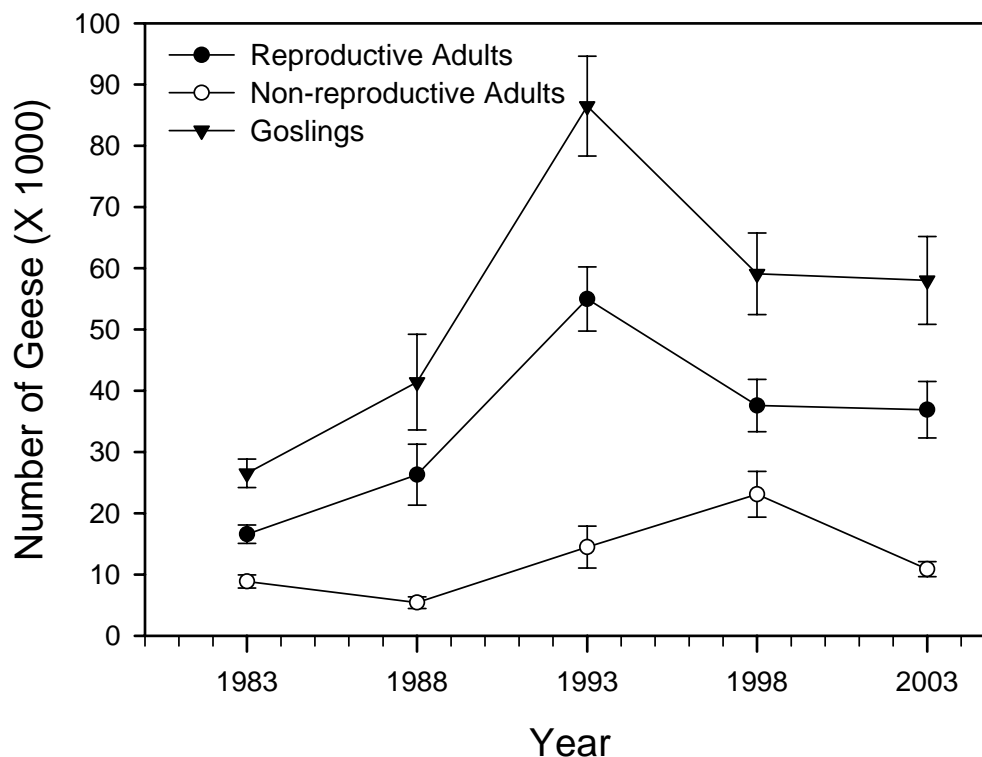
#### 4.3.1.1 Population Surveys

Aerial surveys performed every five years since 1983 showed that the total number of adult geese breeding on South plain of Bylot Island greatly increased from 1983 to 1993, passing from  $16,573 \pm 1,520$  birds to  $55,000 \pm 5,238$  birds in this 10-year period (Fig.45). Following the peak of 1993, the number of breeding adults declined to  $37,575 \pm 4,269$  in 1998 and remained stable through 2003 ( $36,885 \pm 4,610$ ). It should be noted, however, that 1993 was a record year of reproduction, which may have slightly inflated the size of the breeding population compared to subsequent years. Indeed, most birds that do not reproduce or lose their nest early during the breeding cycle leave Bylot Island to moult elsewhere during the summer (Reed et al. 2003), which reduces the size of the local population during brood rearing.

The same population trend was observed for goslings. Their number increased from  $26,517 \pm 2,320$  in 1983 to a peak of  $86,471 \pm 8,147$  birds in 1993, and then decreased to  $59,107 \pm 6,658$  in 1998 and remained stable in 2003 ( $58,017 \pm 7,168$ ). The number of non- and failed-breeders (adults without young) generally followed the same trend except that numbers peaked in 1998 ( $23,097 \pm 3,721$  compared to  $8,867 \pm 1,062$  in 1983), and then dropped to  $10,854 \pm 1,224$  in 2003. For all years, the average number of snow geese (all reproductive status confounded) on the South plain of Bylot Island was  $101,309 \pm 18,134$  birds (Fig. 45).

Brood densities varied among years, following the same trends observed in the breeding population. In 1983, when the population was low, the average brood density ( $5.2 \pm 0.5$  broods  $\text{km}^{-2}$ ) was more than three times lower than that observed in 1993 ( $17.0 \pm 1.6 \text{ km}^{-2}$ ; Table 1). However, it is interesting to note that the increase in brood density was much greater in low quality habitats (mostly mesic communities; from  $0.8 \pm 0.3$  brood  $\text{km}^{-2}$  in 1983 to  $12.1 \pm 2.2$  broods  $\text{km}^{-2}$  in 1993) than in good quality habitats (wetland areas; from  $16.4 \pm 1.6$  broods  $\text{km}^{-2}$  in 1983 to  $29.9 \pm 3.3$  broods  $\text{km}^{-2}$  in 1993). This indicates that as the Snow Goose population increased, its distribution on Bylot Island also changed. At low breeding numbers, brood distribution was characterized by few areas of high and moderate brood densities, with a large

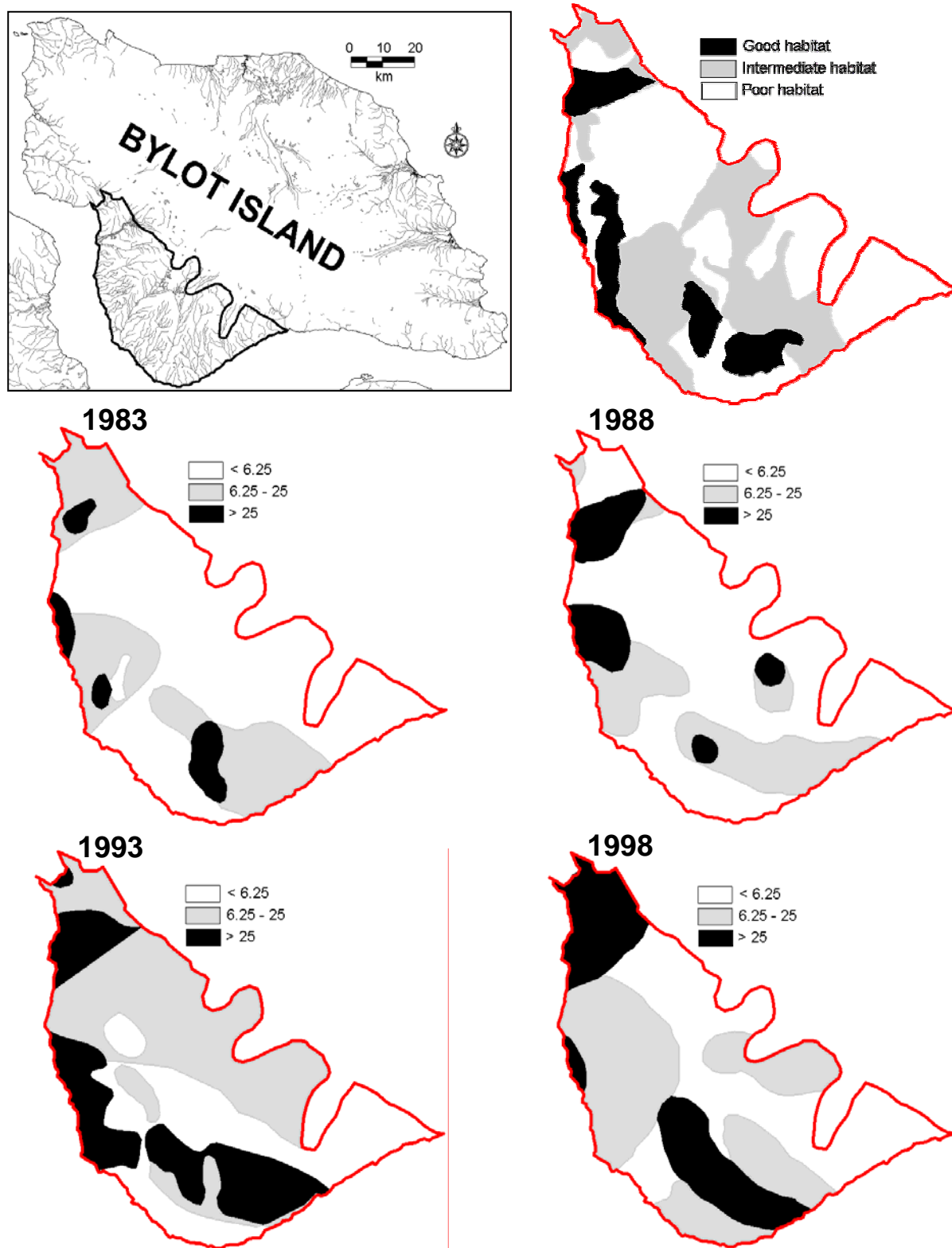
proportion of the south plain having low brood densities (e.g. 1983 and 1988). With the increasing numbers, the area of high to moderate densities greatly expanded, leaving only a small area with low brood densities (1993 and 1998; Fig. 46).



**Figure 45.** Estimated population size (mean  $\pm$  SE) of Greater Snow Geese on the South plain of Bylot Island at 5-year interval from 1983 to 2003.

**Table 1.** Snow goose brood densities (mean  $\pm$  SE) in relation to habitat quality on Bylot Island at 5-year interval from 1983 to 1998. Densities are given in broods per km<sup>2</sup>.

Year	Good Habitat	Intermediate Habitat	Poor Habitat	Total
1983	16.4 $\pm$ 1.6	5.6 $\pm$ 0.9	0.8 $\pm$ 0.3	5.2 $\pm$ 0.5
1988	14.9 $\pm$ 1.7	7.8 $\pm$ 2.1	6.1 $\pm$ 2.8	8.2 $\pm$ 1.6
1993	29.9 $\pm$ 3.3	16.0 $\pm$ 3.3	12.1 $\pm$ 2.2	17.0 $\pm$ 1.6
1998	22.9 $\pm$ 3.2	10.6 $\pm$ 2.0	7.7 $\pm$ 2.0	11.8 $\pm$ 1.3
2003	14.5 $\pm$ 1.5	11.9 $\pm$ 1.7	10 $\pm$ 2.7	11.6 $\pm$ 1.4



**Figure 46.** Distribution of Greater Snow Goose broods (number of broods per km<sup>2</sup>) on the South plain of Bylot Island as determined by the aerial survey at 5-year intervals, 1983-1998. Map on the top right corner of the figure represents the habitat stratification in terms of quality for geese based on the density of wetlands.

#### 4.3.1.2 Reproduction

The long-term average egg-laying date of geese was 12 June ( $n = 4091$ ), but egg-laying date showed large inter-annual variations (annual minimum: 6 June in 1993, maximum: 20 June in 1992). Analyses revealed no temporal trend in egg-laying dates (linear regression:  $R^2 = 0.008$ ,  $df = 14$ ,  $P = 0.751$ ). However, it should be noted that since the instauration of a spring hunt for geese in Québec (1999), median egg-laying dates were all late or very late, except in 2003 (Fig. 47). The spring hunt disrupted the accumulation of fat by geese in spring, and this had a negative impact on subsequent reproduction (reduced reproductive effort and delayed phenology; Mainguy et al. 2002, Bêty et al. 2003, Féret et al. 2003, Reed et al. 2004).

Because incubation has a set time length in birds (23-24 days in snow geese), egg hatching dates followed the same trends as laying dates. Over 15 years, average hatching date was 9 July ( $n = 3188$ ), and the earliest and latest annual median hatching dates were 3 and 15 July, respectively (Fig. 47). There was no detectable long-term trend in hatching date ( $R^2 = 0.016$ ,  $df = 13$ ,  $P = 0.649$ ).

Estimates of nest densities in the central portion of the colony provide an indication of yearly reproductive effort (Reed et al. 2004). Since 1996, the average nest density in the area was  $191 \pm 10$  nests  $\text{km}^{-2}$  ( $n = 8$ ; annual minimum: 100, maximum: 358; Fig. 48). There was no temporal trends in nest density ( $R^2 = 0.012$ ,  $df = 6$ ,  $P = 0.816$ ).

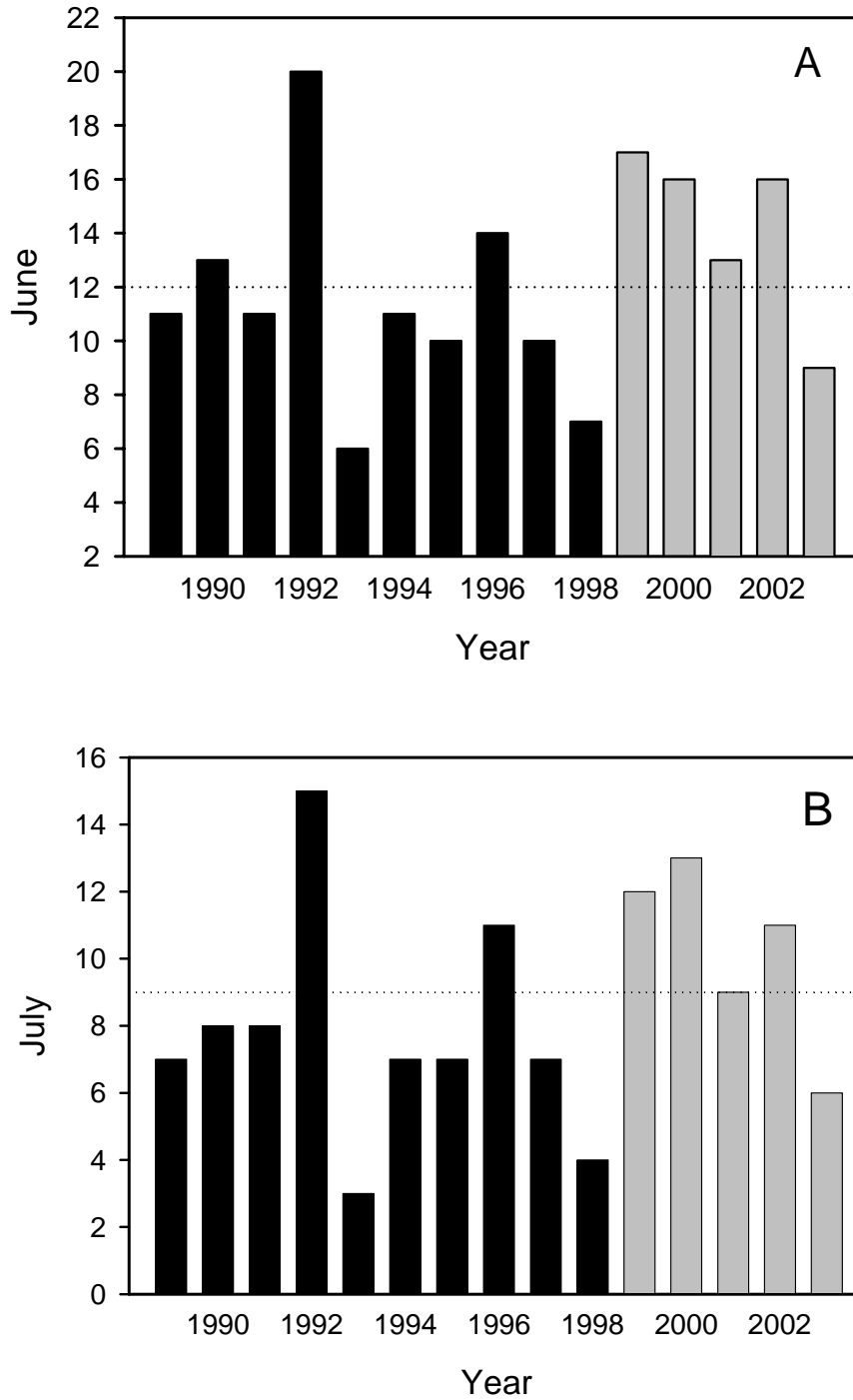
The overall average clutch size of Snow Geese on Bylot Island was  $3.91 \pm 0.029$  ( $n = 3814$ ) eggs per nest (annual minimum: 3.12, maximum: 4.41; Fig. 48). The mean annual clutch size showed a strong inverse relationship with the laying date: it was large when geese laid their eggs early and small when they laid their eggs late in the season ( $R^2 = 0.560$ ,  $df = 13$ ,  $P = 0.001$ ). We did not find any temporal trends in clutch size ( $R^2 = 0.003$ ,  $df = 14$ ,  $P = 0.849$ ).

Overall, the percentage of goose nests that hatched (nesting success) averaged 63 % ( $n = 3969$ ), but this parameter varied considerably among years (from a minimum of 14% in 1995 and 1999 to a maximum of 89% in 1993; Fig. 49). Environmental conditions and, most importantly, predator density determined nesting success because predation is the main cause of nesting failure for Snow Geese. In decreasing order of importance, main predators are the Arctic Fox, Parasitic Jaeger, Glaucus Gull and Common Raven (*Corvus corax*). Nesting success tended to

show periodic variations due to the cyclic fluctuations in lemming abundance (Bety et al. 2002, 2003). When lemmings were low, such as in 1995 and 1999, predators turned to goose eggs, leading to poor nesting success. This effect was amplified in areas where the nest density was low, such as in areas away from the main colony, or in years when nest density was low, such as in years of late snow-melt in spring. We detected no long-term trend in nesting success ( $R^2 = 0.013$ ,  $df = 14$ ,  $P = 0.682$ ), possibly due to the large inter-annual fluctuations in nesting success.

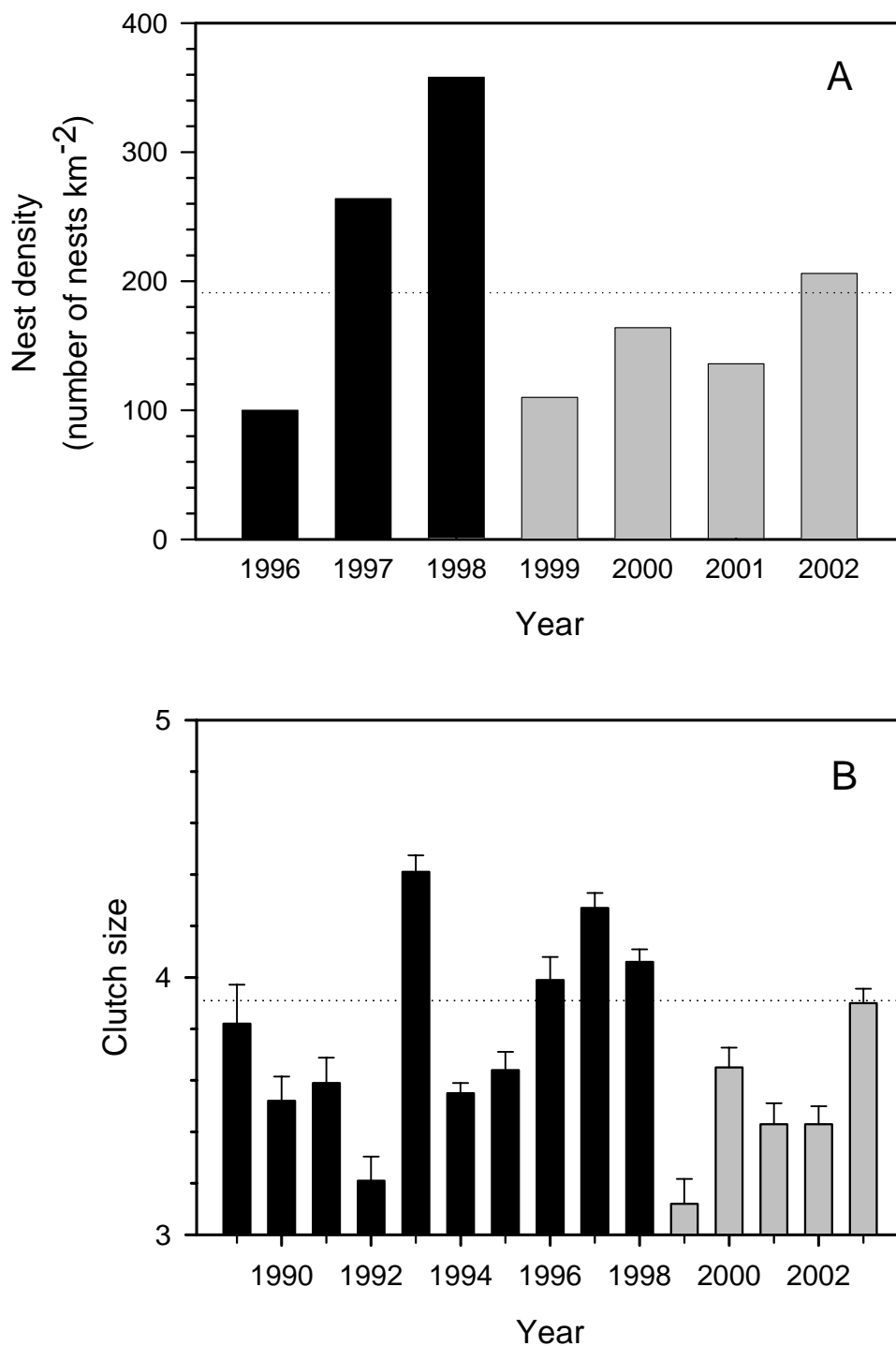
Cumulative faeces density provides information on the density of broods grazing in wetlands of Bylot Island over the summer. From 1990 to 2003, faeces density at the end of the summer in wetlands of the Qarlikturvik Valley averaged  $5.65 \pm 0.37$  faeces  $m^{-2}$ . From 1998 to 2003, average faeces density was similar at Pointe Dufour, another brood-rearing area ( $5.22 \pm 0.76$  faeces  $m^{-2}$ ) but lower at the main goose nesting colony ( $3.68 \pm 0.34$  faeces  $m^{-2}$ , Fig.50). There was no temporal trend in cumulative faeces density at the end of the summer at any of the three sites ( $R^2 = 0.012$ ,  $df = 12$ ,  $P = 0.725$  for the Qarlikturvik Valley;  $R^2 = 0.30$ ,  $df = 4$ ,  $P = 0.339$  for Pointe Dufour and  $R^2 = 0.343$ ,  $df = 5$ ,  $P = 0.222$  for the main goose nesting colony) (Fig. 50). More detailed information is available on the seasonal accumulation of faeces in the Qarlikturvik valley. In all years, faeces density was low throughout the month of June but increased steadily during July and August, reflecting the fact that geese use this area to rear the goslings after hatch (Fig. 51) There was no accumulation of goose faeces in 1999 because of the almost complete breeding failure of geese that year, and the near absence of broods on the island throughout the summer.

