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ASPECTS OF BOREAL FOREST HYDROLOGY: FROM STAND TO WATERSHED

Bart Nijssen

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ABSTRACT

This report evaluates land surface hydrologic processes in the boreal forest using observations collected during the Boreal Ecosystem Atmosphere Study (BOREAS), carried out in the boreal forest of central Canada from 1994 to 1996.. Three separate studies, each of which constitutes a journal publication, are included. The first study describes the application of a spatially-distributed hydrologic model, originally developed for mid-latitude forested environments, to selected BOREAS flux measurement sites. Compared to point observations at the flux towers, the model represented energy and moisture fluxes reasonably well, but shortcomings were identified in the soil thermal submodel and the partitioning of evapotranspiration into canopy and subcanopy components. As a first step towards improving this partitioning, the second study develops a new parameterization for transmission of shortwave radiation through boreal forest canopies. The new model accounts for the transmission of diffuse and direct shortwave radiation and accounts for multiple scattering in the canopy and multiple reflections between the canopy layers. Simulated sub-canopy radiation compared well with observations at a mature jack pine site, but errors were larger at a mature black spruce site. Absolute model errors were small in all cases compared to above-canopy radiation. The final study evaluates the origin of apparent water balance anomalies in the White Gull Creek Basin in the BOREAS Southern Study area during the 1994--1996 period, with particular emphasis on the fate of precipitation that occurred during an unusually wet period during July, 1994. Although precipitation was balanced by evapotranspiration and runoff in 1995 and 1996, it exceeded the sum of the latter two terms by 89 mm in 1994. Because field observations did not suggest

increased storage at the end of the 1994 growing season, it seems likely that most of the excess precipitation evaporated when the basin was extremely wet after the heavy precipitation in July 1994. This suggests that the evaporative fluxes measured at the BOREAS flux towers may have under-represented the flux from the larger area during periods when the basin was very wet.

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ACKNOWLEDGMENTS

The research described in this report is based on the Ph.D. dissertation of the author, funding for which was provided by a grant No. NASG 5-7300 from the National Aeronautics and Space Administration under the BOREAS (BOReal Ecosystem-Atmosphere Study) project. The field data used in this study were collected by a number of BOREAS investigators. J.-L. Roujean of Centre National de la Recherche Scientifique, Toulouse, France provided the below-canopy PAR[1] data sets for summer 1994 used in Chapter 4. W. Ni[2] of Raytheon STX (Lanham, MD) provided the GORT results shown in Figure 4.2. Streamflow and precipitation data used in Chapters 3 and 5 were collected by R. Soulis and N. Kouwen from the Department of Civil Engineering, University of Waterloo, Ontario, Canada. The southern study area snow course data used in Chapter 5 were collected by M. Dalman, P. Pacholek, and V. Heap for Atmospheric Environment Service, Canada. R. E. Davis and J. P. Hardy of the U. S. Army Corps of Engineers Cold Regions Research Engineering Laboratory (Hanover, NH) provided the below-canopy radiation data sets for winters 1994 and 1996 used in Chapter 4, as well as snow data used in Chapter 5. Meteorological measurements collected by the Saskatchewan Research Council were used throughout the study. Mature black spruce tower *flux* data used in Chapters 3 and 5 were collected by P. G. Jarvis, J. M. Massheder, J. B. Moncrieff, M. B. Rayment, S. Hale, and S. Scott of the Institute of Ecology and Resource Management, Edinburgh University, Scotland. Mature black spruce flux data in the northern study area used in Chapter 3 were collected by S. C. Wofsy, J. W. Munger, B. C. Daube, M. L. Goulden, K. A. Boering, and J. D. Burley from the Division of Engineering and Applied Sciences at Harvard University. Mature aspen flux data (Chapter 5) were collected and processed in 1994 by G. den Hartog and H: H. Neumann of Atmospheric Environment Service, Canada, and in 1996 by T. A. Black and Z. Nesic of the University of British Columbia, Canada. Mature jack pine flux measurements (Chapters 3 and 5) were obtained and prepared by D. Baldocchi and C. Vogel of the Atmospheric Turbulence and Diffusion Division, NOAA, Oak Ridge, Tennessee. Flux data at the fen site (Chapter 5) were collected by S. B. Verma and his colleagues of the University of Nebraska-Lincoln. The young aspen data (Chapter 5) were collected by P. Bessemoulin, D. Puech, G. Bouhours, G. Lachaud, E. Gizard and J. Marcel of the Centre National de Recherches Meteorologiques, Toulouse, France. Flux data at the young jack pine site (Chapter 5) were collected and processed by D. Anderson, R. Striegl, and K. Wickland of the United States Geological Survey. The efforts of NASA Goddard Space Flight Center staff in processing and archiving the data are greatly appreciated.

[1]PAR – photosynthetically active radiation

[2]Now at: Department of Geography, University of Maryland, College Park, Maryland

DEDICATION

This work is dedicated to my parents, J.M. Nijssen and M.G.C. Nijssen-Hermans, who never failed to encourage me.

Chapter 1

INTRODUCTION

This dissertation presents three studies of hydrological processes in the boreal forest, the circumpolar belt of high-latitude forest in Eurasia and North America that generally lies between 50°N and 70°N. Interest in the relationship between the boreal forest and the global climate system has heightened in recent years because the predicted amount of global warming is generally greater in this region than elsewhere globally, and because the region plays an important role in the global carbon cycle. The Boreal Ecosystem Atmosphere Study (BOREAS) was initiated in 1992 to study the interaction between the boreal forest and the global climate system. Data collection for this experiment took place from 1993–1996 at two sites in the boreal forest of Central Canada, resulting in a large, coherent data set of atmosphere, vegetation, and soil characteristics. The BOREAS project, the physical and hydrologic characteristics of the boreal forest, and the interaction between the boreal forest and the climate system are the topic of Chapter 2.

One of the main objectives of the BOREAS project was to collect observations that would support development and testing of process models that describe the exchanges of radiative energy, water, heat, carbon, and trace constituents between the boreal forest and the atmosphere [*Sellers et al.*, 1995]. The original intent of the reported research was to adapt a spatially-distributed, physically-based hydrological model for application in the boreal forest. Chapter 3 describes the application of the distributed hydrology-soil-vegetation model (DHSVM) [*Wigmosta et al.*, 1994] to specific locations in the BOREAS area, in order to identify the strengths and weaknesses of this model. Applied as a point model, DHSVM demonstrated considerable skill in simulating the observed energy and mositure fluxes, although shortcomings were identified in the soil thermal submodel and the partitioning of evapotranspiration into its canopy and subcanopy components. This chapter was published in 1997 as B. Nijssen, I. Haddeland, and D. P. Lettenmaier, Point evaluation of a surface hydrology model for BOREAS, *J. Geophys. Res.*, *102*, 29,367–29,378, 1997.

As a first step towards improvement of both the soil thermal model and the division of evapotranspiration between the soil and vegetation layers, a better representation of the transmission of shortwave radiation through the boreal forest canopy was developed. Simultaneous above and below canopy radiation measurements are only rarely made, largely because the subcanopy radiation environment is usually highly variable, both in space and time. The availability of such measurements as part of the BOREAS project allowed the development of a simple radiation transmission model, which accounts for canopy geometry and solar zenith angle. The development of this model and the evaluation of its performance for two different boreal forest types are the subject of Chapter 4. This chapter was published in 1999 as B. Nijssen and D. P. Lettenmaier, A simplified approach for predicting shortwave radiation transfer through boreal forest canopies, *J. Geophys. Res.*, *104*, 27,859–27,868, 1999.

Early application of DHSVM in a spatially-distributed mode over the White Gull Creek basin in the BOREAS southern study area for the 1994 growing season showed that the main model response to a large rainfall event in July 1994 :onsisted of a greatly overestimated runoff peak [*Nijssen et al.*, 1996]. Whereas peak runoff of 25.4 m^3/s was observed on July 21, 1994 following heavy precipitation on July 18–19, modeled discharge reached a peak as high as 76.4 m^3/s on July 23. Not only was the runoff peak overestimated, but the total amount of runoff during and following the heavy precipitation in July 1994 was overpredicted as well. During the period from July 13–August 5, 1994 128.3 mm of precipitation fell on the White Gull Creek basin. While the observed areal average runoff for this same period was 35.6 mm, the predicted runoff was 76.8 mm, even though DHSVM modeled the evapotranspiration at the towers to within 10% when run at the flux tower sites. The discrepancy between these two results is an important issue in scaling the results from the flux towers to the watershed and beyond. If the precipitation did not

Chapter 2

BOREAS AND THE BOREAL FOREST

2.1 The Boreal Ecosystem-Atmosphere Study

2.1.1 Large-Scale Field Experiments

The Boreal Ecosystem Atmosphere Study (BOREAS) was initiated in 1992 as part of the International Satellite Land Surface Climatology Project (ISLSCP), which in turn is sponsored by the World Climate Research Program - Global Energy and Water Cycle Experiment (WCRP-GEWEX). BOREAS was a large-scale international research program, designed to improve understanding of the exchange of energy, moisture and trace gases, between the boreal forest and the atmosphere. BOREAS initially included 85 science teams, mostly from the United States and Canada. Funding for most American investigators was provided by the National Aeronautics and Space Administration (NASA), with participation from the National Oceanographic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the United States Geological Survey (USGS), and the Environmental Protection Agency (EPA). Participating Canadian agencies included the Canada Centre for Remote Sensing (CCRS), Environment Canada, the Natural Sciences and Engineering Research Council (NSERC), Agriculture Canada, the National Research Council (NRC), Heritage Canada (Parks), the Canadian Forest Service, the Institute for Space and Terrestrial Science, and the Royal Society of Canada. Although some activities started in 1993, the main BOREAS field activities took place in 1994 and in 1996. Some monitoring activities were continued in 1995. *Sellers et al.* [1995] provide a good overview of the BOREAS project.

One of the main obstacles to the improvement of land-surface parameterizations and the evaluation of land-surface models is a lack of appropriate observations [*Gates et al.*, 1996]. To address result in additional runoff or evapotranspiration, then where was it stored? *Suyker et al.* [1997] reported that the water level in a wetland in the southern study area rose by 10 cm following the storm of July 18–19, but dropped to pre-storm levels by August 5. The same rise and fall was observed in the streamflow hydrographs. To explore what happened to this "missing" water, it was decided that rather than attempting further model refinements, a better understanding of catchment scale processes would result from a careful analysis of the water balance of the White Gull Creek basin for the 1994–1996 observation period. This water balance study is the topic of Chapter 5.