The overall gosling:adult ratio measured at the end of the summer during goose banding averaged 1.04:1 (Fig. 52). Annual gosling:adult ratio was related to mean egg-laying date ( $P < 0.001$ ) and nesting success ( $P = 0.031$ ; overall multiple regression model:  $R^2 = 0.603$ ,  $F = 10.9$ ,  $P = 0.002$ ). The production of goslings was higher in years when egg laying was early and nesting success was high. No temporal trend in the gosling:adult ratio was detected ( $R^2 = 0.062$ ,  $df = 13$ ,  $P = 0.391$ ).

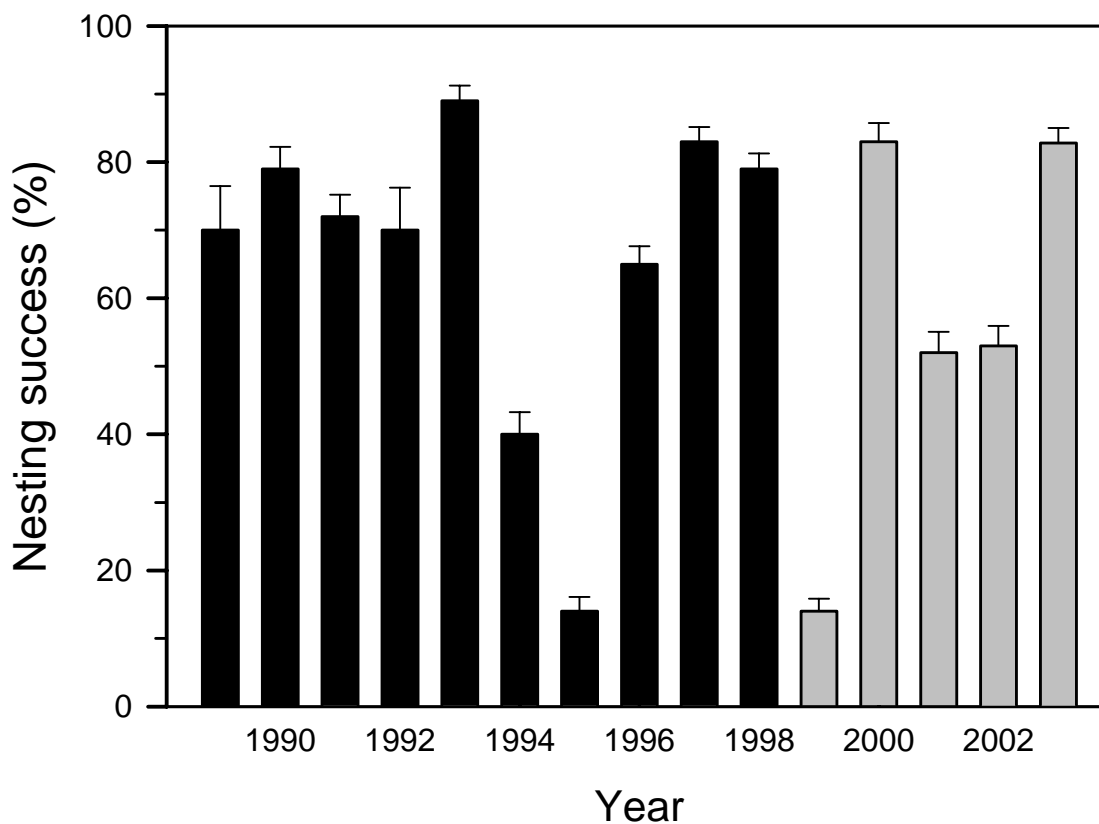


**Figure 47.** Median annual (A) egg-laying dates and (B) egg-hatching dates of Greater Snow Geese on Bylot Island from 1989 to 2003. Grey columns represents years during which a spring hunt occurred in Quebec. The dotted line shows the mean for the whole period. For laying date, total sample size = 4091 (annual sample size ranging from 52 to 804) and for egg hatching date, total sample size = 3188 (annual sample size ranging from 45 to 794).

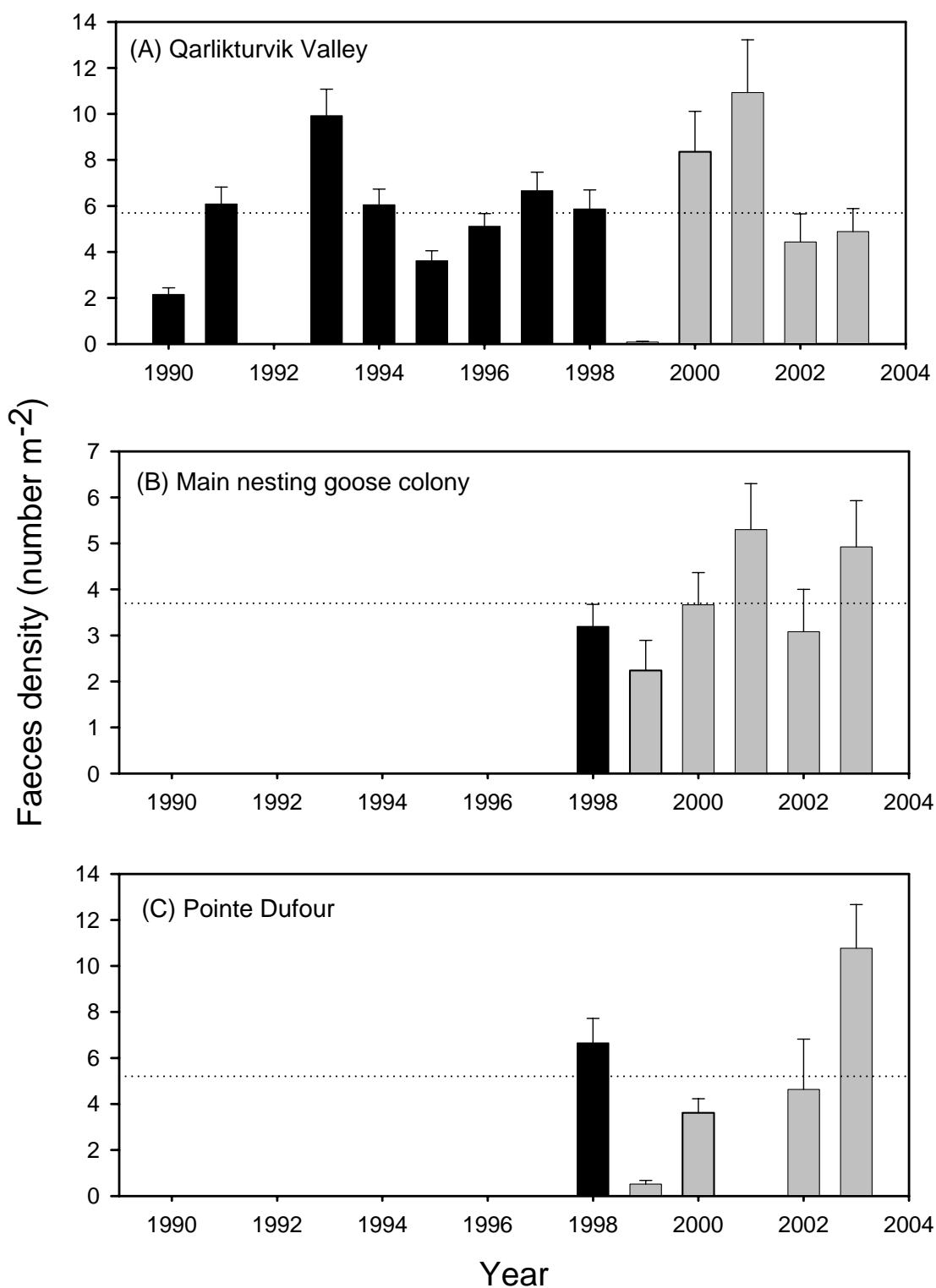




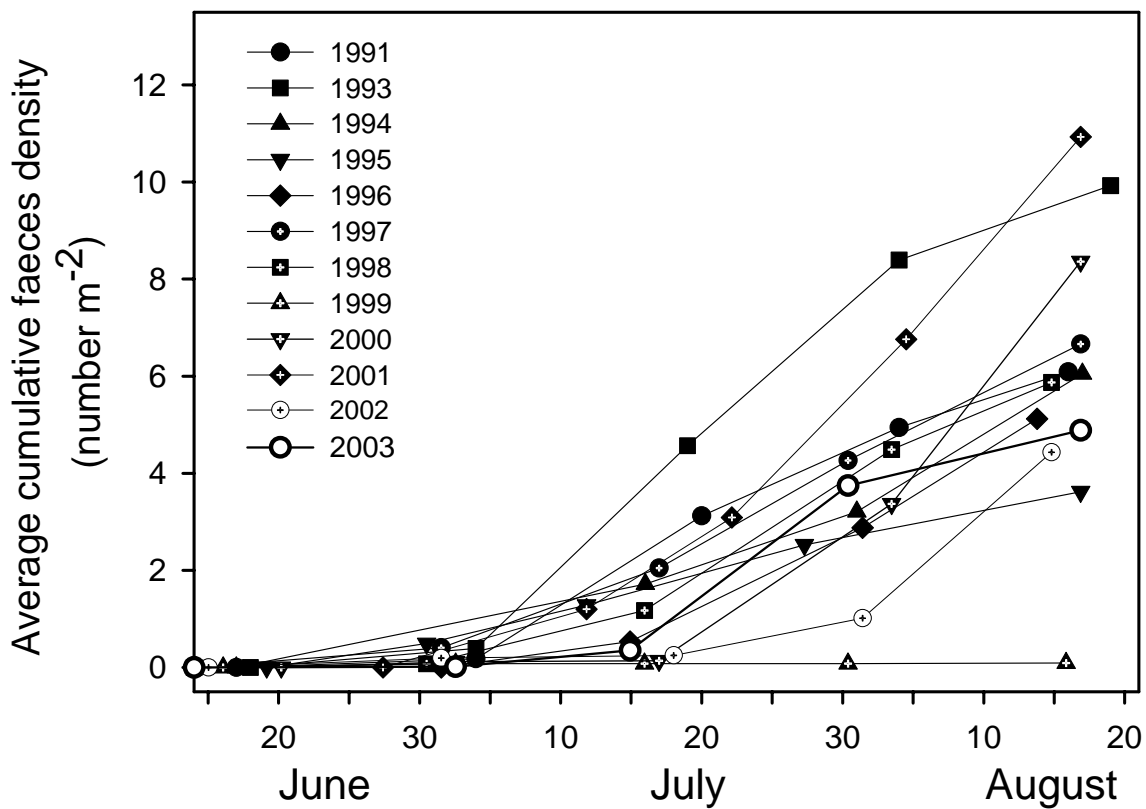
**Figure 48.** Annual (A) nest density of Greater Snow Geese from 1996 to 2002 and (B) clutch size (mean  $\pm$  SE) from 1989 to 2003 on Bylot Island. For clutch size, total sample size = 3814 (annual sample size ranging from 85 to 794). Grey columns represents years during which a spring hunt occurred in Quebec. The dotted line shows the mean for the whole period.



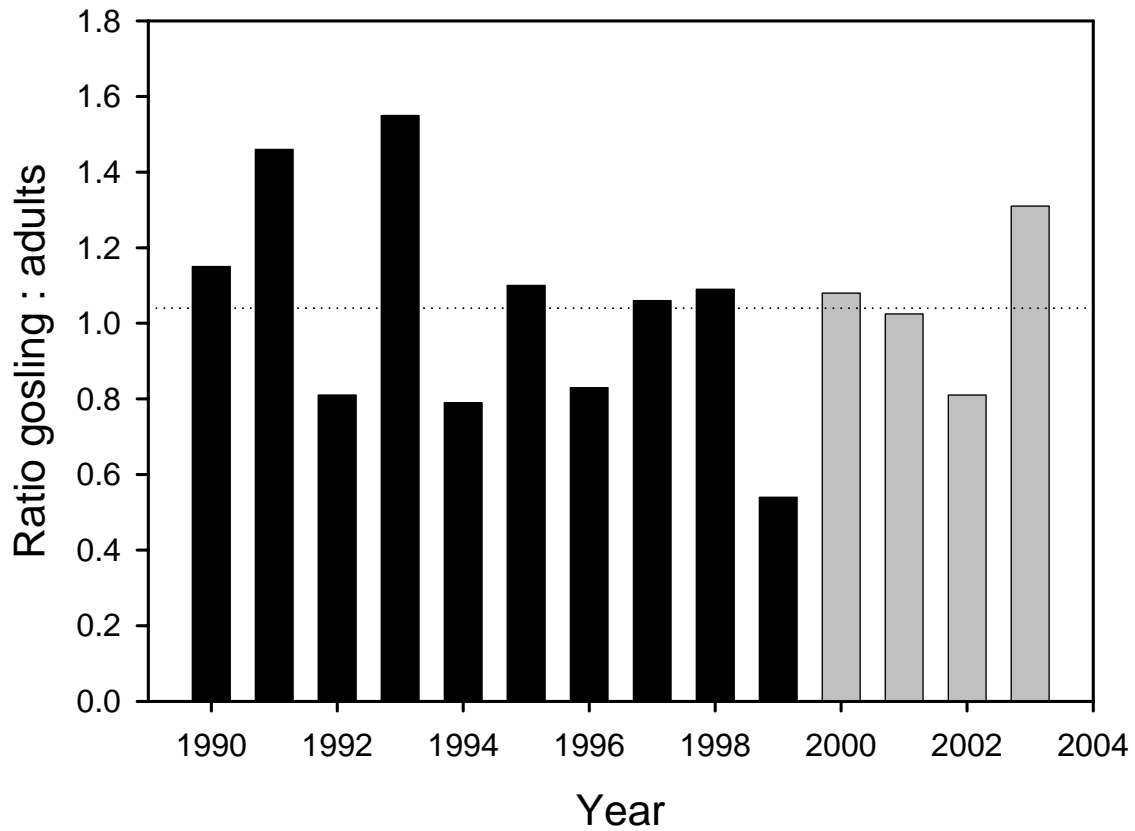
**Figures 49.** Annual nesting success (percentage of nests where at least one egg hatched; mean  $\pm$  SE) of Greater Snow Geese on Bylot Island from 1989 to 2003. Total sample size = 3969 (annual sample size ranging from 62 to 372). Grey columns represents years during which a spring hunt occurred in Quebec. The dotted line shows the mean for the whole period.



**Figure 50.** Average cumulative faeces density at the end of August (mean  $\pm$  SE) on Bylot Island for (A) the Qarlikturvik Valley (1990-2003;  $n = 156$ ), (B) the main nesting goose colony (1998-2003;  $n = 72$ ) and (C) Pointe Dufour (1998-2003; 60). There were no data for the Qarlikturvik Valley in 1992 and at Pointe Dufour in 2001. Grey columns represent years during which a spring hunt occurred in Quebec. The dotted line shows the mean for the whole period.



**Figure 51.** Average cumulative faeces density showing the use of the Qarlikturvik Valley by Greater Snow Goose families on Bylot Island throughout the summer ( $n = 12$  transects of  $1 \times 10$  m each year).



**Figure 52.** Annual gosling:adult ratio during goose banding on Bylot Island from 1990 to 2003. Total sample size = 44,345 (annual sample size ranging from 729 to 5259). Grey columns represents years during which a spring hunt occurred in Quebec. The dotted line shows the mean for the whole period.

### ***4.3.2 Collared and Brown Lemmings***

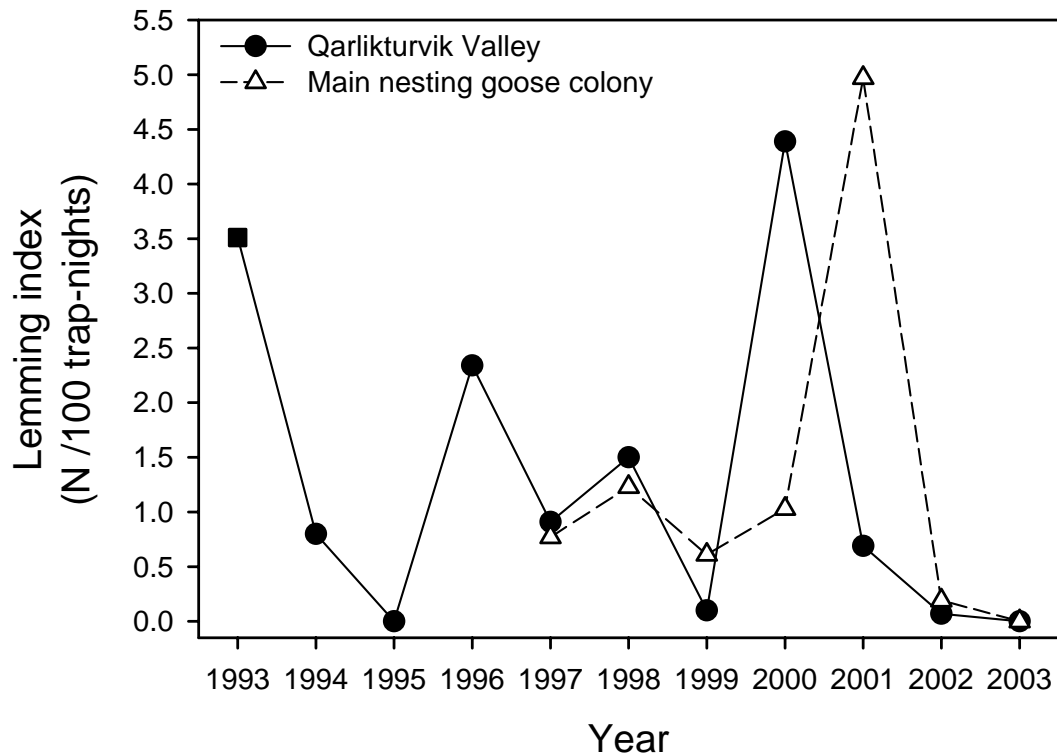
As commonly observed in the Arctic, lemming populations have been going through marked cycles of abundance on Bylot Island. Our longest record in the Qarlikturvik Valley indicated that cycles lasted 3 to 4 years, with peak abundance occurring in 1993, 1996 and 2000 (Fig. 53). In all 3 cycles followed thus far, the increase phase has always been faster (1 year) than the decreasing phase (2-3 years). The difference in abundance between the peak and low phases of the cycles was more than 50-fold. Trapping conducted at the main goose colony suggested that the two sites generally fluctuated in synchrony except for the last population peak which occurred a year later than in the Qarlikturvik Valley (2001 vs 2000, respectively; Fig. 53).

The abundance of the two lemming species differed between the two sites. In the Qarlikturvik Valley, the site with the highest density of wetlands, brown lemmings were more abundant than collared, whereas at the main goose colony, where mesic communities were most abundant, the reverse was true, except during the 2001 lemming peak (Fig. 54). The population dynamics of the two lemming species also differed. The population of brown lemmings has been going through much deeper cycles than the one of collared lemmings at both sites (Fig. 54). During peak years, abundance of brown lemmings was almost 10 times higher than collared lemmings, but in low years that species was equally scarce (in the Qarlikturvik Valley) or rarer (at the main goose nesting colony) than collared lemmings. Although population cycles were much more obvious in brown than collared lemmings, the abundance of both species tended to fluctuate synchronously. The large annual fluctuations in lemming abundance precluded the examination of long-term trend in abundance.

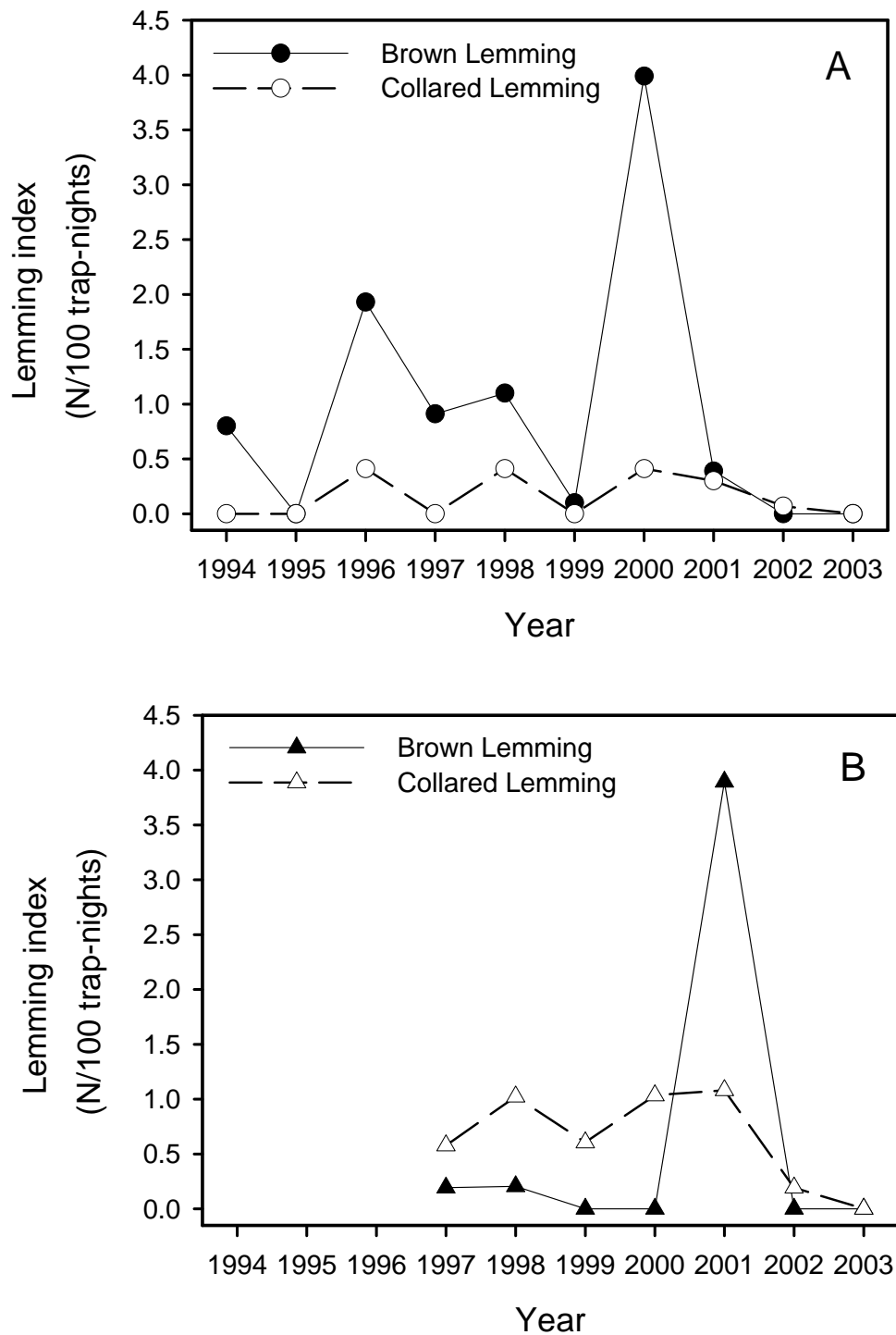
### ***4.3.3 Arctic and Red Foxes***

#### ***4.3.3.1 Denning Activity***

From 1993 to 2002, the number of known dens on Bylot Island gradually increased from 6 to 55. During the extensive survey of 2003, 42 new dens were found, bringing the total of known dens to 97. On average, 41 % of dens showed signs of activity over the 10-year period (2% for red fox and 39% for Arctic fox). Activity at denning site fluctuated between years from a high of 67% in 1993 and 1997 to a low of 6% in 2002 (Fig. 55). There was a tendency for signs



**Figure 53.** Index of lemming abundance (number caught per 100 trap-nights) in the Qarlikturvik Valley and the main goose nesting colony on Bylot Island from 1993 to 2003. Although no lemmings were trapped in 1993, an estimate was derived based on a winter nest survey (see methods).



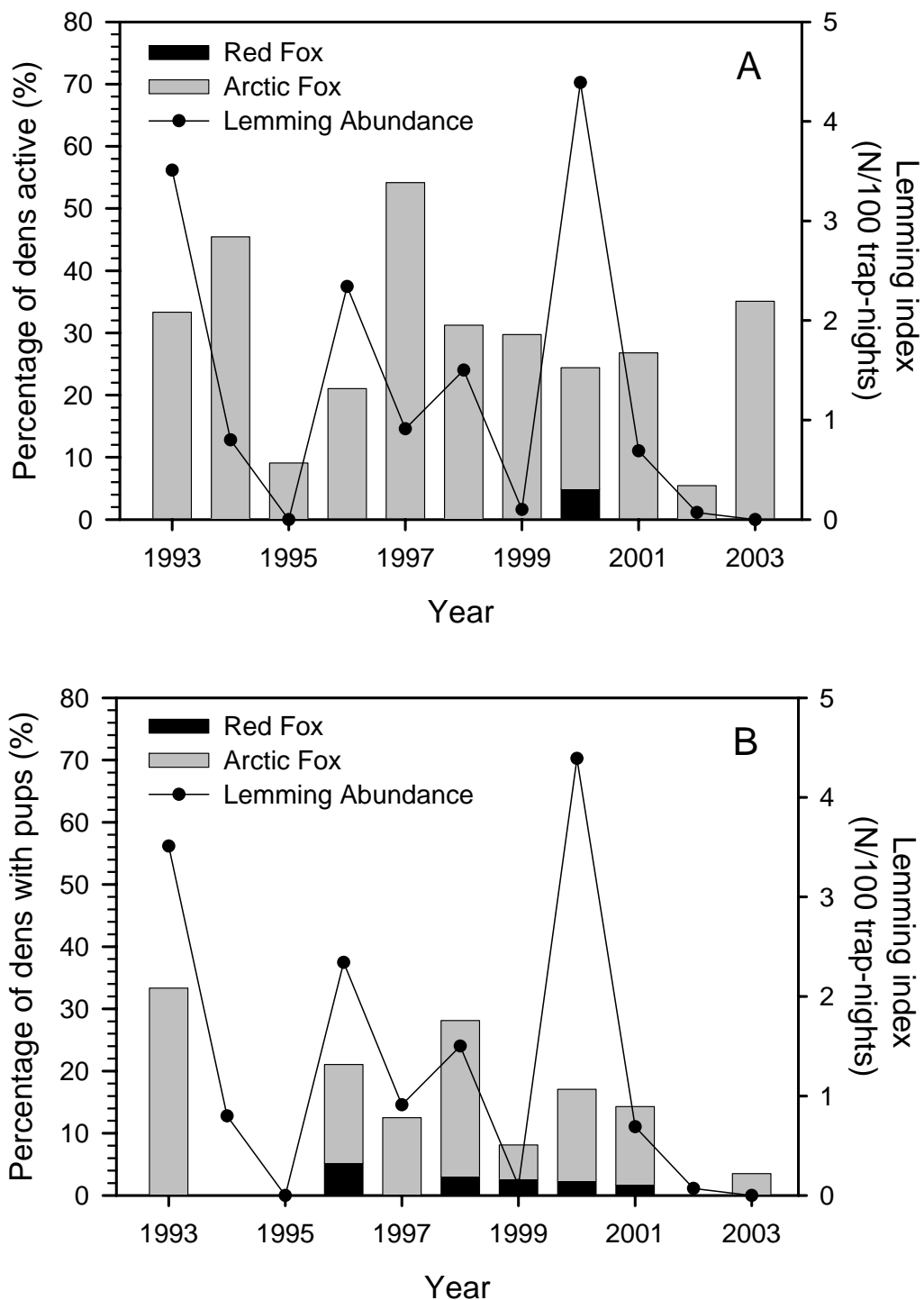
**Figure 54.** Index of brown and collared lemmings abundance (number caught per 100 trap-nights) in (A) the Qarlikturvik Valley and (B) the main goose nesting colony on Bylot Island from 1994 to 2003.



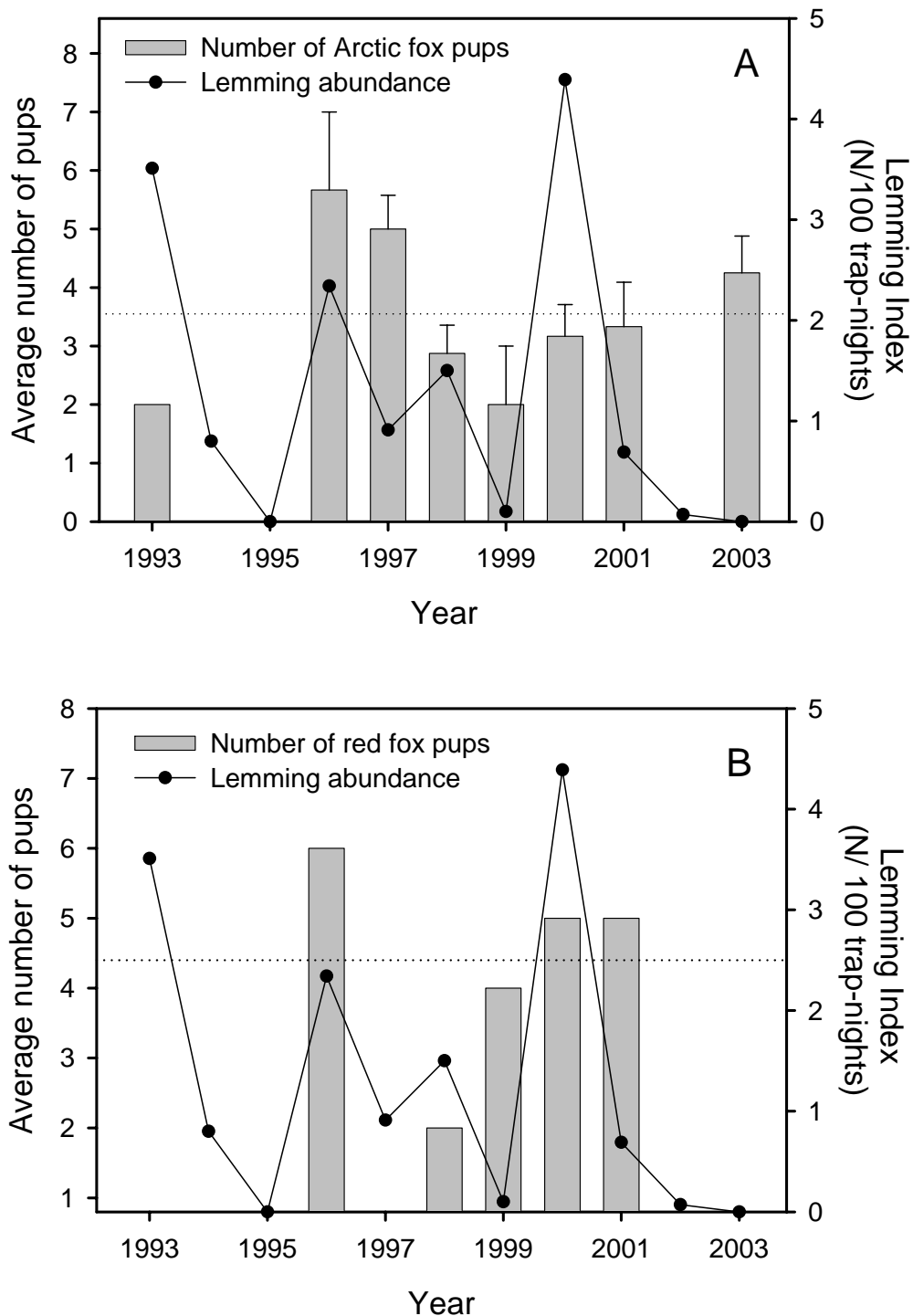
of fox activity at dens to be associated with lemming abundance. Breeding activity at dens was confirmed in 6 out of 10 years for Arctic foxes and 5 out of 10 years for the red fox (Fig. 55). However, the absence of recorded breeding activity in 1994 and 1995 may in part be explained by the low number of dens in these years (only 11 known dens). The percentage of dens showing breeding activity averaged 13% overall but fluctuated considerably in relation to the lemming abundance. The percentage of dens with pups was similar in years of high and intermediate lemming abundance (17% vs 19%, respectively) but this value plummeted in years of low lemming abundance (3%, Fig. 55). Given the strong association between breeding activity at fox dens and lemming abundance, we found no temporal trend in proportion of dens used ( $R^2 = 0.126$ ,  $df = 10$ ,  $P = 0.284$ ). Overall, we recorded 6.6 times more arctic fox than red fox litters.

#### 4.3.3.2 Litter Size

Overall, the average litter size of Arctic fox on Bylot Island was  $3.55 \pm 0.30$  ( $n = 33$ ) pups and  $4.4 \pm 0.68$  ( $n = 5$ ) for the red fox. For both species, average litter size was quite variable from year to year (Fig. 56), and appeared influenced to some extent by lemming abundance: litter sizes tended to be large in years of peak lemming populations and small in years of low lemming abundance (Fig. 56). The year 2003 was an exception to this rule since fox litter size was higher than average ( $4.25 \pm 0.63$  pups,  $n = 4$ ) even though lemming abundance extremely low. However, with the instauration of a more thorough fox monitoring program in 2003, the number of pups per litter may have been closer to the true value than in previous years when it should be considered only a minimum value. We did not find any temporal trend in foxes litter sizes (Arctic fox:  $R^2 = 0.008$ ,  $df = 7$ ,  $P = 0.832$ , red fox:  $R^2 = 0.003$ ,  $df = 4$ ,  $P = 0.935$ ).



**Figure 55.** Annual percentage (%) of arctic and red fox dens (A) showing signs of activity and (B) showing signs of reproduction (i.e. presence of pups) in relation to the index of lemming abundance on Bylot Island from 1993 to 2003. Total sample size = 403 (annual sample size ranging from 3 to 114)



**Figure 56.** Annual (A) Arctic and (B) red fox litter size (mean  $\pm$  SE) in relation to the index of lemming abundance on Bylot Island from 1993 to 2003. Total sample size for the Arctic fox = 33 (annual sample size ranging from 1 to 8). Total sample size for the Red fox = 5 (annual sample size always = 1). There was no data on Arctic fox litter size in 1994, 1995 and 2003 red fox litter size in 1993, 1994, 1995, 2002 and 2003. The dotted lines show the means for the whole period.

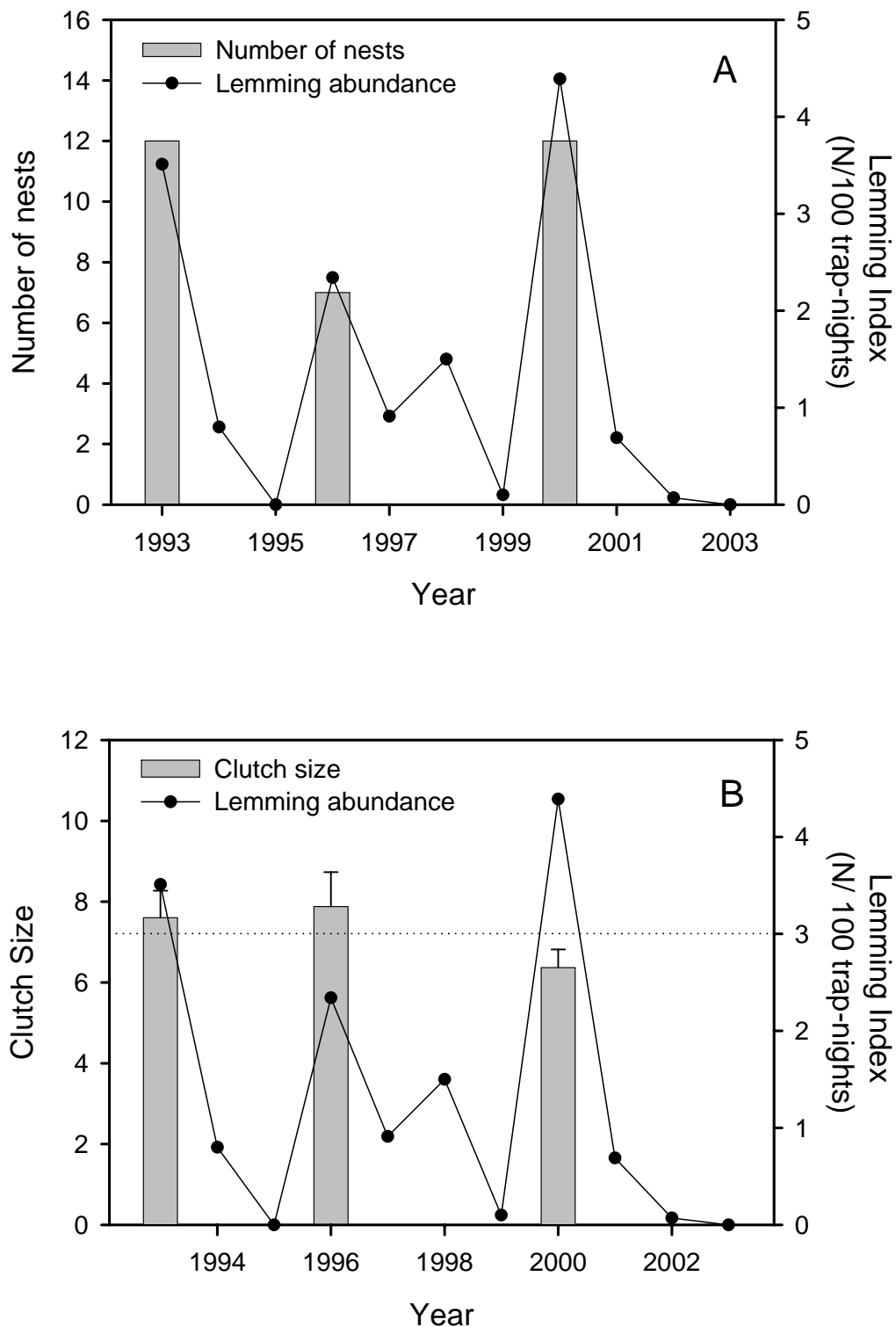
#### **4.3.4 Snowy Owls**

All Snowy Owl nests found on Bylot Island were located in the Qarlikturvik Valley, except for two nests found in the goose colony in 1996. Most owl nests were found along slopes, generally on hills bordering the valley to the north or south (Fig. 1). There was a very strong association between owl nesting and lemming abundance as owl nested on Bylot Island only in years of peak lemming abundance, which occurs every 3 to 4 years (Fig. 57). In these years, the number of owl nests found varied from 8 to 12 and higher number of nests occurred in years of particularly strong peaks of lemming abundance. We never found owl nests in between lemming peaks.

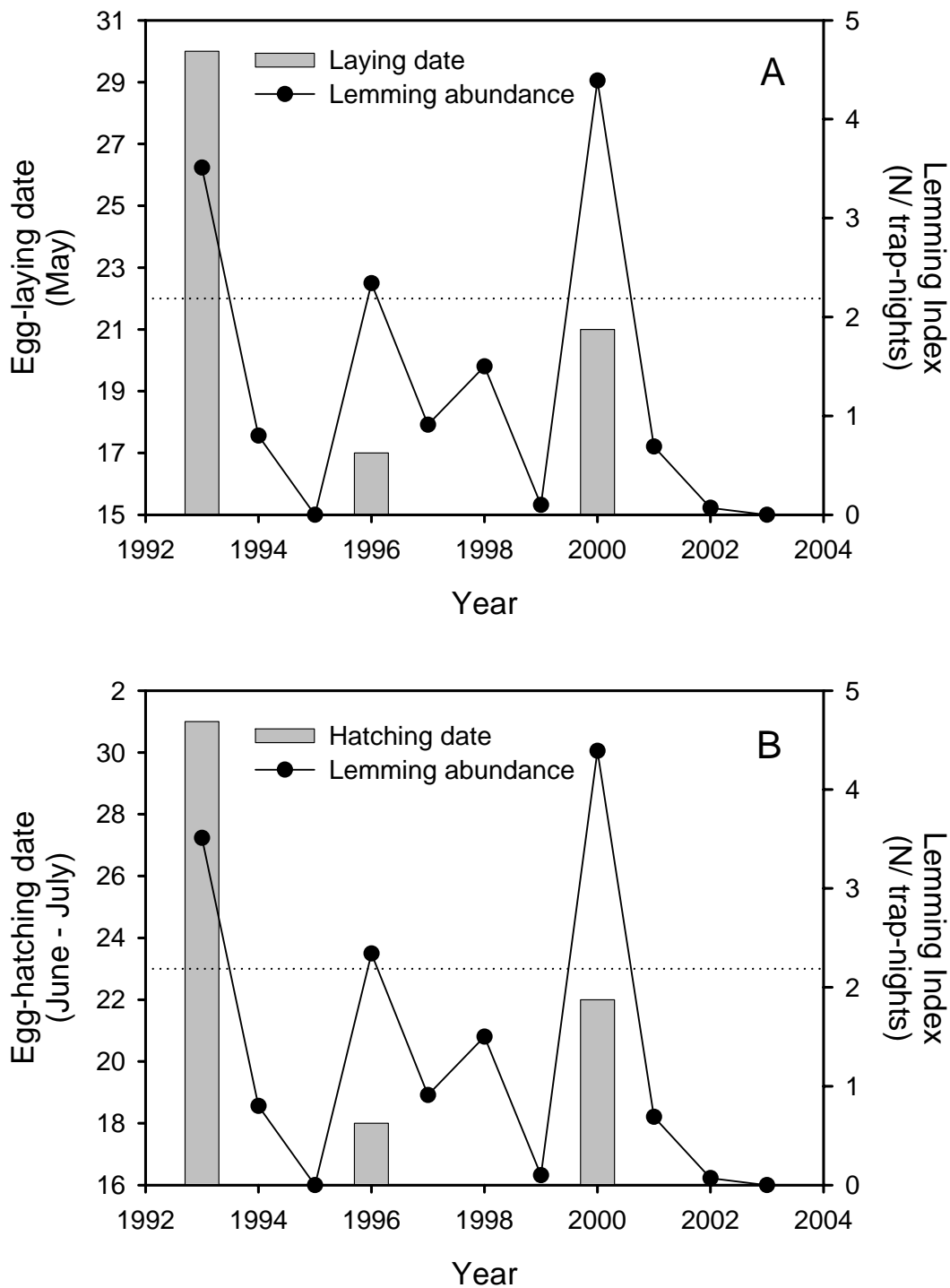
Owls nested quite early compared to other species of birds. Average laying date of the first egg was 22 May (range: 9 May to 5 June;  $n = 17$ ) and average hatching date of first egg was 23 June (range: 10 June to 7 July;  $n = 17$ ; Fig. 58). Overall, the average clutch size in owls nests was  $7.21 \pm 0.38$  eggs ( $n = 32$ ; range: 3-11 eggs per nest). The average clutch size varied only slightly among years but did not appear to be influenced by lemming abundance. Indeed, the lowest yearly average clutch size was recorded in 2000 ( $6.36 \pm 0.45$  eggs/nest) even though the highest lemming abundance was recorded that year (Fig. 57). The intermittent nesting of owl precluded the examination of temporal trend in the data.