The results from the three studies are summarized in Chapter 6. This last chapter also presents the conclusions and some recommendations for further research.

this issue a number of large-scale field experiments have been executed in different climatic regions around the globe. The first of these experiments was HAPEX-MOBILHY (Hydrologic Atmospheric Pilot Experiment - Modelisation du Bilan Hydrique) which was conducted in a 100×100 km mixed forest and cropland site in southwestern France from 1985 till 1987 under the auspices of the WCRP [*André et al.*, 1986]. This experiment was conducted to provide [*André et al.*, 1986]

> "a data base of hydrological, pedological, surface, and atmospheric parameters against which it will be possible to test and develop parameterization schemes of hydrological budget and evaporation flux to be implemented in atmospheric GCMs".

The International Satellite Land Surface Climatology Project organized a similar experiment in a 15×15 km prairie grassland site near Manhattan, Kansas, with field phases in 1987 and 1989 [*Sellers et al.*, 1992]. The main objectives of the First ISLSCP Field Experiment (FIFE) were to gain a better understanding of the biologic controls on land surface-atmosphere interactions, and to investigate the use of satellites observations for inferring climatologically significant land surface parameters [*Sellers et al.*, 1992]. This project was followed by the European Field Experiment in Desertification-Threatened Areas (EFEDA) in Central Spain in 1991 [*Bolle*, 1993], the HAPEX-Sahel project in Northern Africa in 1993 [*Goutorbe et al.*, 1997], the Northern Hemisphere Climate Processes Land-Surface Experiment (NOPEX) in Central Sweden [*Haldinn et al.*, 1998], BOREAS [*Sellers et al.*, 1995], and the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) in Brazil with the main field phase from 1998 till 2000 [*LBA Science Planning Group*, 1996].

Although each of these projects focused on a different geographical region, and consequently addressed somewhat different research questions, they all were designed to:

1. Gain a better understanding of the role of land surface processes in the climate system.
2. Develop parameterizations of the important land surface processes at the scale at which climate and weather models are applied (on the order of 10^3–10^4 km^2).

3. Develop methods to infer climatologically important land surface parameters from remote sensing observations.

The research reported here was conducted as part of BOREAS, for which the central scientific issues were defined as:

1. The sensitivity of the boreal forest biome to changes in the physical climate system.

2. The carbon cycle and biogeochemistry in the boreal forest.

3. Biophysical feedbacks between the boreal forest and the physical climate system.

The limited field observation period of BOREAS made it impossible to measure the ongoing effects of climate change on the boreal forest ecosystem directly. Instead, the experiment focused on data collection that would allow the development and testing of process models that in turn could be applied to evaluate the effect of global change on the boreal forest. Thus the experimental objectives of BOREAS were described as [*Sellers et al.*, 1995]:

1. Improve the process models that describe the exchanges of radiative energy, water, heat, carbon, and trace constituents between the boreal forest and the atmosphere.

2. Develop methods for applying the process models over larger areas using remote sensing and other integrative techniques.

2.1.2 Experimental Setup

The experimental setup of BOREAS was geared towards measuring moisture, energy, and trace gas fluxes between the boreal forest and the atmosphere over a range of spatial and temporal scales. These measurements were carried out for the most representative vegetation types in the region. and under different climatic conditions. The measurement strategy was similar to the one developed for FIFE [*Sellers et al.*, 1992] and HAPEX-Sahel [*Goutorbe et al.*, 1997].

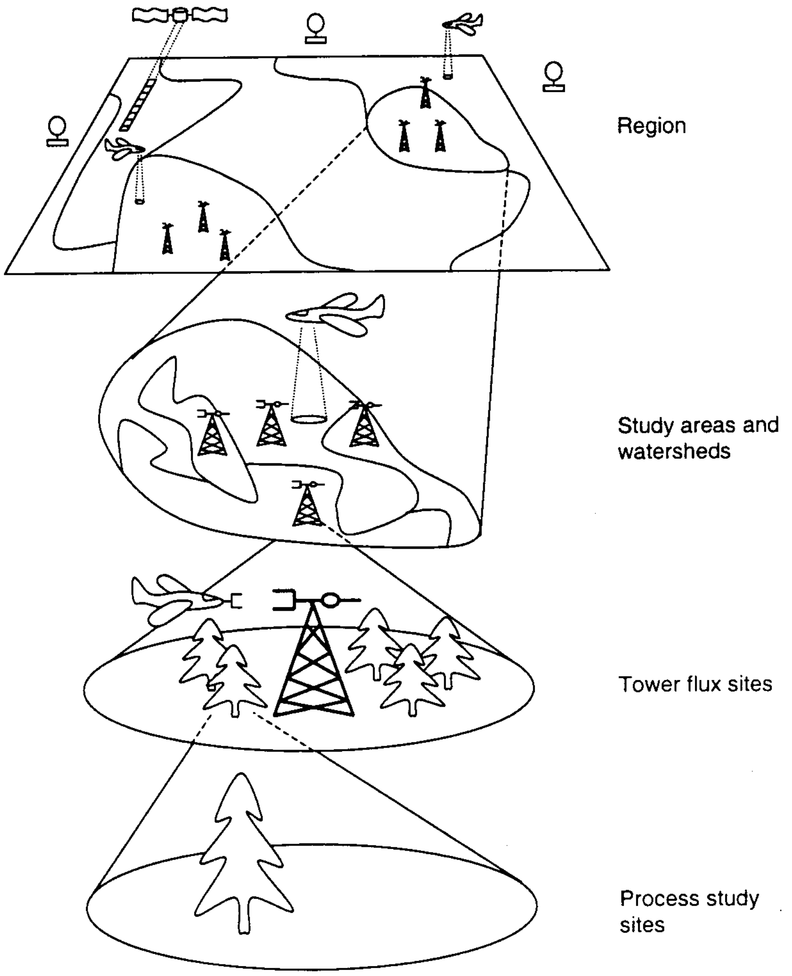


Figure 2.1: BOREAS scale domains.

A nested approach was used to integrate observations and models over a range of spatial scales. The scale domains were defined as illustrated in Figure 2.1:

Region: The region consisted of a roughly 1000 km$\times$1000 km area in central Canada (Figure 2.2), covering 18 degrees of longitude (94°W to 111°W) and 9 degrees of latitude (51°N to 60°N). This area covered most of the central and northern parts of Saskatchewan and Manitoba. The region was the domain for satellite remote sensing, meteorological data

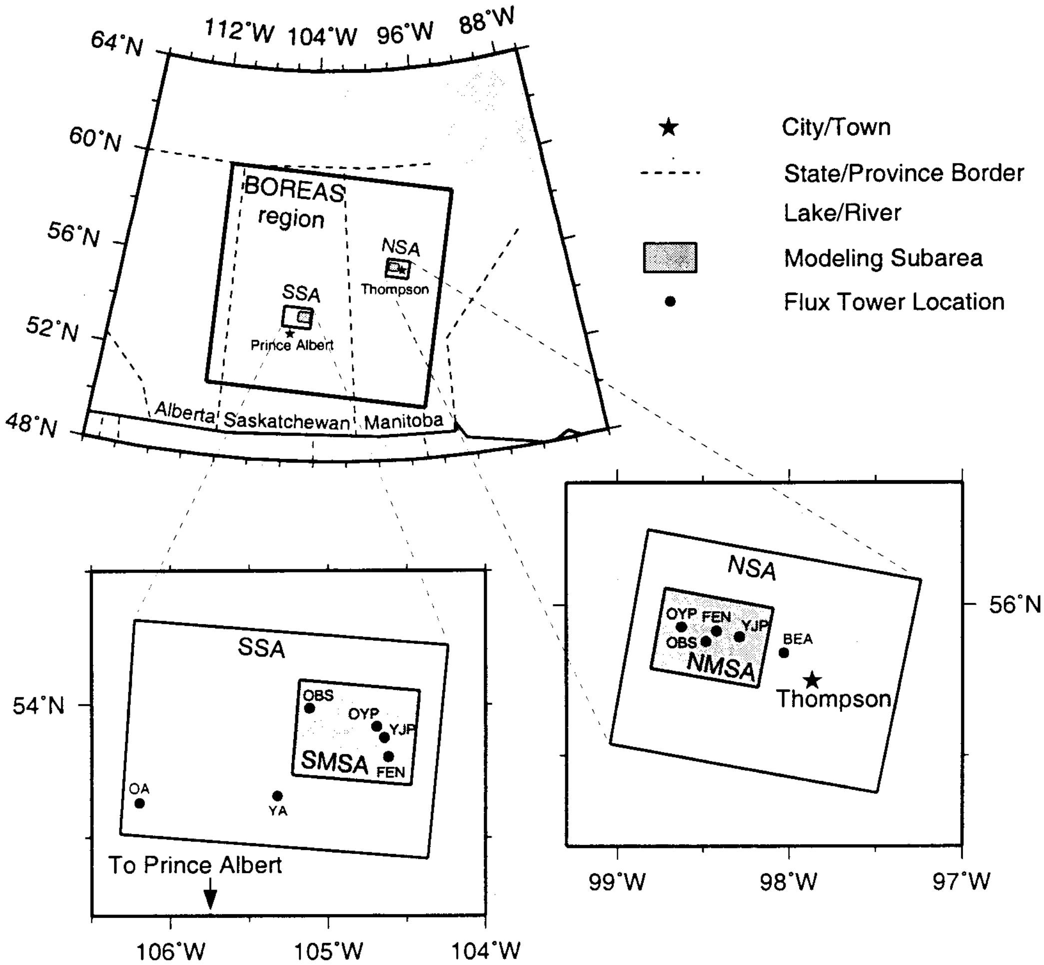
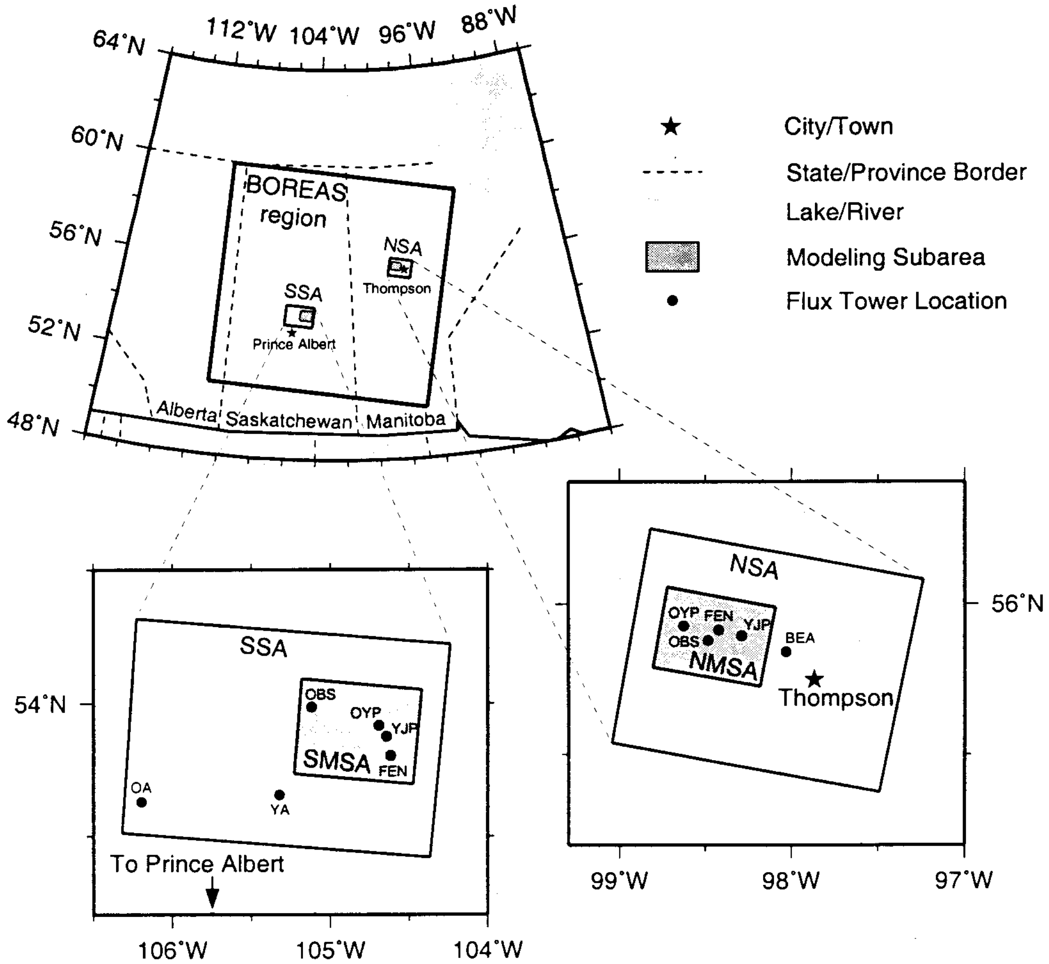