#### **4.3.5 Lapland Longspurs**

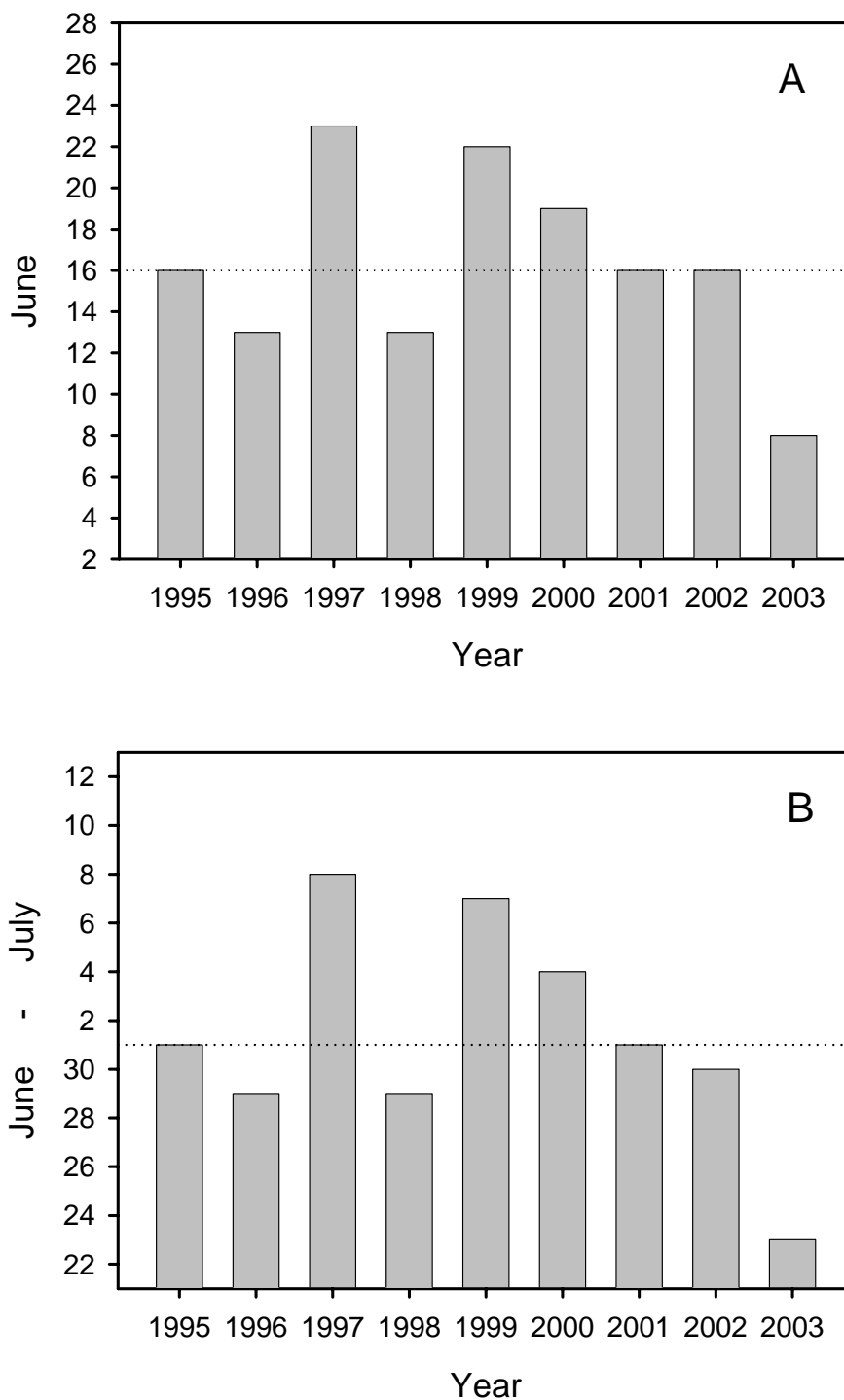
The number of Lapland Longspur nests found varied annually from 5 to 22. However, these annual variations more likely reflect variations in sampling effort among years than true variation in abundance. The average laying date of the first egg was 17 June (range: 1 June to 3 July;  $n = 58$ ) and the average hatching date of the first egg was 3 July (range: 18 June to 20 July;  $n = 58$ ). Both egg-laying and egg-hatching dates presented inter-annual variations, but no temporal trends were detected (Fig. 59; laying date:  $R^2 = 0.028$ ,  $df = 58$ ,  $P = 0.212$ ; hatching date:  $R^2 = 0.039$ ,  $df = 58$ ,  $P = 0.159$ ).



**Figure 57.** Annual (A) number of nests and (B) clutch size (mean  $\pm$  SE) of Snowy Owl on Bylot Island in relation to lemming abundance from 1993 to 2003. For the clutch size, total sample size = 29 (annual sample size ranging from 8 to 11). The dotted line shows the mean for the whole period.

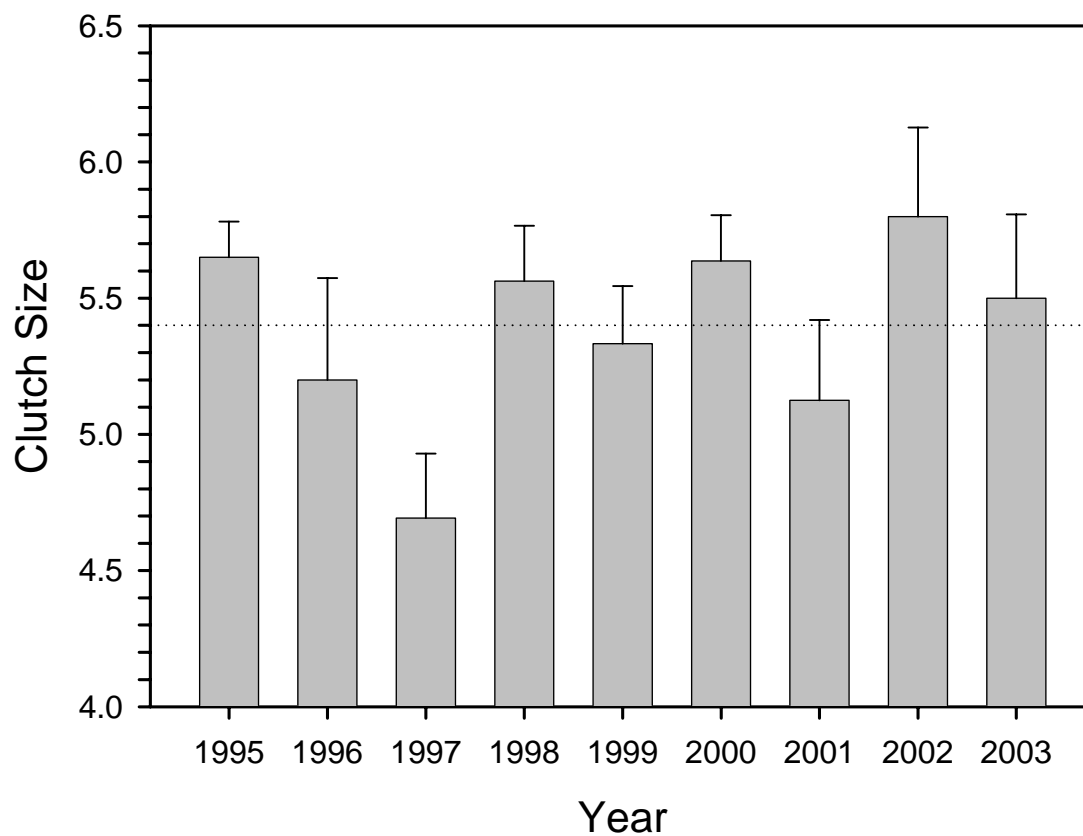


**Figure 58.** Annual median (A) laying date and (B) hatching date of Snowy Owls on Bylot Island in relation to lemming abundance from 1993 to 2003. The total sample size for laying and hatching dates = 17 (annual sample size ranging from 2 to 9). The dotted lines show the means for the whole period.



**Figure 59.** Annual median (A) laying date and (B) hatching date of Lapland Longspurs, on Bylot Island from 1995 to 2003. The total sample size for laying dates = 58 (annual sample size ranging from 2 to 15). The total sample size for hatching dates = 52 (annual sample size ranging from 2 to 14). The dotted lines show the means for the whole period.

Overall, clutch size of Lapland Longspurs averaged  $5.45 \pm 0.08$  eggs per nest (range: 3 to 7;  $n = 110$ ). Average clutch size varied annually but no significant temporal trend was observed (Fig. 60). There was a tendency for average annual clutch sizes to be inversely related to average laying dates (i.e. clutch size tended to be reduced in late years;  $R^2 = 0.209$ ,  $df = 55$ ,  $P = 0.0004$ ).



**Figure 60.** Annual clutch size (mean  $\pm$  SE) of Lapland Longspurs from 1995 to 2003. The dashed line shows the mean for the whole period. Total sample size = 110 (annual sample size ranging from 5 to 22).



### 4.3.6 Plant Monitoring in Wetlands

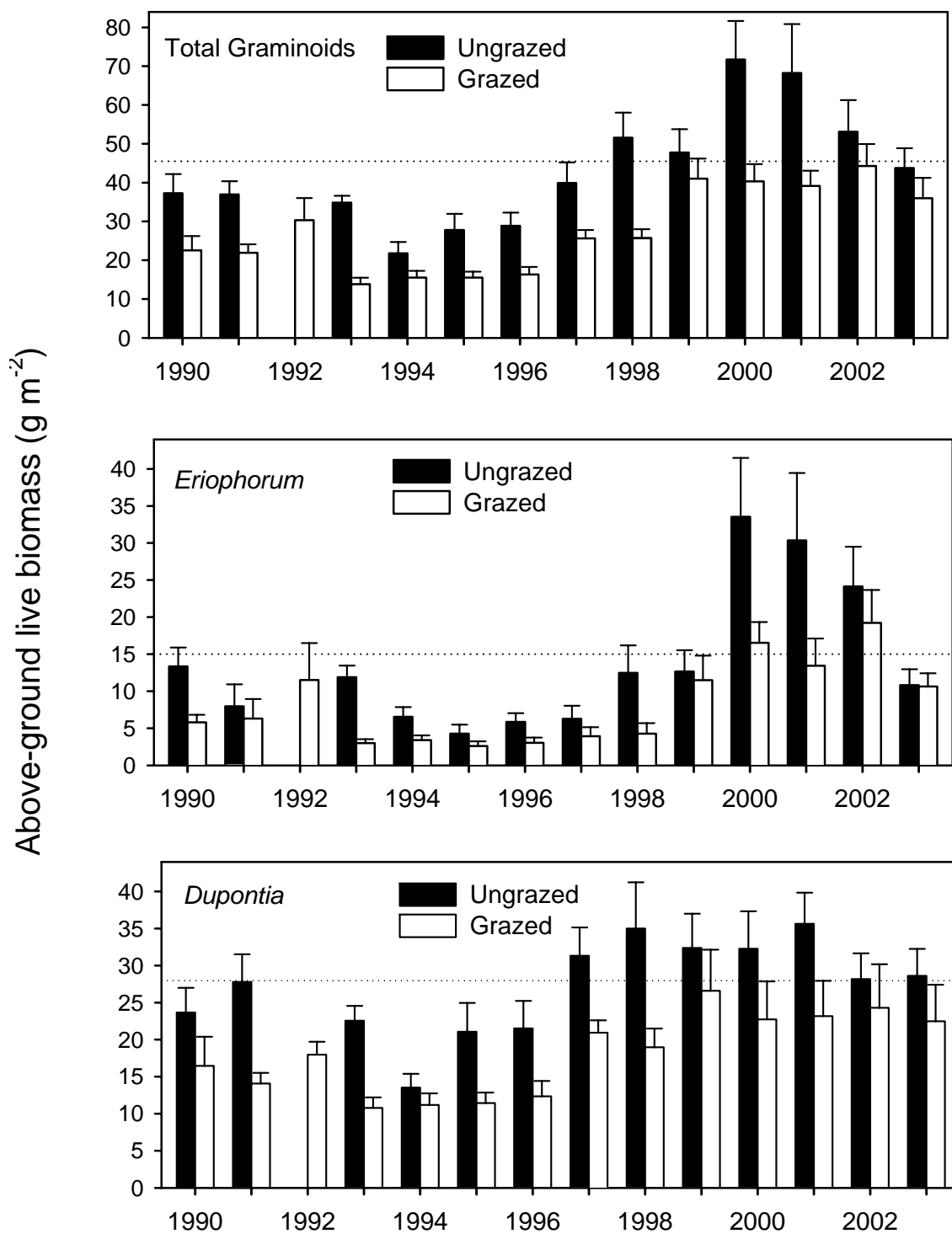
#### 4.3.6.1 Plant production

Wetland communities on Bylot Island are largely dominated by graminoid plants (i.e. >90 % by sedges and grasses), and thus only these plants are considered here. Among the 3 sites where wetland plants are monitored on Bylot Island (Fig. 1), the longest time series comes from the Qarlikturvik Valley site. From 1990 to 2003, above-ground biomass of graminoids at the end of the summer averaged  $45.5 \pm 5.5 \text{ g m}^{-2}$  in ungrazed areas of the Qarlikturvik Valley. This value is good index of total above-ground production of graminoids at the end of the summer (Gauhtier et al. 1995). There was, however, considerable variation in annual production, with a low value of  $21.8 \pm 2.9 \text{ g m}^{-2}$  in 1994 and a high value of  $71.7 \pm 9.9 \text{ g m}^{-2}$  in 2000 (Fig. 61). Graminoid biomass was dominated by *Dupontia fisheri* ( $28.0 \pm 2.3 \text{ g m}^{-2}$  on average or 63 % of the biomass) followed by *Eriophorum scheuchzeri* ( $14.7 \pm 3.4 \text{ g m}^{-2}$  or 33 % of the total biomass).

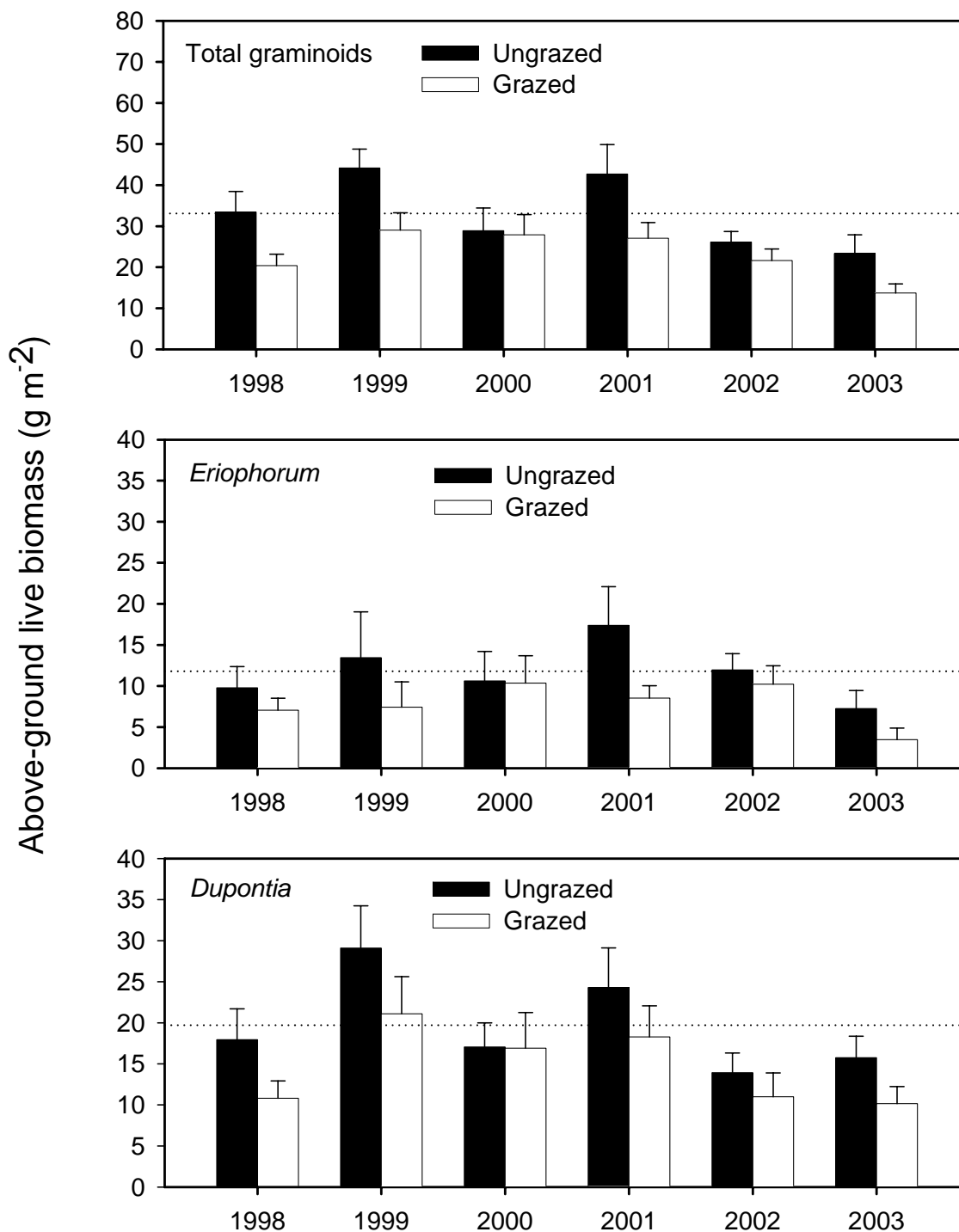
From 1990 to 2003, the biomasses of total graminoids, *Eriophorum* and *Dupontia* have shown significant increasing trends in the Qarlikturvik Valley. Over this 10-year period, average biomasses increased by 19 % for total graminoids ( $R^2 = 0.136$ ,  $df = 154$ ,  $P < 0.0001$ ; data log-transformed), 55 % for *Eriophorum* ( $R^2 = 0.073$ ,  $df = 154$ ,  $P = 0.0007$ ) and 16 % ( $R^2 = 0.058$ ,  $df = 154$ ,  $P = 0.003$ ) for *Dupontia*. Despite these overall increasing trends, visual inspection of Fig. 61 suggests several short-term trends. Indeed, biomass tended to decline slightly between 1990 and 1994, increased considerably from 1994 to 2000, and has declined again since then. These fluctuations were most pronounced for *Eriophorum*, which increased dramatically between 1999 and 2000. Indeed, *Eriophorum* accounted for 45-47 % of the total graminoid biomass from 2000 to 2002 compared to 27 % in 1999 (Fig. 61). Although these fluctuations may suggest a long-term cycle in plant production, the time series is not long enough to draw any firm conclusion at this stage.