Figure 2.2: BOREAS region and study areas in Central Canada. SSA: southern study area, NSA: northern study area, SMSA: southern modeling subarea, NMSA: northern modeling subarea, OA: old (mature) aspen, YA: young aspen, OJP: old (mature) jack pine, YJP: young jack pine, FEN: fen, OBS: old (mature) black spruce, BEA: beaver pond.

acquisition, and large-scale modeling, and was large enough to occupy several GCM[1] grid cells.

Study areas: The study areas were located in the region (Figure 2.2), and were the focus of satellite and airborne remote sensing studies, airborne flux measurements, and meso-scale

[1]GCM: General Circulation Model



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modeling. Two study areas were selected, one near the northern limit of the boreal forest near Thompson, Manitoba, and one near the southern limit of the boreal forest near Prince Albert, Saskatchewan. The northern study area (NSA) measured about 100 km$\times$80 km (Figure 2.2), and the southern study area (SSA) measured about 130 km$\times$90 km (Figure 2.2).

Transect: The transect was the area connecting and including the two study areas. This area received attention to study the gradients in vegetation types and climate.

Modeling subareas: Part of each of the study areas was designated as a modeling subarea. The northern modeling subarea (NMSA) was 40 km$\times$30 km, while the southern modeling subarea (SMSA) was about 50 km$\times$40 km. The subareas were the focus of modeling activities, and the development of gridded data products. To provide the necessary data for model development and application, these areas had the highest priority for airborne remote sensing studies and flux measurements.

Tower flux sites: Flux measurement towers were installed in each of the study areas to measure the energy, moisture and carbon fluxes between the boreal forest and the atmosphere. The flux towers were located in the center of areas of about 1 km^2 of homogeneous vegetation cover, and were expected to measure fluxes representative of this vegetation type. In the southern study area flux towers were installed in a mature aspen stand in Prince Albert National Park (Old Aspen – SSA-OA), a mature black spruce stand (Old Black Spruce – SSA-OBS), a mature jack pine stand (Old Jack Pine – SSA-OJP), a young aspen stand (Young Aspen – SSA-YA), a young jack pine stand (Young Jack Pine – SSA-YJP), and a fen site (SSA-FEN). All sites, except the mature aspen site, were located within the boundaries of the southern modeling subarea. In the northern study area flux towers were installed in a mature black spruce stand (NSA-OBS), a mature old jack pine stand (NSA-OJP), a young jack pine stand (NSA-YJP), and a fen site (NSA-FEN). In addition, a small tower was installed at a beaver pond site. All sites were within the boundaries of the northern

Table 2.1: BOREAS field campaigns.

Field Campaign		Period	Duration (days)	Golden Days[a] SSA	NSA
1993					
	IFC-93	08/09/1993 – 08/29/1993	21		
1994					
	FFC-W	02/02/1994 – 02/18/1994	17	02/05/1994 – 02/09/1994	02/05/1994 – 02/09/1994
	FFC-T	04/12/1994 – 05/02/1994	21	04/17/1994 – 04/19/1994	04/17/1994 – 04/20/1994
	IFC-1	05/24/1994 – 06/16/1994	24	06/05/1994 – 06/09/1994	06/05/1994 – 06/12/1994
	IFC-2	07/19/1994 – 08/10/1994	23	07/21/1994 – 02/25/1994	08/03/1994 – 08/08/1994
	IFC-3	08/30/1994 – 09/19/1994	21	09/10/1994 – 09/17/1994	09/05/1994 – 09/10/1994, 09/17/1994
1996					
	FFC-W	02/27/1996 – 03/15/1996	18		
	IFC-1	04/02/1996 – 04/28/1996	27		
	IFC-2	07/09/1996 – 08/09/1996	32		
	IFC-3	10/01/1996 – 10/20/1996	20		

[a] For each IFC in 1994 the days that provided the best atmospheric conditions for remote sensing were designated "Golden Days". Remote sensing data acquired on these days received priority in processing.

modeling subarea.

Auxiliary and process study sites: About 80 auxiliary and process sites were used for investigator studies, mainly carbon cycle studies, or to provide ground observations to correlate with remote sensing measurements.

The BOREAS field period lasted from 1993 through 1996, with the majority of the field measurements taken during the focused and intensive field campaigns (FFCs and IFCs respectively) in 1994 and 1996 (Table 2.1). Only the mature aspen tower in the south and the mature black spruce tower in the north operated almost continuously during the entire BOREAS period. Routine weather observations and the acquisition of images from satellite based remote sensing platforms also continued throughout most of the period. To coordinate efforts, the 85 BOREAS science teams were grouped into six disciplinary groups: airborne fluxes and meteorology (AFM), tower fluxes (TF), terrestrial ecology (TE), trace gas biochemistry (TGB), hydrology (HYD), and remote sensing science (RSS). In addition, BOREAS staff supported field operations, and implemented the BOREAS Information System (BORIS), which was used by all BOREAS investigators to store and exchange BOREAS data sets. Detailed information about the BOREAS experimental setup and field operations is provided in the BOREAS experiment plans [*BOREAS Science Team*, 1994, 1996].

2.2 The Boreal Forest

2.2.1 Spatial Extent

The boreal forest or taiga denotes the mixture of cool coniferous and deciduous forest in the high latitudes of the Northern Hemisphere. It forms a circumpolar belt through Canada, Scandinavia, and Siberia, which in places is up to 1000 km wide (Figure 2.3) [*Larsen*, 1980]. Estimates of the area occupied by the boreal forest vary depending on the definition [*Bonan and Shugart*, 1989; *Dixon et al.*, 1994; *Kirschbaum et al.*, 1996b]. *Goldammer and Furyaev* [1996] give an areal estimate of 12 million km^2, of which 9.2 million km^2 are closed forest. The latter number corresponds to about 29% of the global forested area, and 73% of the total coniferous area. More than 70% of the boreal forest lies in Eurasia.

Various climatological measures correlate with the location of the northern and southern limits of the boreal forest, especially summer air temperatures, and the location of arctic air masses [*Larsen*, 1980]. A good overview of the different indicators for the location of the transition zone between the boreal forest and the tundra is given by *Sirois* [1992]. The 10°C isotherm of mean monthly temperature during the warmest month is commonly used to indicate the position of the arctic tree line, and *Larsen* [1980] suggests the July 13°C isotherm for the northern limit of the boreal forest. Other measures for the transition zone between the boreal forest and the