Wetland plant monitoring at the two other sites (main goose nesting colony and Pointe Dufour) has been conducted since 1998 only. Average above-ground biomass of graminoids at Pointe Dufour was similar to that encountered in Qarlikturvik Valley ( $51.4 \pm 4.6 \text{ g m}^{-2}$  vs  $56.0 \pm 3.5 \text{ g m}^{-2}$ , respectively; in the latter case, the mean value was for the same time period, i.e. 1998-2003), but both values were higher than that encountered at the main nesting goose colony ( $33.7$

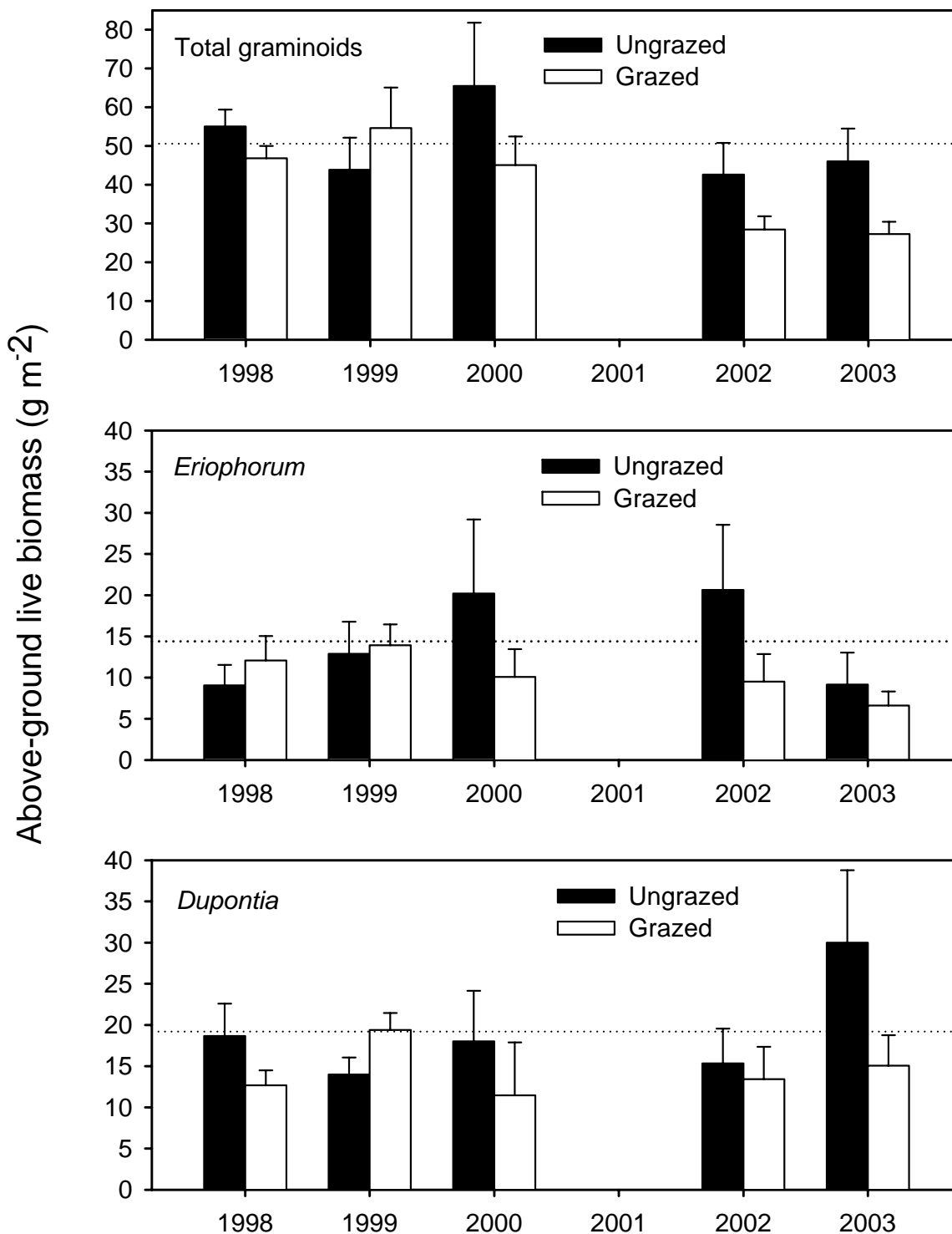
$\pm 2.2 \text{ g m}^{-2}$ ;  $F = 14.7$ ,  $df = 2,186$ ,  $P < 0.0001$ ). This suggests that plant production is higher in major brood-rearing areas than at the main nesting colony. *Dupontia* accounted for 60 % of the biomass ( $20.3 \pm 1.6 \text{ g m}^{-2}$ ) and *Eriophorum* for 35 % ( $11.9 \pm 1.5 \text{ g m}^{-2}$ ) at the goose colony (Fig. 62); these proportions were similar to those in the Qarlikturvik Valley for the same period (57 % and 37 %, respectively). However, these proportions were lower at Pointe Dufour, as *Dupontia* accounted for 38% of the biomass ( $19.4 \pm 2.5 \text{ g m}^{-2}$ ) and *Eriophorum* for 29 % ( $14.8 \pm 2.7 \text{ g m}^{-2}$ ) (Fig. 63). The reason for this difference is that *Carex* accounted for a sizeable fraction of graminoid biomass at Pointe Dufour ( $17.2 \pm 2.9 \text{ g m}^{-2}$  or 34 % of the total) unlike in the Qarlikturvik Valley and the main goose nesting colony where it accounted for a negligible fraction (6 % and 5 %, respectively). Therefore, the specific composition of wetlands was more similar in the Qarlikturvik Valley and the main goose nesting colony than at Pointe Dufour. In contrast with the Qarlikturvik Valley, there was no significant temporal trend in above-ground graminoid biomass at Pointe Dufour ( $R^2 = 0.001$ ,  $df = 59$ ,  $P = 0.81$ ) whereas graminoid biomass showed a significant decreasing trend at the main nesting colony since 1998 ( $R^2 = 0.067$ ,  $df = 70$ ,  $P = 0.029$ ).



**Figure 61.** Annual live above-ground biomass (mean  $\pm$  SE, dry mass) of (A) all graminoids, (B) *Eriophorum scheuchzeri* and (C) *Dupontia fisheri* around 15 August in grazed and ungrazed wet meadows of the Qarlikturvik Valley, Bylot Island, from 1990 to 2003 ( $n = 12$  each year). There is no data from ungrazed area in 1992. The dotted line shows the mean plant production for the whole period.



**Figure 62.** Annual live above-ground biomass (mean  $\pm$  SE, dry mass) of (A) all graminoids (B) *Eriophorum scheuchzeri* and (C) *Dupontia fisheri* around 15 August in grazed and ungrazed wet meadows of the main nesting goose colony, Bylot Island, from 1998 to 2003 ( $n = 12$  each year). The dotted line shows the mean plant production for the whole period.



**Figure 63.** Annual live above-ground biomass (mean  $\pm$  SE, dry mass) of graminoids (B) *Eriophorum scheuchzeri* and (C) *Dupontia fisheri* around 15 August in grazed and ungrazed wet meadows of Pointe Dufour, Bylot Island, from 1998 to 2003 ( $n = 12$  each year). The dotted line shows the mean plant production for the whole period.

#### 4.3.6.2 Goose Grazing Impact

From 1990 to 2003, Greater Snow Geese removed on average  $36.7 \pm 3.8$  % of the total annual production,  $37.7 \pm 6.4$  % of the *Eriophorum* production and  $31.0 \pm 4.1$  % of the *Dupontia* production in wetlands of the Qarlikturvik Valley. This grazing impact varied considerably from year to year with the highest value recorded in 1993 (60.2 % of total production consumed), and the lowest values recorded in 1999, 2002 and 2003 (14.1 %, 16.6 % and 17.8%, respectively, of total production removed; Fig.61). No long-term significant trend was detected in the impact of goose grazing on total graminoids and *Eriophorum* ( $R^2 = 0.0001$ ,  $df = 99$ ,  $P = 0.749$ ;  $R^2 = 0.026$ ,  $df = 83$ ,  $P = 0.140$ , respectively). However, the impact of goose grazing on *Dupontia* decreased significantly by 39 % since 1990 ( $R^2 = 0.067$ ,  $df = 96$ ,  $P = 0.01$ ). Moreover, there was a significant relationship between the proportion of biomass grazed by geese in a given year and the young:adult ratio at banding, which is an index of production of young during the summer (Fig. 64). Therefore annual variation in the amount of plant consumed by geese can be explained by variations in the size of the “local” goose population, which is dependent of the reproductive effort of geese in spring and their nesting success.

The average proportion of annual production consumed by geese at the main nesting goose colony ( $28.6 \pm 6.1$  %; Fig. 62) and at Pointe Dufour ( $30.0 \pm 5.4$  %; Fig. 63) was similar to the amount consumed in the Qarlikturvik Valley for the same time period ( $30.9 \pm 6.7$  %; 1998-2003). At the goose colony, geese removed on average  $32.2 \pm 5.7$  % of the *Eriophorum* production and  $24.9 \pm 3.1$ % of the *Dupontia* production. Similar values at Pointe Dufour were  $26.4 \pm 11.7$  % for *Eriophorum* and  $26.1 \pm 8.9$  % for *Dupontia*. There was no significant temporal trend in goose grazing impact at the nesting goose colony ( $R^2 = 0.014$ ,  $df = 47$ ,  $P = 0.043$  for the total graminoids) whereas the grazing impact on total graminoids increased significantly at Pointe Dufour ( $R^2 = 0.105$ ,  $df = 40$ ,  $P = 0.004$ ). From 1998 to 2003, the proportion of total biomass removed at Pointe Dufour increased by 78 %. This increasing trend was mainly due to the significantly increasing proportion of *Eriophorum* biomass removed by grazing ( $R^2 = 0.025$ ,  $df = 27$ ,  $P = 0.007$ ), since there was no temporal trends for the grazing impact on *Carex* and *Dupontia* ( $R^2 = 0.0.0$ ,  $df = 31$ ,  $P = 0.441$ ;  $R^2 = 0.005$ ,  $df = 32$ ,  $P = 0.693$ ).

Overall, the proportion of the annual production of *Eriophorum* consumed by geese was higher than that of *Dupontia* (at least in the Qarlikturvik Valley and at the nesting goose colony),

even though the latter plant is the most abundant in wetland communities. This is because *Eriophorum* is the preferred food plant of goslings (Manseau and Gauthier 1993).

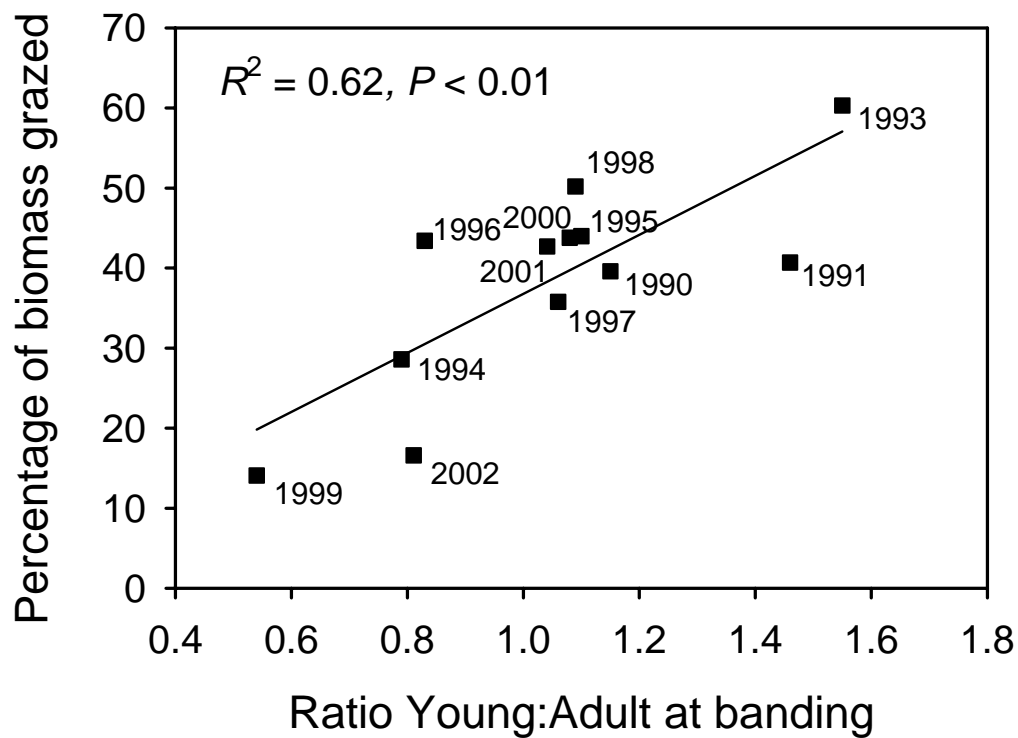
#### **4.3.7 Plant Monitoring in Mesic Communities**

##### 4.3.7.1 Number of Flowers

Data from the International Tundra Experiment provided information on the average number of flowers produced each year and the phenology of four vascular plant species in mesic communities. The average number of flowers produced by individual plant (or ramet for *Salix arctica*) was 10.8 for *Dryas integrifolia*, 2.8 for *Saxifraga oppositifolia*, 0.5 for *Salix Arctica* male, 0.2 for *Salix arctica* female and 1.0 for *Luzula nivalis*. *Dryas intergrifolia*, the plant that produced the highest number of flowers, was the only one showing significant inter-annual variability in flower production ( $F = 19.87$ ,  $df = 3$ ,  $87 P < 0.001$ ; Fig. 65), with a decreasing trend in the number of flowers produced since 2000. No trends were detected in the other monitored species.

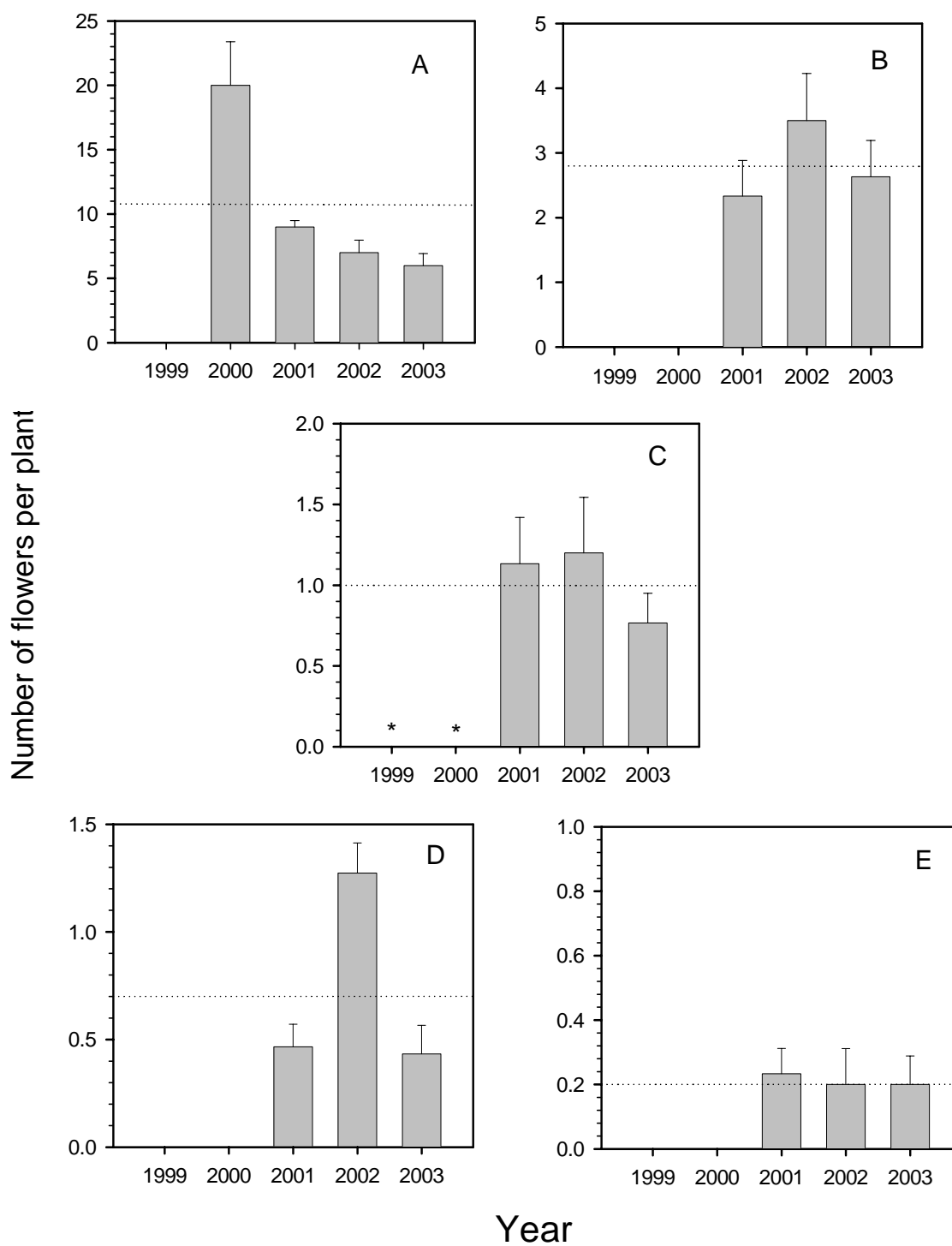
##### 4.3.7.2 First Flowering Date

From 1999 to 2003 the average date of first flowering for the species monitored in mesic communities was 30 June for *S. oppositifolia*, 3 July for *S. Arctica* male, 3 July for *S. arctica*, 6 July for *L. nivalis* and 12 July for *D. integrifolia*. For all the monitored species, the average first flowering date has been advancing significantly since 1999 (Fig. 66). Over a 5-year period, this represents an advance in flowering date of 3 days for *Dryas integrifolia*, 3 days for *Saxifraga oppositifolia*, 6 days for *Salix Arctica* male, 6 days for *Salix arctica* female and 9 days for *Luzula nivalis* on average.

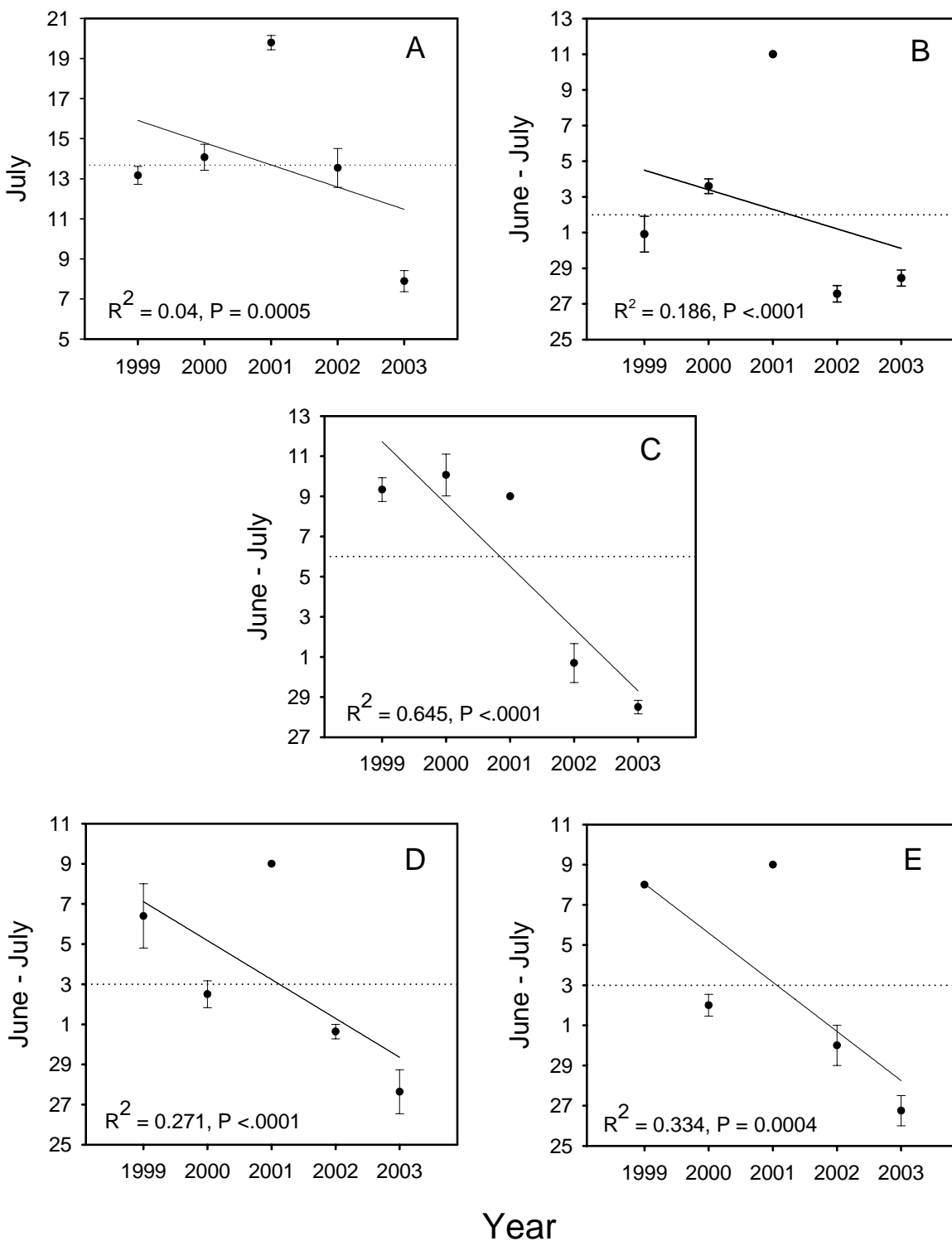


**Figure 64.** Relationship between percentage of biomass grazed by geese in the Qarlikturvik Valley and the annual production of young estimated when goose families are captured for banding at the end of the summer, Bylot Island (from Gauthier et al. 2004a).





**Figure 65.** Number of flowers (mean  $\pm$  SE;  $n = 30$  each year) produced annually by (A) *Dryas integrifolia*, (B) *Saxifraga oppositifolia*, (C) *Luzula nivalis*, (D) *Salix arctica* males, and (E) *Salix arctica* female in mesic communities of Bylot Island from 1999 to 2003. For *Dryas integrifolia*, bars with different letters differ significantly ( $P < 0.05$ ). For all species except *Dryas integrifolia*, there was no data for 1999 and 2000. There was no data for *Dryas integrifolia* in 1999.