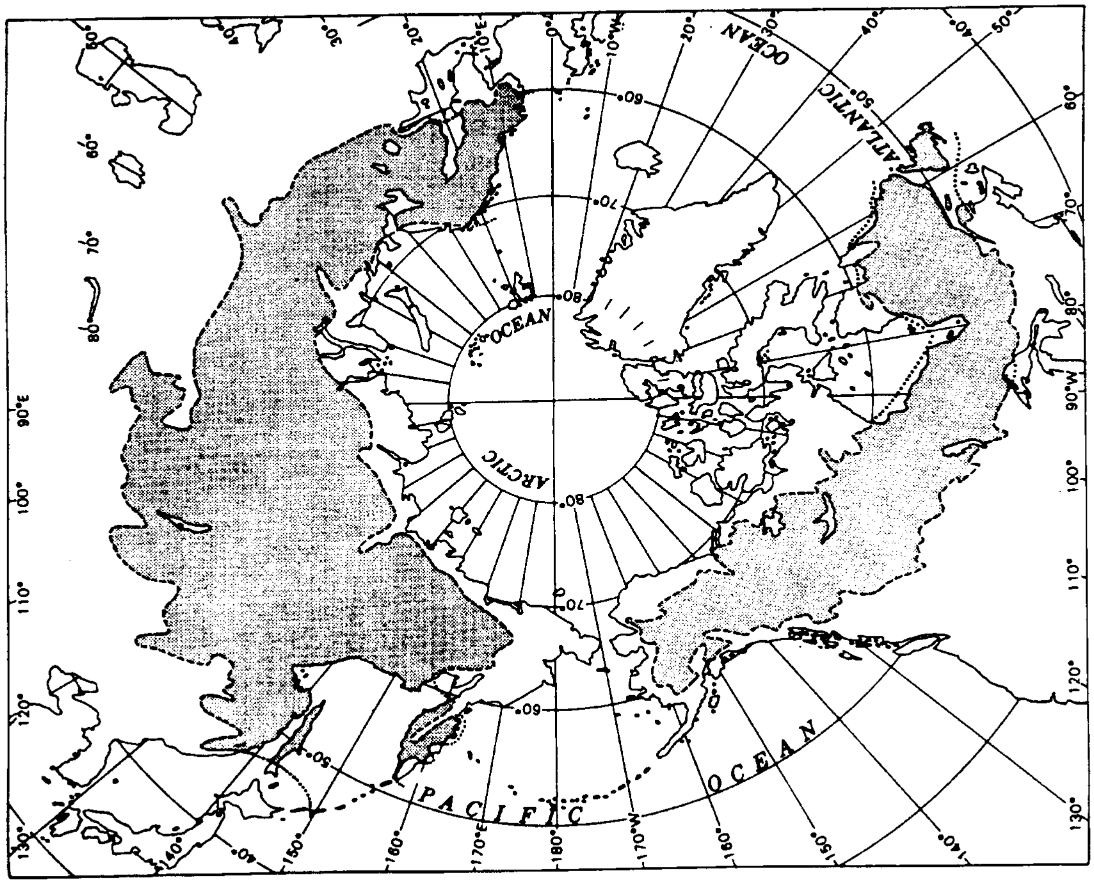

Figure 2.3: Extent of the boreal forest [*Larsen*, 1980].

tundra, or for the northern limit of the boreal forest, include the line where Thorntwaite's potential evapotranspiration is approximately 340–350 mm, the modal July position of the climatic frontal zone between the arctic air masses and the southern air masses, and various measures that use mean yearly or seasonal net radiation as a threshold.

Pielke and Vidale [1995] pose the hypothesis that it is not the position of the arctic front that establishes the northern limit of the boreal forest, but rather that the transition between the boreal forest and the tundra itself significantly influences the preferred position of the front. Because the albedo of the boreal forest is lower than the albedo of the tundra, a larger amount of the incoming energy is absorbed by the landscape. This increase in available energy is not accompanied by an increase in evapotranspiration, because of cold soils and the strong control of the vegetation on the evapotranspiration. Consequently, most of this energy results in a heating of the vegetation and lower atmosphere. The resulting deep boundary layers and differential heating between the tundra and the boreal forest influence the location of the spring and summer position of the arctic front. In North America the arctic tree line coincides with the transition from discontinuous to continuous permafrost, but in parts of Siberia the continuous permafrost zone penetrates far into the boreal forest [*Sveinbjörnsson*, 1992]. Of course, most of these climatic measures are strongly correlated.

The southern border of the boreal forest is less well defined, because the boreal forest transitions to many different vegetation types, depending on the existing regional climate [*Larsen*, 1980], and because of encroachment of agricultural areas. A number of climatic measures correlate with the southern limit of the boreal forest. In eastern Canada the southern limit coincides more or less with the July 18°C isotherm, but as a result of drier conditions the forest boundary lies north of this line in the western provinces of Saskatchewan and Alberta [*Larsen*, 1980]. *Pastor and Mladenoff* [1992] quote a number of other degree-day and evapotranspiration-precipitation ratio thresholds that have been used in North America. Although climatological measures correlate with the forest boundaries, the specific biochemical and physiological plant processes that determine these boundaries are not clear [*Bonan and Shugart*, 1989; *Larsen*, 1980; *Sirois*, 1992; *Sveinbjörnsson*, 1992].

A better understanding of the processes that determine the limits of the boreal forest is needed to make meaningful estimates of changes in its range as a result of changes in climate. *Larsen* [1980] suggests that even though the limits appear to be thermally established, the main determinant of the northern limit might be the photosynthetic capacity of the trees. Warm-season temperature is linked to net radiation and thus the total energy available at the earth surface. *Bonan and Shugart* [1989] argue that in cold climates extreme or anomalous climatic fluctuations may be more limiting to plant processes than average weather patterns. *Sveinbjörnsson* [1992] identifies five different processes that contribute to reduced tree growth towards the tree line: insufficient photosynthesis, insufficient or excessive respiration, reduced positive carbon balance, increased tissue loss, and (vaguely defined) soil processes. In the case of respiration, it is not clear whether trees near the tree line respire too much and thus limit growth, or whether they respire too little and fail to create enough energy for growth. Increased tissue loss is caused by snow and ice loads, and grazing by herbivores. Both soil temperature and nutrient availability influence tree growth.

Bonan and Sirois [1992] performed a model study to evaluate the effect of air temperature on individual tree growth and the northern and southern range limits of black spruce (*Picea mariana*), the most common tree species in most of the North American boreal forest. When only temperature was allowed to affect the carbon flux, they found that black spruce foliage could maintain a positive carbon balance over a wide temperature range. Black spruce could grow far south of its current range limit, but grew optimally at its southern range limit. They concluded that factors other than air temperature, such as reduced reproductive capability, and chilling requirements for bud burst, are responsible for the northern and southern limits of the boreal forest.