**Figure 66.** Annual first flowering date (mean ± SE; n = 30) of (A) *Dryas integrifolia*, (B) *Saxifraga oppositifolia*, (C) *Luzula nivalis*, (D) *Salix arctica* male, and (E) *Salix arctica* female in mesic communities of Bylot Island from 1999 to 2003. The solid lines show significant temporal trends (P < 0.05).

## **4.4 Relations Between Climate and Biological Data**

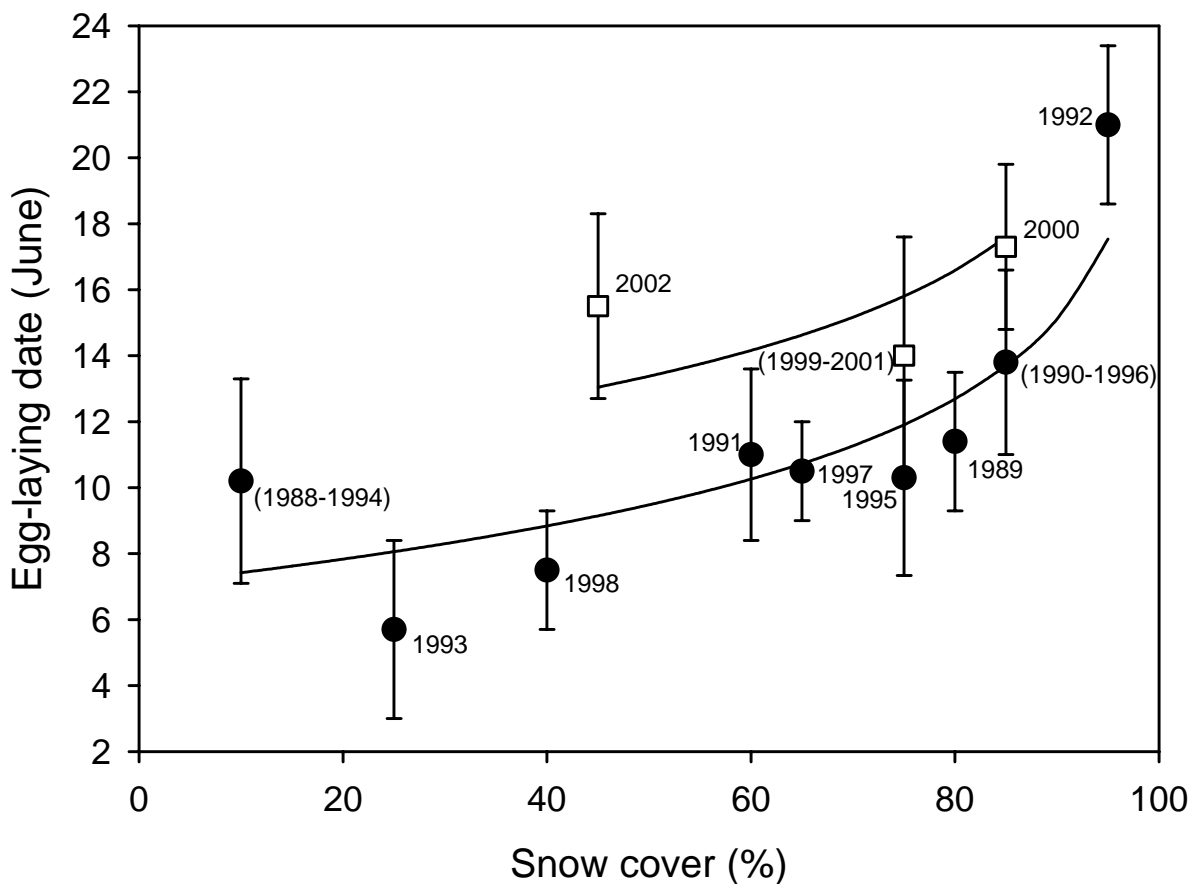
At this stage, only exploratory analyses on the links between climatic and biological variables have been conducted. In this section, we present the few significant relationships that have been found so far. In particular, an in depth analysis of the links between all stages of Greater Snow Goose reproduction and several climatic variables is currently the subject of a Master student thesis at Université Laval. Therefore, much remains to be done on this topic and new analyses will become possible with the continuation of our monitoring in the future.

### ***4.4.1 Greater Snow Goose Reproduction***

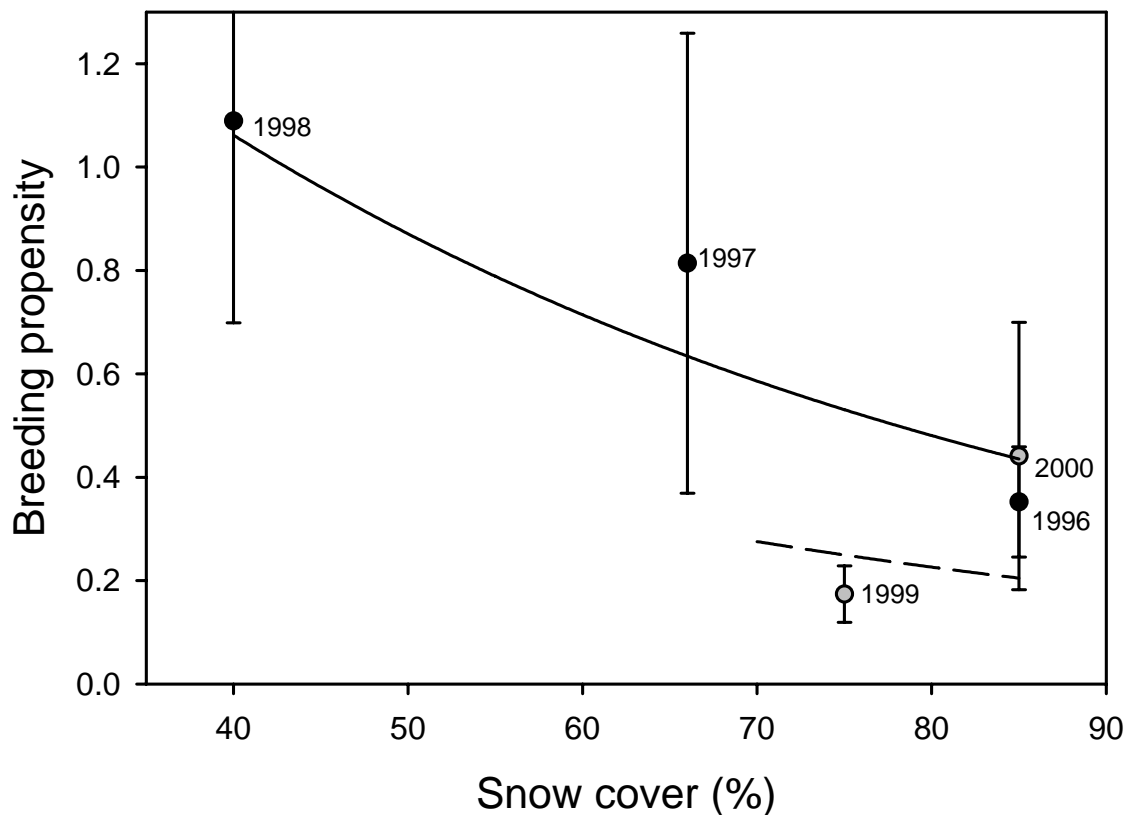
We have so far found two strong associations between goose reproduction and climatic variables. These associations were found with one variable associated with phenology (egg-laying date) and one with reproductive effort of geese (breeding propensity, which is the proportion of mature, adult females that attempt to breed each year). A first relationship was found between egg-laying date of geese and the percentage of snow cover on 5 June (Fig. 67). Egg-laying was delayed in years of late snow melt, and the relationship was curvilinear, suggesting a threshold effect (i.e. when snow-free area on 5 June dropped below ca 20 %, the impact on laying date of geese increased rapidly). Secondly, there was a relationship between breeding propensity and the percentage of snow cover on 5 June (Fig 68). Again, the proportion of female attempting to breed was reduced in years of late snowmelt.

### ***4.4.2 Lapland Longspur Reproduction***

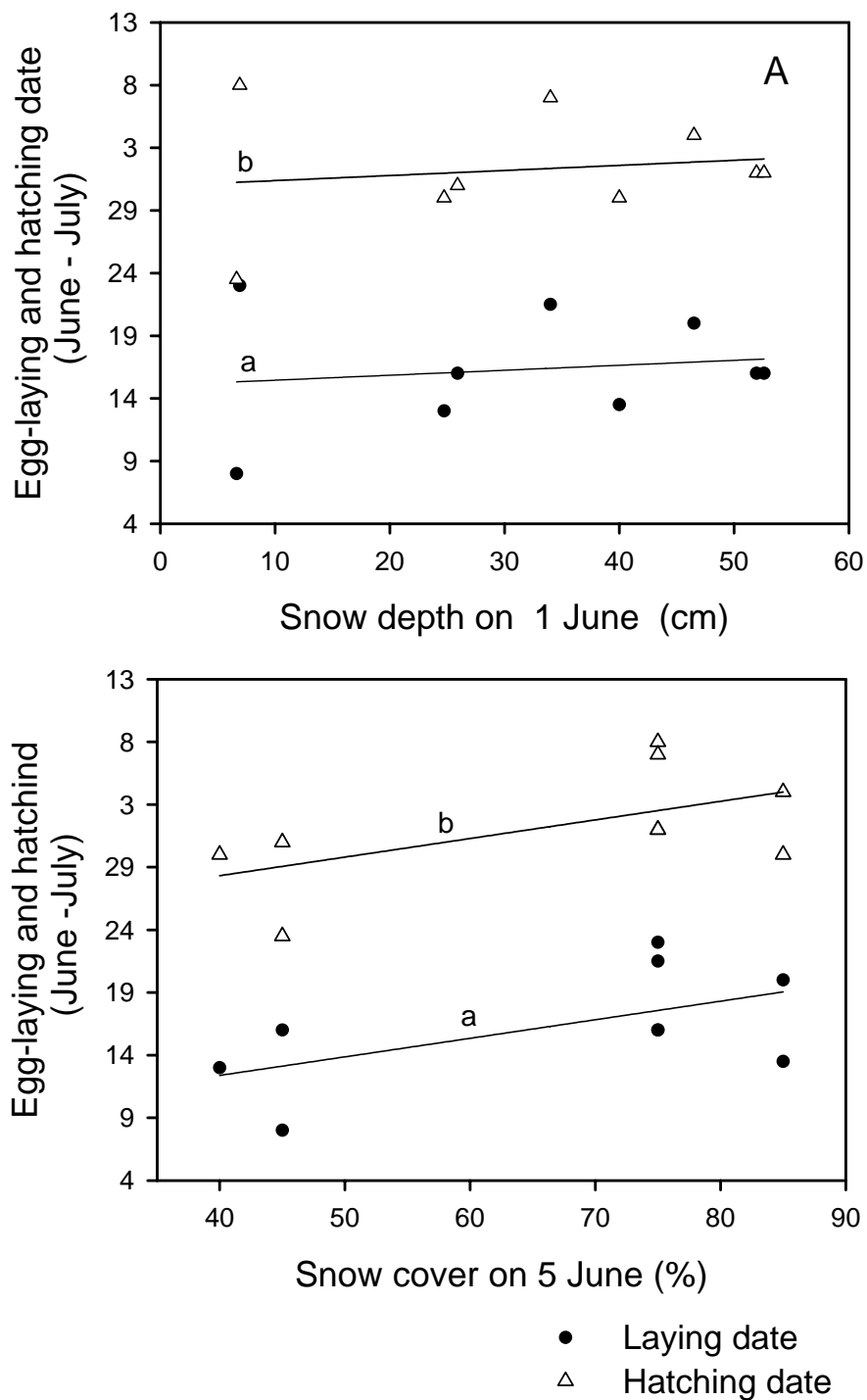
Several aspects of the reproduction of Lapland Longspurs were affected by climatic variables. Both laying and hatching dates of longspurs were positively related to snow depth on 1 June, percentage snow cover on 5 June, and inversely related to number of days above 0°C and average summer air temperatures (Figs. 69 and 70). Nesting phenology of birds was delayed in years with late snowmelt (i.e. years high snow depth and snow cover in early June) and cool summer temperature (i.e. years with a low number of frost-free days and low summer air temperatures). Clutch size was also influenced by the number of days above 0°C and the average summer air temperature (Fig. 71). Lapland Longspurs laid more eggs in years with high summer air temperature and a high number of frost-free days.



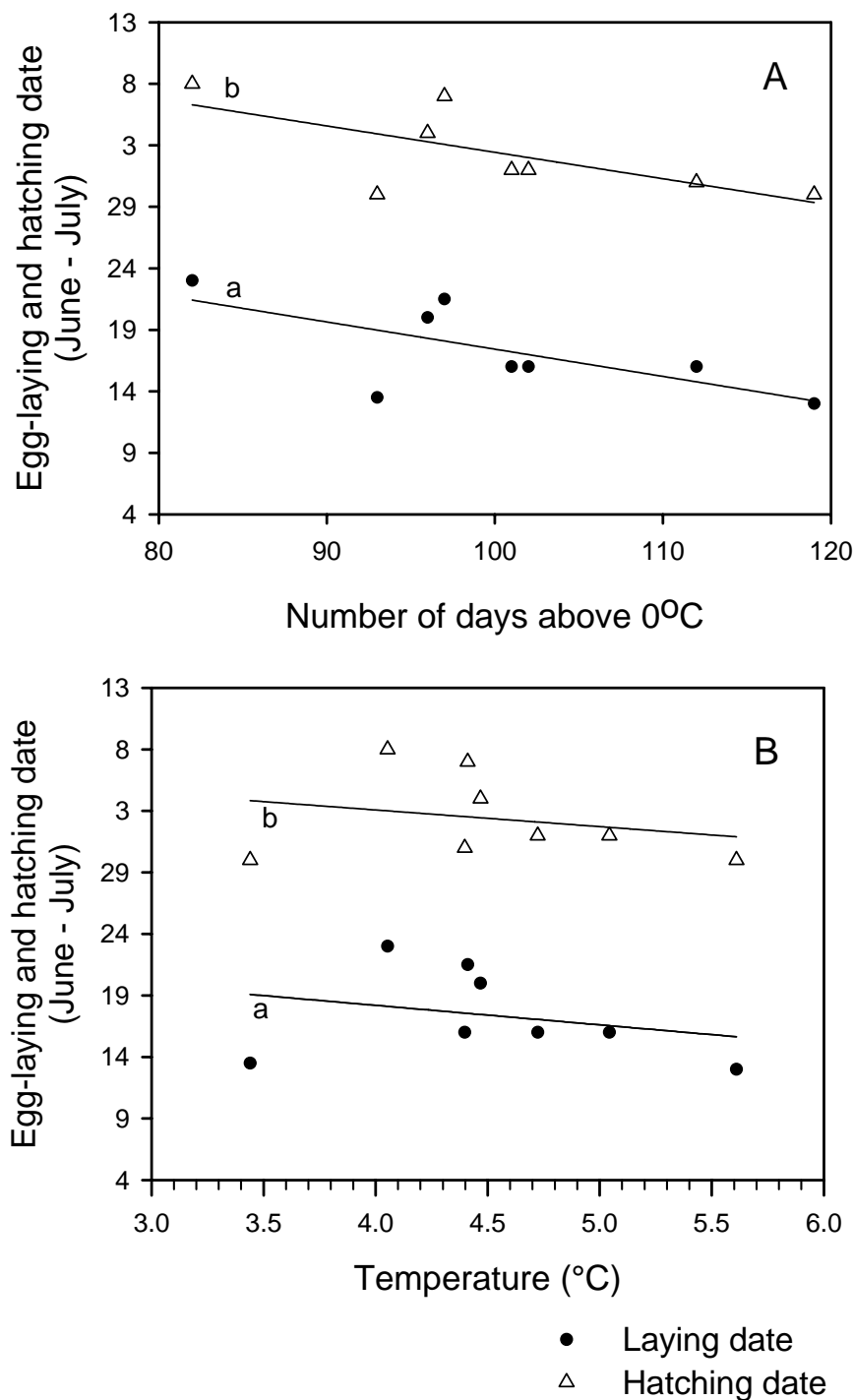
**Figure 67.** Egg-laying date of Greater Snow Geese in relation to percentage snow cover on 5 June in the Qarlikturvik Valley of Bylot Island in years with hunting on the spring staging area (white squares, from 1999 to 2002) and without (black circles, from 1988 to 1998). Corresponding years are near each data point. Values are mean  $\pm$  1 SD (each dot represents 52 to 522 nests). Multiple linear model: snow cover (log-transformed),  $F_{1, 3674} = 2220$ ,  $P < 0.001$ ; Hunting (on staging area: yes = 1, no = 0),  $F_{1, 3674} = 1086$ ,  $P < .001$ . From Bêty et al. (2003).



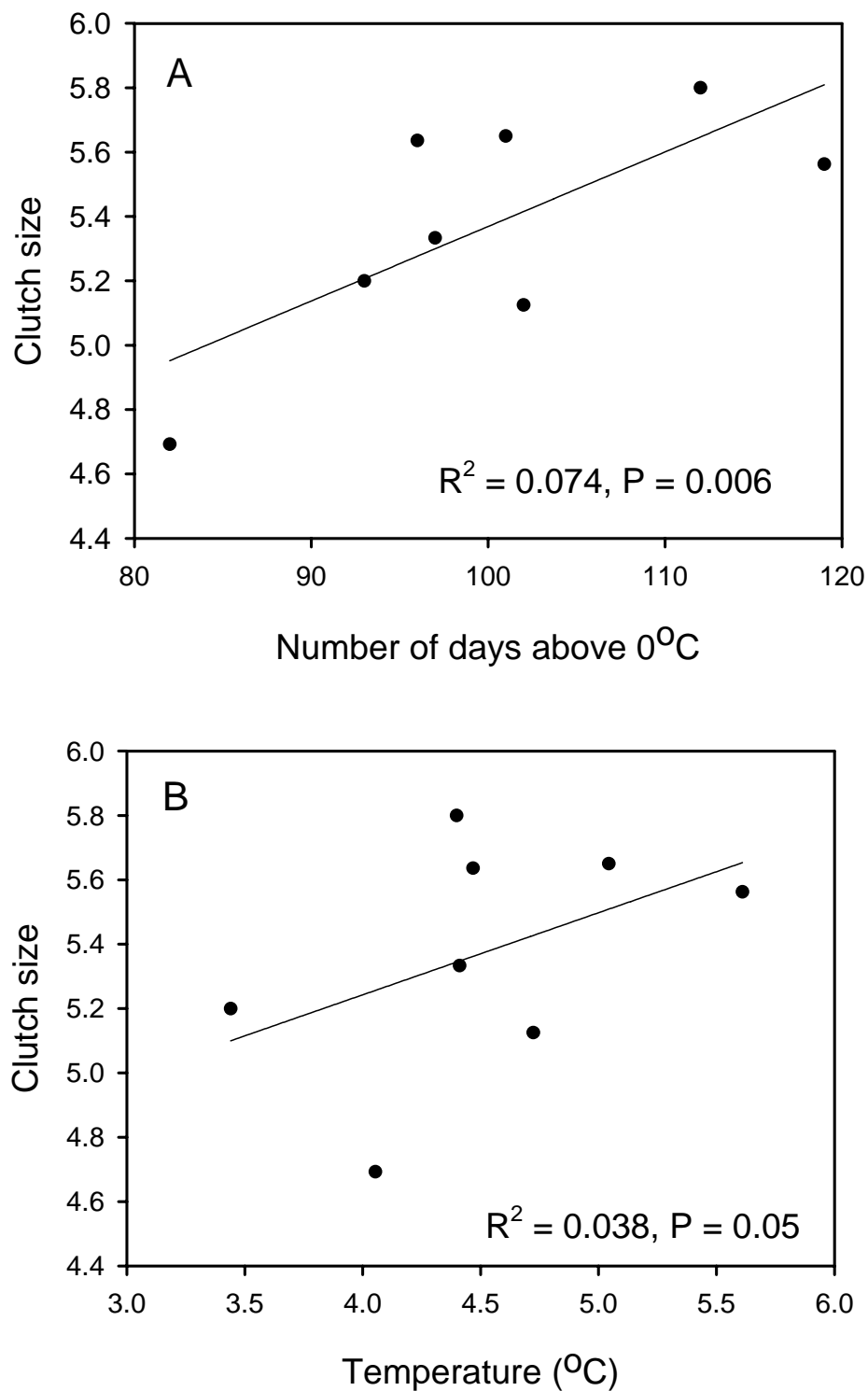
**Figure 68.** Breeding propensity (mean  $\pm$  SE) of female Greater Snow Geese in relation to percentage snow cover on 5 June in the Qarlikturvik Valley of Bylot Island from 1996 to 2001. Corresponding years are near each data point. The solid line and dark dots represents years without a spring hunt and the dashed line and grey dots represent years with a spring hunt. Lines are predicted values of breeding propensity from model:  $\text{logit}(\text{breeding propensity}) = 0.79 [\pm 0.67] - 2.05 [\pm 0.96] * \text{snow cover} - 0.78 [\pm 0.35] * (0: \text{no spring hunt}; 1: \text{spring hunt})$ . From Reed et al. (2004).



**Figure 69.** Laying and hatching dates of Lapland Longspurs in relation to (A) snow depth on 1 June and (B) percentage of snow cover on 5 June on Bylot Island from 1995 to 2003. Linear regression with snow depth on 1 June: (a) laying date  $R^2 = 0.072$ ,  $df = 57$ ,  $P = 0.047$ , (b) hatching date  $R^2 = 0.075$ ,  $df = 51$ ,  $P = 0.05$ . Linear regression with snow cover on 5 June: (a) laying date  $R^2 = 0.187$ ,  $df = 57$ ,  $P = 0.0007$ , (b) hatching date  $R^2 = 0.172$ ,  $df = 51$ ,  $P = 0.002$ . Each data point shows the annual mean.



**Figure 70.** Laying and hatching dates of Lapland Longspur in relation to (A) number of days above 0°C and (B) average summer air temperature on Bylot Island from 1995 to 2003. Linear regression with number of days above 0°C: (a) laying date  $R^2 = 0.237$ ,  $df = 51$ ,  $P = 0.0003$ , (b) hatching date  $R^2 = 0.213$ ,  $df = 45$ ,  $P = 0.001$ . Linear regression with summer temperature: (a) laying date  $R^2 = 0.099$ ,  $df = 51$ ,  $P = 0.023$ , (b) hatching date  $R^2 = 0.077$ ,  $df = 45$ ,  $P = 0.063$ . Each data point shows the annual mean.



**Figure 71.** Clutch size of Lapland Longspur in relation to (A) number of days above 0°C and (B) average summer air temperature on Bylot Island from 1995 to 2003 ( $n = 110$ ). Each data point shows the annual mean.

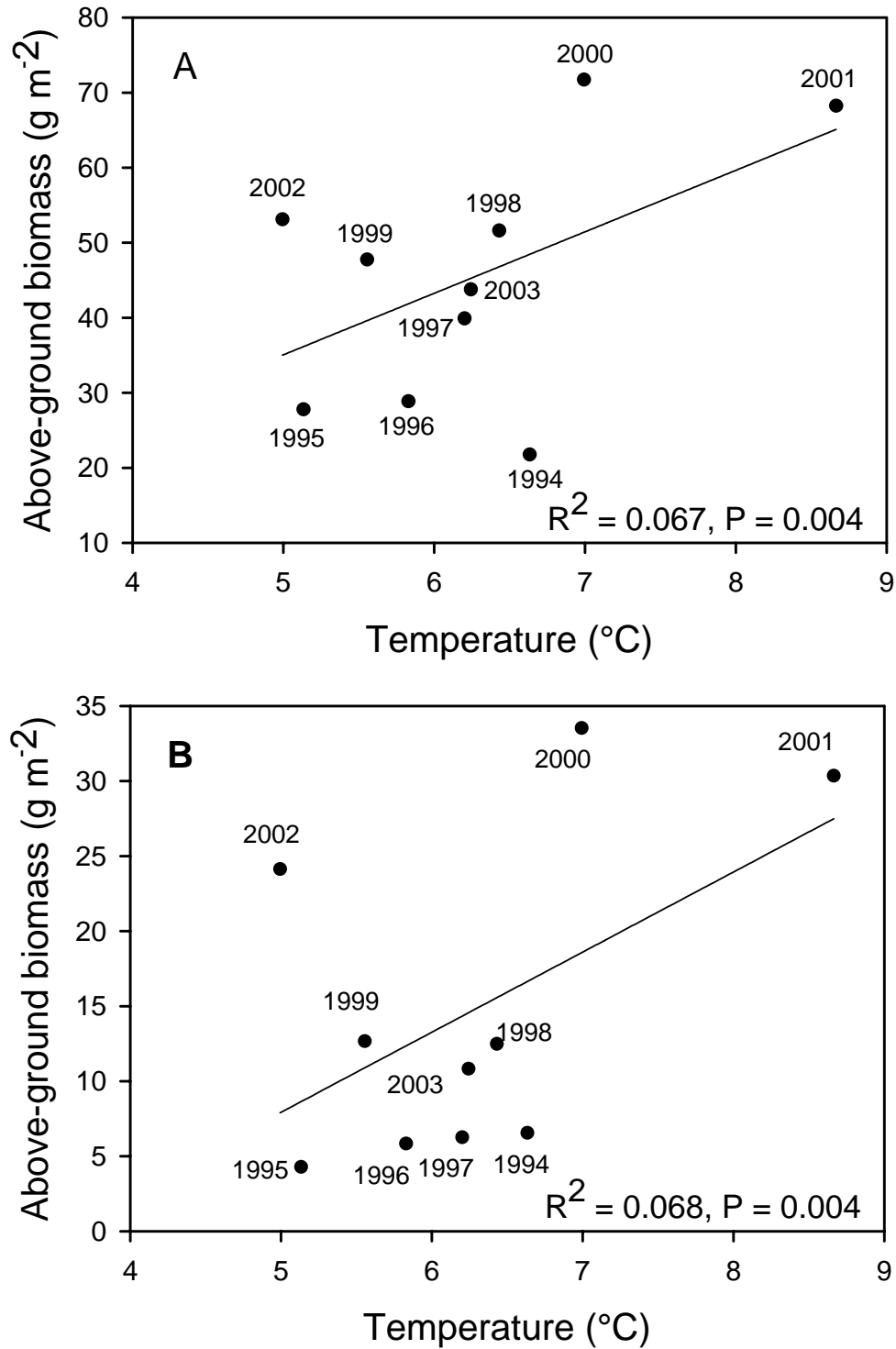


#### **4.4.3 Climate and Plant Production in Wetlands**

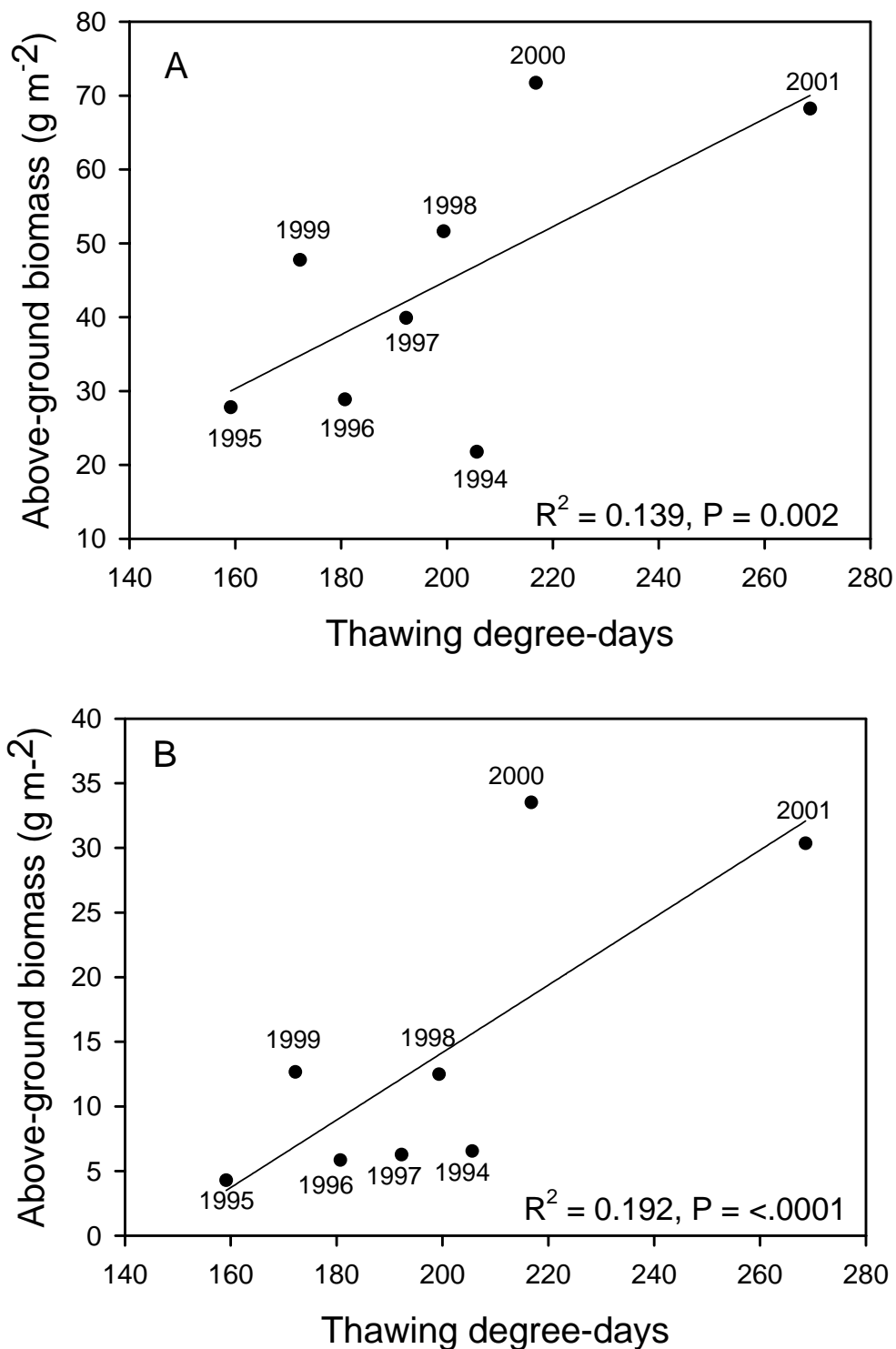
The above-ground live biomass of graminoids at the end of the summer (i.e. the annual production) in wetlands of the Qarlikturvik Valley was affected by climatic variables. Annual production of all graminoids and of *Eriophorum* was positively related to the average air temperature (Fig. 72) and number of thawing degree-days in July (Fig. 73), although not for the grass *Dupontia* (air temperature:  $R^2 = 0.020$ ,  $df = 119$ ,  $P = 0.121$ ; number of thawing degree-days:  $R^2 = 0.038$ ,  $df = 95$ ,  $P = 0.056$ ). The production of *Eriophorum* was greater in years with warm temperature in July and this was sufficient to increase the total production of wetland graminoids in those years. No other relationships were found between climatic variables and graminoids in wetlands (e.g. there was no relationship with either average summer temperature or the total number of thawing degree-days for the whole summer). This suggests that climatic conditions during mid-summer (i.e. the month of July) are critical for the growth of wetland graminoids.

#### **4.4.4 Climate and Plant Phenology in Mesic Communities**

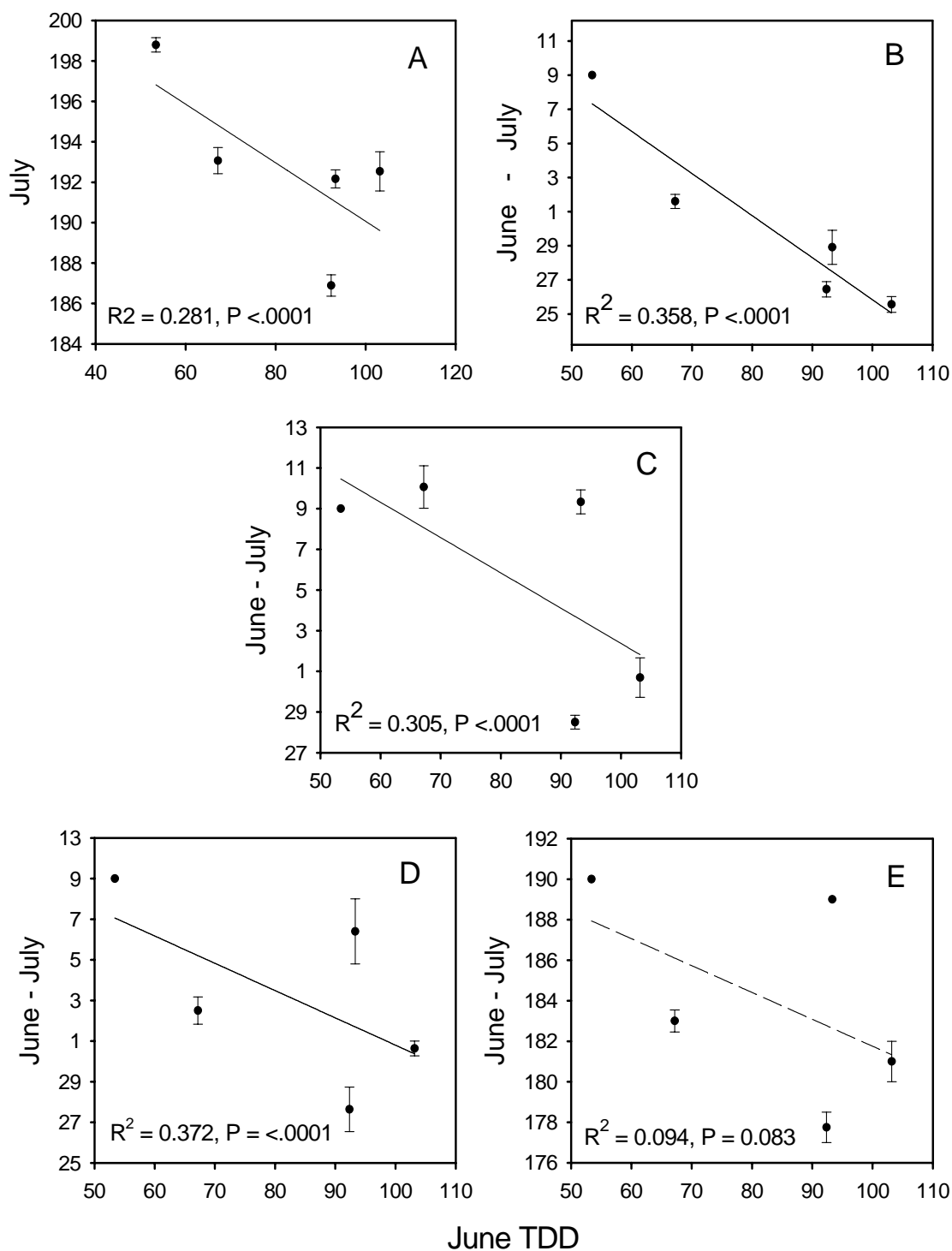
The phenology of plants in mesic communities was influenced by climatic variables. The date of first flowering in of all plant monitored but female *Salix arctica* was positively related to June thawing degree-days (TDD; Fig 74). Therefore, for most all plant species, flowering is advanced in years with warm temperature in June. June TDD did not influence the number of flowers produced in most plant species ( $P > 0.24$  in all cases), except for *Dryas integrifolia* that interestingly showed an inverse relationship between the number of flowers it produced and June TDD ( $R^2 = 0.053$ ,  $df = 119$ ,  $P = 0.011$ ). Moreover, there was no influence of climatic conditions in the previous growing season (i.e. TDD in June of the previous year) on the timing of flowering in the current year. Therefore, plants of mesic communities appear most sensitive to climatic conditions in early summer, i.e. in June.



**Figure 72.** Above-ground biomass of (A) all graminoids and (B) *Eriophorum* around 15 August in relation to average July air temperature on Bylot Island from 1990 to 2003 ( $n = 120$ ). Each data point shows the annual mean.



**Figure 73.** Above-ground biomasses of (A) total graminoids and (B) *Eriophorum* around 15 August in relation to average July number of thawing degree-days (TDD) on Bylot Island from 1990 to 2001?? ( $n = 96$ ). Each data point shows the annual mean.



**Figure 74.** Date of first flowering (mean  $\pm$  SE) in relation to June thawing degree-days for (A) *Dryas integrifolia*, (B) *Saxifraga oppositifolia*, (C) *Luzula nivalis*, (D) *Salix arctica* male, (E) *Salix arctica* female on Bylot Island from 1999 to 2003 (minimum  $n = 32$ , maximum  $n = 94$ ). Linear relationships are represented by a solid line when significant ( $P < 0.05$ ) and by a dashed line when approaching significance ( $0.05 < P < 0.15$ ).

## 5 DISCUSSION

### 5.1 Climatic regime of Bylot Island and surrounding area

Among the four seasons, it is during the summer that the climatic regime of Bylot Island was the most different. The summer was the only season when mean air temperature was above freezing. Although temperature was highest in July, the amount of solar radiation reaching the ground was maximum much earlier than that. The peak in solar radiation was in May, which is earlier than the summer solstice of June when the sun elevation is highest. Increased cloud covering probably reduces the amount of radiation reaching the ground as the summer progresses and explains this pattern. The increased cloud covering is likely due to increasing evaporation, and hence air moisture, during the summer as the ground snow cover and ice cover of lakes and sea progressively disappear. This, in turn, explains the gradual increase in rainfall from June to August. The summer wind regime was also markedly different than in the other seasons. The strong summer winds in comparison to other seasons presumably result from increased spatial variability in temperature between the air, snow-free ground, glaciers, sea ice and sea water during the summer. This not only affected wind speed but also prevailing wind direction during the summer.

The climatic regime of Bylot Island (Qarlikturvik Valley), Pond Inlet and Nanisivik were generally similar in terms of annual temperature. The largest differences were found between Nanisivik and the 2 other sites. The greater distance between Nanisivik and the other 2 stations than between Bylot Island and Pond Inlet may partly explain these differences. However, the difference in elevation between Nanisivik (400m ASL) and the other 2 stations (<50m ASL) may be the principal factor. The high elevation may explain why temperatures are colder in Nanisivik than at Bylot/Pond from late spring to late autumn. In contrast, the warmer winter and early spring temperature at Nanisivik may be due to the cold air flowing from higher elevation down to the valleys and creating winter thermal inversions at Pond Inlet and, especially, in the Qarlikturvik Valley of Bylot Island.

The annual precipitation regime was generally similar between Pond Inlet and Nanisivik, although the latter site received more snow and less rainfall on an annual basis. Summer (June to August) snowfall was noticeably higher at Nanisivik than Pond Inlet. These differences may

again be related to the higher elevation of the former site. At both sites, peak snowfalls are in autumn, with a smaller peak in spring, as little snowfall during the cold, dark winter. Comparison in precipitation regime between the 3 sites is only possible for summer rainfall because no precipitation data are collected at other seasons on Bylot Island. Rainfall is generally similar among sites during the summer except in June when rainfall is lower at Nanisivik, presumably because more precipitation falls as snow than rain during this season.

Average and peak snow depths were highest at Nanisivik and lowest on Bylot Island. The evolution of snow depth from autumn to spring is apparently the parameter that differed the most among the three sites. At Nanisivik and Pond, snow depth mostly increased in autumn, whereas the greatest increase occurred in spring on Bylot Island. It is unknown if this is a genuine difference across sites, or simply due to a peculiar pattern of snow accumulation in one year on Bylot Island, the snow depth record being very short at this site. Snow-melt was rapid in June at all 3 sites, but occurred slightly earlier at Bylot Island and later at Nanisivik.

## **5.2 Recent climatic trends at Bylot Island, Pond Inlet, and Nanisivik**

This section revealed some of the most interesting results of our report. Air temperature data indicated that both Pond Inlet and Nanisivik have experienced a strong warming trend during the summer, and a weaker warming trend in spring and autumn over the past 3 decades. However, no trend was detected in winter at these two sites. Curiously, no similar trend was detected in air temperature at Bylot Island during the summer, but a warming trend was detected in winter, in contrast to Nanisivik and Pond Inlet. The reason for this difference is unknown but may be related to the shorter time series available at this site (only 10 years), which prevented us to really examine long-term trends unlike at the two other sites. Previous analyses of temperature records in northern Canada had suggested that the eastern Canadian Arctic had experienced a cooling trend during spring and summer from the 1950's to the 1980's in contrast to the rest of the country (Climatic Research Unit 1992, Walsh 1993, Allard et al. 1995, Skinner et al. 1998). This climatic "anomaly" was centered in Baffin Bay and along the eastern coast of Baffin Island, and included the north Baffin area. Thus, our analysis revealed that this cooling trend has been replaced by a rapid warming trend in recent decades in the north Baffin area, as found across most of the Arctic (Weller 1998, Moritz et al. 2002). This suggests that the climatic anomaly of the eastern Canadian Arctic may have disappeared in recent years.

Even more interesting is the fact that the warming trend was strong in the summer and absent in winter because this is in contradiction with most Global Circulation Models (GCM). Indeed, these models generally predict a much stronger warming trend in winter than in summer in the Arctic (Rowntree et al. 1993, Rowntree 1997). Although it remains to be seen if this discrepancy is due to a local anomaly or some deficiencies in the theoretical models, the observed trend has important implications for the terrestrial arctic ecosystem. Indeed, because most of the biological activity occurs during the summer, we may expect impacts of these changes on several components of the ecosystem in the near future.

The negative trends in soil temperature at 2 and 10-cm observed in recent years at Bylot Island are puzzling and contrast with the warming trend in air temperature observed in Pond Inlet, and the warming trend in winter temperature at Bylot Island. Soil temperature is influenced by several factors, including the temperature and level of the underlying permafrost, the water regime in summer and especially the degree of insulation provided by the soil and winter snow accumulation. The latter effect explains why soil temperature remains about 10°C warmer than air temperature in winter. If winter snow accumulation has decreased or the insulating properties of snow have changed in recent years, this could be an explanation for the cooling trend observed in soil temperature. Consistent with this hypothesis, the strongest cooling trends have been observed in winter and spring, when snow accumulation is generally highest. However, the absence of data on snow depth before 2001 on Bylot Island does not allow us to test this hypothesis. Weak cooling trends in soil temperature were also observed in summer and autumn when snow accumulation on the ground is absent or relatively thin, so other factor may also be involved. During these seasons, solar radiation or the amount of moisture in the ground may be important in affecting soil temperature. Finally, it should be pointed out that this analysis rests on measurement taken at a single site. Future analyses should aim at cross-validating these trends in soil temperatures at our other stations. These analyses nonetheless suggest that complex interactions may take place between several climatic variables.

In contrast to temperature, we did not detect consistent trends in precipitation. A weak increasing trend in summer rainfall was detected at Nanisivik but not Pond Inlet. This may be partly explained by the relatively large amount of summer precipitation falling as snow in Nanisivik in contrast to Pond Inlet. It is possible that the warming trend in air temperature

observed in summer may have increased the proportion of precipitation falling as rain at the expense of snow at Nanisivik. The weak decreasing trend in snowfall detected at Pond Inlet in autumn could also be related to the warming trend that was observed (i.e. a higher proportion of precipitation falling as rain rather than snow in recent years). Curiously, despite this decreasing trend in autumn snowfall, a weak increasing trend in average winter snow depth was detected at Pond Inlet. The larger inter-annual variability in precipitation than in temperature may hinder the detection of long-term trends for this parameter. Thus, longer time series may be required to better assess long-term trends.

Another detected trend that is somewhat surprising is the strong decline in average summer wind speed. One could have expected the opposite because the observed summer warming trend could have increased spatial variability in temperature, and thus generated more wind. However, if cloud cover has also increased, this may have contributed to reduced wind. Future analyses should examine this pattern in more details in order to determine if this decrease in average wind speed is due to a reduction in the number of days with noticeable wind, a general reduction in wind speed, a reduction in maximum wind speed, or a combination of all these factors.

### **5.3 Temporal trends in the ecosystem**

The most significant temporal change that has occurred in the terrestrial ecosystem of Bylot Island is the large increase in the Greater Snow Goose population. The increase observed on Bylot Island over the past 2 decades has followed the same trend than the increase observed for the population as a whole (Menu et al. 2002, Reed et al. 2002). The causes of population increases in geese are complex but have apparently little to do with events occurring in the Arctic. Changes in agricultural practices in southern Canada and the US have encouraged geese to switch from feeding in natural marshes to agricultural lands in winter and during spring migration over the second half of the XX<sup>th</sup> century, and this appears to be the primary causes for increases in snow goose populations (Jefferies et al. 2003, Gauthier et al. 2004b). The food subsidy that geese receive while feeding in farmlands enhanced winter survival and enabled geese to arrive in the Arctic with improved body condition, allowing them to attenuate density-dependent effects on reproduction. Thus, because of migratory connectivity (Webster et al. 2002,



Jefferies et al. 2004), events occurring thousand of kilometers away from the Arctic (i.e. change in agricultural practices in the south) may have a large impact on the terrestrial arctic ecosystem.

In contrast to other goose populations elsewhere in the Arctic (e.g. Lesser Snow Geese, *Chen caerulescens caerulescens*, along west Hudson Bay; Jano et al. 1998), Greater Snow Geese have not exceeded yet the theoretical carrying capacity of wetlands of Bylot Island (Massé et al. 2001). Our data nonetheless show that geese consume a high proportion of annual plant production in wetlands of Bylot Island, especially for *Eriophorum* (Gauthier et al. 1995, this report). Detailed analyses have shown that intense goose grazing reduces the annual production of *Eriophorum* and changes the specific composition in wetlands (Gauthier et al. 2004a,c). Although wetlands are the preferred habitats of geese on Bylot Island (Hughes et al. 1994a,b), a significant amount of grazing also occurs in mesic communities (Duclos 2002). Future monitoring should therefore aim at determining the impact of goose grazing in this habitat.

The large cyclical fluctuations of lemming populations also have a strong influence on the terrestrial ecosystem of Bylot Island. The causes of these population cycles still remain controversial, although either specialized plant-herbivore (Turchin et al. 2000) or predator-prey interactions (Gill et al. 2003) may be the primary cause. On Bylot Island, we have little evidence that lemmings have a strong impact on the vegetation even in years of peak abundance, and thus a predator-prey interaction may be a more plausible explanation for these cycles (Gauthier et al. 2004b). Our data show that lemmings have a strong impact on the local abundance and reproduction of predators such as arctic foxes and Snowy Owls. Previous analyses have also revealed indirect interactions between lemmings and other herbivores like geese due to shared predators. Indeed, when lemmings crash, predators will turn to other source of foods such as goose eggs, leading to very high predation rate on geese in those years, whereas the reverse is true in years of high lemming abundance (Bêty et al. 2002, Gauthier et al. 2004a). However, the role of predators in shaping and even driving the lemming cycle in this community remains to be shown. Furthermore, the effect on predator populations and on predator-lemming interactions of an abundant alternative prey such as geese that has increased considerably in recent decades is also unknown. Changes in the lemming cycles may have important effects on the terrestrial ecosystem, as was reported in northern Sweden where lemming cycles disappeared during several decades (Angerbjörn et al. 1995). However, such changes can only be detected by a long-term

monitoring program (i.e. more than a decade) due the 3 to 4-year periodicity of the lemming cycle.

#### **5.4 Relationships between climatic factors and biological variables**

Our preliminary analyses between climatic and biological variables revealed several links. The strongest links were found between the phenology of reproduction in several bird and plant species and air temperature or snow-melt pattern. Phenological adjustments of species in response to annual climatic variations largely depend of their phenotypic plasticity and provide an indication of their capacity to respond to directional changes resulting from climate warming (Berteaux et al. 2004). The strong influence of some climatic variables on the reproduction of Greater Snow Geese and Lapland Longspurs suggest that several arctic species may have the ability to adapt to climate change in the short term. However, this response may not be universal as suggested by the study of Crick et al. (1997) which showed that some but not all bird species advanced their nesting phenology in response to the warming trend that occurred in the British Isles during the XX<sup>th</sup> century.

Several factors may limit the capacity of species to respond to climate change. The situation may be especially problematic in migratory species like birds if climate change occurs at different rates in different part of the annual range of the species. For instance, most GCMs predict a stronger warming of the climate in the polar regions than in temperate areas where most arctic bird species winter. Therefore, if the bird migration schedule of birds remains unchanged due to an absence of climate warming at their wintering or spring staging site in temperate areas, then their arrival time on the arctic breeding site may not be advanced, thus greatly limiting their ability to adjust their reproductive phenology to the changing arctic climate. Such limitations have already been documented in passerines birds breeding in temperate Europe, where climate has warmed, and wintering in tropical areas where climate has not changes (Both and Visser 2001).

Another problem is that the impact of climate warming will not be felt equally by all species, especially across trophic levels, and this may result in a mismatch between some species and their food resources. For instance, many biological processes, be it bird reproduction, the onset of plant growth or the onset of insect development, are conditioned by snow-melt in spring,

as shown by several relationships in this report. However, once initiated, the speed of bird reproduction is not influenced by climate due to physiological constraints (e.g. the time to lay a given number of eggs or the incubation time to hatch is fixed in birds). In contrast, plant growth or insect development will be accelerated in response to elevated temperature (e.g. the accumulation of degree-days) as we found on Bylot Island. The consequence may be that the period of peak food demand, which occurs after hatch during the period that young chicks are growing, may no longer match with the period that food quality is highest (e.g. at the beginning of plant growth for young geese, Lepage et al. 1998) or most abundant (e.g. the period of insect emergence in passerine birds like buntings). Again, such phenomenon has recently been documented in Europe where climate warming has advanced the date of peak insect availability but not the nesting phenology of a passerine bird, and this had an adverse effect on bird reproduction due to the mismatch between the timing of peak food demand and availability (Sanz et al. 2003)

Even though phenological adjustments may be the most immediate response of species to climate warming, eventually change in abundance or distribution may occur. Our analyses showed that plant production in wetlands of Bylot Island is in part limited by temperature as production was generally higher in years where temperature in July was warmer. This suggests that local plant abundance may respond relatively rapidly to climate change. In contrast, because animals have greater dispersal ability than plants, their distribution may change more rapidly than plants. An interesting situation is the one of Arctic and red foxes. The red fox is a relatively newcomer in the Arctic, as this species apparently invaded Baffin Island from south to north only during the XX<sup>th</sup> century (MacPherson 1964). On Bylot Island, red fox is at the northern limit of its actual range in Canada and our data shows that it is much less abundant than arctic fox. However, red fox could potentially benefit from the current warming trend by expanding further its distribution in the Arctic and increasing its abundance at the expense of arctic fox. Because red fox is larger than arctic fox, it may be a superior competitor than arctic fox when both species compete for food or denning sites. In northern Sweden, arctic fox has been almost completely replaced by red fox, although the causes of this replacement are poorly known (Tannerfeldt et al. 2002)

## 6 CONCLUSIONS

Our analyses revealed that the North Baffin area is currently experiencing a detectable warming trend like many other arctic regions. However, we did not find consistent trends in precipitations, though the data were not as good as for temperature. We also showed that these trends were not uniform across seasons, and that various climatic parameters (e.g. air temperature, ground temperature, wind speed, precipitations and snow cover) were affected differently. Biological variables related to phenology, and especially the phenology of reproduction, were those that were most strongly related to climatic variables. These variables, which are also relatively easy to monitor, should thus receive most attention because they should allow early detection of the impacts of climate warming on ecosystems. Even though we provided evidence of the influence of climatic variables on several biological variable, predicting the impacts of climate warming on arctic ecosystems is complex because biological systems may be affected by the climate in several ways, both directly and indirectly (e.g. though effects on higher or lower levels of the food web). Furthermore, different components of the biota may be affected at different rates, further affecting interactions among species or trophic levels. Our database on greater snow goose reproduction, which is our largest and longest monitoring program on Bylot Island, will be very helpful in the short-term to uncover some of these complex interactions (an in depth analysis of the links between all stages of goose reproduction and several climatic variables is currently the topic of a Master student thesis at Université Laval). With the continuation of our monitoring program planned for the coming years, updates of the climatic trends revealed in this report will be possible, and further analyses of links between various climate variables and other biological components (e.g. plants, other bird species, and mammals) will become possible. This should further our understanding of climate impacts on arctic regions, and assist decision-makers in their policies.

## 7 REFERENCES

- Allard, M., B. Wang & J. Pilon. 1995. Recent cooling along the southern shore of Hudson Strait, Québec, Canada, documented from permafrost temperature measurements. *Arctic and Alpine Research* 27:157-166.
- Angerbjörn, A., M. Tannerfeldt, A. Bjärvall, M. Ericson, J. From, & E. Norén. 1995. Dynamics of the arctic fox population in Sweden. *Annales Zoologici Fennici* 32:55-68.
- Balling, R.C. 1997. Analysis of daily and monthly spatial variance components in historical temperature records. *Physical Geography* 18:544-552.
- Balling, R.C., P.J. Michaels, & P.C. Knappenberger. 1998. Analysis of winter and summer warming rates in gridded temperature time series. *Climate Research* 9:175-181.
- Batt, B.D.J. (ed.). 1998. The Greater Snow Goose: report of the Arctic Goose Habitat Working Group. Arctic Goose Joint Venture Special Publication, U.S. Fish and Wildlife Service, Washington, D.C. and Canadian Wildlife Service, Ottawa, Ontario.
- Beauvais, G.P. & S.W. Buskirk. 1999. Modifying estimates of sampling effort to account for sprung traps. *Wildlife Society Bulletin* 27: 39-43.
- Berteaux, D., D. Réale, A. G. McAdam & S. Boutin. 2004. Keeping pace with fast climate change: can arctic life count on evolution? *Integrative and Comparative Biology* (in press).
- Bêty, J. & G. Gauthier. 2001. Effects of nest visits on predators activity and predation rate in a snow goose colony. *Journal of Field Ornithology* 72:573-586.
- Bêty, J., G. Gauthier, & J.-F. Giroux. 2003. Body condition, migration and timing of reproduction in snow geese: a test of the condition-dependent model of optimal clutch size. *American Naturalist* 162:110-121.
- Bêty, J., G. Gauthier, E. Korpimäki & J.-F. Giroux. 2002. Shared predators and indirect trophic interactions: lemming cycles and arctic-nesting geese. *Journal of Animal Ecology* 71:88-98.
- Both, C. & M. E Visser. 2001. Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. *Nature* 411:296-298.
- Climatic Research Unit. 1992. World Climate Disc. Grid-box temperature dataset. University of East Anglia, Norwich, UK.
- Crick, H. Q. P., C. Dudley, D. E. Glue & D. L. Thomson. 1997. UK birds are laying eggs earlier. *Nature* 388:526-526.
- Duclos, I. 2002. Milieux mésiques et secs de l'île Bylot, Nunavut (Canada): Caractérisation et utilisation par la Grande Oie des neiges. Msc. Thesis, Université du Québec à Trois-Rivières, Trois-Rivières, PQ, Canada.

- Féret, M., G. Gauthier, A. Béchet, J.-F. Giroux & K. Hobson. Effect of a spring hunt on nutrient storage by greater snow geese in southern Québec. *Journal of Wildlife Management* 67:796-807.
- Gauthier, G., J. Bêty, J.-F. Giroux, & L. Rochefort. 2004a. Trophic interactions in a High Arctic Snow Goose colony. *Integrative and Comparative Biology* (in press).
- Gauthier, G., J.-F. Giroux, A. Reed, A. Béchet & L. Bélanger. 2004b. Interactions between land use, habitat use and population increase in greater snow geese: what are the consequences for natural wetlands? *Global Change Biology* (submitted).
- Gauthier, G., J.-F. Giroux & L. Rochefort. 2004c. The impact of goose grazing on arctic and temperate wetlands. *Proceedings XXIII<sup>rd</sup> International Ornithological Congress, Beijing, China* (in press).
- Gauthier, G., R.J. Hughes, A. Reed, J. Beaulieu & L. Rochefort. 1995. Effect of grazing by greater snow geese on the production of graminoids at an arctic site (Bylot Island, NWT, Canada). *Journal of Ecology* 83:653-664.
- Gauthier, G., E. Lévesque, M.-C. Cadieux, and C. Gagnon. 2004d. A compendium of protocols used for ecological monitoring on Bylot Island, Sirmilik National Park of Canada. Unpublished report, Centre d'études nordiques, Université Laval.
- Gauthier, G., L. Rochefort & A. Reed. 1996. The exploitation of wetland ecosystems by herbivores on Bylot Island. *Geoscience Canada* 23:253-259.
- Gilg, O., L. Hanski & B. Sittler. 2003. Cyclic dynamics in a simple vertebrate predator-prey community. *Science* 302:866-868.
- Hansell, R.I.C., J.R. Malcolm, H. Welch, R.L. Jefferies & P.A. Scott. 1998. Atmospheric change and biodiversity in the Arctic. *Environmental Monitoring and Assessment* 49:303-325.
- Hughes, R.J., G. Gauthier & A. Reed. 1994. Summer habitat use and behaviour of greater snow geese *Anser caerulescens atlanticus*. *Wildfowl* 45:49-64.
- Jano, A.P., R.L. Jefferies & R.F. Rockwell. 1998. The detection of vegetational change by multitemporal analysis of LANDSAT data: the effects of goose foraging. *Journal of Ecology* 86:93-99.
- Jefferies RL, H.A.L. Henry & K.F. Abraham. 2002. Agricultural nutrient subsidies to migratory geese and ecological change to Arctic coastal habitats. *In* G.A. Polis, M.E. Power & G.R. Huxel, *Food Webs at the Landscape Level* (eds.). University of Chicago Press, Chicago, USA.
- Jefferies, R.L., R.F. Rockwell & K.F. Abraham. 2004. Agricultural food subsidies, migratory connectivity and large-scale disturbance in Arctic coastal systems: a case study. *Integrative and Comparative Biology* (in press).

- Lepage, D., D. N. Nettleship & A. Reed. 1998. Birds of Bylot Island and adjacent Baffin Island, Northwest Territories, Canada, 1979 to 1997. *Arctic* 51:125-141.
- MacPherson, A. H. 1964. A northward range extension of the red fox in the eastern Canadian arctic. *Journal of Mammalogy* 45:138-140.
- Mainguy, J., J. Bêty, G. Gauthier & J.-F. Giroux. 2002. Are body condition and reproductive effort of laying greater snow geese affected by the spring hunt? *Condor* 104:156-162.
- Manseau, M. & G. Gauthier. 1993. Interactions between greater snow geese and their rearing habitat. *Ecology* 74:2045-2055.
- McCarty, J.P. 2002. Ecological consequences of recent climate changes. *Conservation Biology* 15:320-331.
- Massé, H., L. Rochefort & G. Gauthier. 2001. Carrying capacity of wetland habitats used by breeding greater snow geese. *Journal of Wildlife Management* 65:271-281.
- Menu, S., G. Gauthier & A. Reed. 2001. Survival of juvenile greater snow geese immediately after banding. *Journal of Field Ornithology* 72:282-290.
- Menu, S., G. Gauthier & A. Reed. 2002. Changes in survival rates and population dynamics of greater snow geese over a 30-year period: implications for hunting regulations. *Journal of Applied Ecology* 39:91-102.
- Molau, U. & P. Mølgaard (eds.). 1996. International Tundra Experiment, ITEX manual. 2<sup>nd</sup> edition. Danish Polar Institute, Copenhagen.
- Moritz, R. E., C. M. Bitz & E. J. Steig. 2002. Dynamics of recent climate change in the Arctic. *Science* 297:1497-1502.
- Reed, A. & P. Chagnon. 1987. Greater snow geese on Bylot Island, Northwest territories, 1983. *Journal of Wildlife Management* 51:128-131.
- Reed, A., H. Boyd, P. Chagnon & J. Hawkings. 1992. The numbers and distribution of greater snow geese on Bylot Island and near Jungersen Bay, Baffin Island, in 1988 and 1983. *Arctic* 45:115-119.
- Reed A., R.J. Hughes & H. Boyd. 2002. Patterns of distribution and abundance of Greater Snow Geese on Bylot Island, Nunavut, Canada 1983-1998. *Wildfowl* 53:53-65.
- Reed, A., J.-F. Giroux & G. Gauthier. 1998. Population size, productivity, harvest and distribution. In B.D.J. Batt (ed.), *The Greater Snow Goose: report of the Arctic Goose Habitat Working Group*, pp. 5-31. Arctic Goose Joint Venture Special Publication, U.S. Fish and Wildlife Service, Washington, D.C. and Canadian Wildlife Service, Ottawa, Ontario.
- Reed, E.T., J. Bêty, J. Mainguy, G. Gauthier & J.-F. Giroux. 2003. Molt migration in relation to breeding success in greater snow geese. *Arctic* 56:76-81.

- Reed, E.T., G. Gauthier & J.-F. Giroux. 2004. Effects of spring conditions on breeding propensity of greater snow goose females. *Animal Biodiversity Conservation* (In press).
- Rowntree, P.R. 1997. Global and regional patterns of climate change: recent predictions for the Arctic. *In* W. Oechel, T. Callaghan, T. Gilmanov, J.I. Holten, B. Maxwell, U. Molau & B. Sveinbjörnsson (eds.), pp. 82-109. *Global change and arctic terrestrial ecosystems. Ecological Studies, Vol 124.* Springer, Berlin.
- Rowntree, P.R., J.M. Murphy & J.F.B. Mitchell. 1993. Climatic change and future rainfall predictions. *Journal of the Institution of Water and Environmental Management* 7:464-470.
- Sanz, J. J., J. Potti, J. Moreno, S. Merino & O. Frías. 2003. Climate change and fitness components of a migratory bird breeding in the Mediterranean region. *Global Change Biology* 9:461-472.
- Shank, C.C. 1993. The Northwest Territories small mammal survey: 1990-1992. Manuscript Report No 72. Department of Renewable Resources, Government of the Northwest Territories, Yellowknife, NWT.
- SAS Institute Inc. 1999. SAS/STAT User's Guide, version 8.0. SAS Institute, Cary, North Carolina.
- Skinner, W. R., R. L. Jefferies, T. J. Carleton, R. F. Rockwell & K.F. Abraham. 1998. Prediction of reproductive success and failure in lesser snow geese based on early season climatic variables. *Global Change Biology* 4:3-16.
- Tannerfeldt, M., B. Elmhagen & A. Angerbjörn. 2002. Exclusion by interference competition? The relationship between red and arctic foxes. *Oecologia* 132:213-220.
- Turchin, P., L. Oksanen, P. Ekerholm, T. Oksanen & H. Henttonen. 2000. Are lemmings prey or predators? *Nature* 405:562-565.
- Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett & V.F. Zakharov. 1999. Global warming and Northern Hemisphere Sea Ice Extent. *Science* 286:1934-1937.
- Walsh, J. E. 1993. The elusive Arctic warming. *Nature* 361:300-301.
- Webster, M. S., P. P. Marra, S. M. Haig, S. Bensch & R. T. Holmes. 2002. Links between worlds: unraveling migratory connectivity. *Trends in Ecology and Evolution* 17: 76-83.
- Weller, G. 1998. Regional impacts of climate change in the Arctic and Antarctic. *Annals of Glaciology* 27:543-552.