2.2.2 *Physical Characteristics*

Large temperature and radiation gradients exist between the northern and southern limits of the boreal forest. Its climate is generally characterized by long, cold winters and short, moderately warm summers. Seasonal variations in mean monthly air temperature can be more than 56°C in eastern Siberia, while seasonal temperature extremes can differ by as much as 100°C [*Bonan and Shugart*, 1989]. The most widely used climate classification system is the one by Köppen [*Lamb*, 1972], which defines boreal forest and snow climates as those climates where the mean temperature of the warmest month is greater than 10°C and the mean temperature of the coldest month is less than -3°C. Most of the boreal forest is dominated by a continental climate and precipitation is generally light. In the North American boreal forest, the mean annual precipitation increases from less than 380 mm in the northwest, to almost 1000 mm in Eastern Canada. In Eurasia mean annual precipitation decreases from more than 510 mm west of the Ural Mountains to less than 250 mm in Eastern Siberia. In both North America and in Eurasia most of the precipitation tends to fall during the summer [*Bonan and Shugart*, 1989].

Species diversity is low in the boreal forest. Fourteen tree species dominate the boreal zone in Scandinavia and Eurasia, and fifteen species dominate in North America [*Nikolov and Helmisaari*, 1992]. Interestingly, none of the boreal tree species has a circumpolar distribution, that is, all are restricted to either North America or Eurasia. In contrast, most moss and lichen species have a circumpolar distribution [*Larsen*, 1980]. The reasons for this are not clear.

Although there are no common tree species, the boreal forests in North America and Eurasia are virtually identical in structure, with a one layer canopy consisting mainly of evergreen coniferous trees, and a ground layer dominated by shrubs and some herbaceous plants. The ground surface is covered by a thick layer of moss and lichen [*Larsen*, 1980]. Outbreaks of insect pests and forest fires are common, and are important factors in shaping the boreal landscape. Lightning-induced fires are the most important natural factor controlling the age structure and species composition of boreal forest [*Goldammer and Furyaev*, 1996]. However, lightning-induced fires currently account for only 15% of recorded fires in the Russian Federation, with most of the remaining fires started by humans, either for agricultural and other land use purposes, or through negligence [*Korovin*, 1996]. Large, high-intensity forest fires lead to the replacement of entire forest stands by new successional species, while low-intensity surface fires favor selection of fire-tolerant trees. Forest fires immobilize carbon sequestered by plants through the formation of elemental or black carbon, which is unavailable to plants, and non-biodegradable. Since most boreal forest fires do not result in lower production of plant mass in the long term, *Goldammer and Furyaev* [1996] suggest that the formation of elemental carbon in forest fires acts as a sink for atmospheric carbon.

2.2.3 The Boreal Forest in the Climate System

Interest in the role of the boreal forest in the climate system has increased for two reasons. First, the boreal forest plays an important role in global biogeochemical cycles, in particular the exchange of the radiatively active gases carbon dioxide (CO_2) and methane (CH_4). Second, the boreal forest influences the global climate through vegetation and albedo effects, and determines the partitioning of available energy into latent and sensible heat over large areas in the northern hemisphere.

Seasonal oscillations in the atmospheric CO_2 concentration in the northern hemisphere are mainly caused by the seasonal dynamics of vegetation growth. Net photosynthesis, corresponding to an uptake of CO_2, occurs only during part of the growing season, while net respiration, corresponding to a release of CO_2 to the atmosphere, dominates during the remaining part of the year. *D'Arrigo et al.* [1987] modeled terrestrial based CO_2 production, using satellite-based NDVI[2] estimates, soil respiration data, and estimates of the net annual productivity for different vegetation types. The predicted CO_2 flux was then advected as an inert tracer using a three-dimensional atmospheric tracer transport model and GCM produced winds. They found that boreal forest photosynthesis and respiration could account for about 50% of the amplitude in the annual cycle of CO_2 concentration measured at Point Barrow, Alaska, and about 30% of the total amplitude at Mauna Loa, Hawaii. They suggested that an increased metabolic activity of land plants may be contributing to a positive trend in the annual amplitude of the CO_2 concentration. As further support for the connection between the annual variation in CO_2 concentration and tree growth, they showed that tree ring based estimates of CO_2 concentration were able to explain 64% of the variance in the annual amplitude observed at Point Barrow, Alaska.

Bonan et al. [1992] describe a model experiment which explores the effect of the albedo of the boreal forest on air temperature. Using a GCM based on the National Center for Atmospheric Research (NCAR) community climate model (CCM-1), they performed simulations with a boreal forest cover, and with the boreal forest replaced by bare ground. Although the magnitude of the temperature changes depended on the treatment of the oceans, global temperatures generally decreased under the bare soil scenario as a result of higher surface albedo. This effect was reinforced when the sea surface temperatures and sea ice were modeled interactively rather than being prescribed. Although results of these kinds of model sensitivity studies have to be treated with

[2]The Normalized Difference Vegetation Index or NDVI is a remote sensing based measure of the greenness of vegetation and is commonly used to derive vegetation parameters, see for example *Sellers et al.* [1994] or *DeFries and Townshend* [1994].

healthy skepticism given the current state of global climate models, they can give some insight into the effects of climate feedbacks.

In a more realistic model experiment, *Foley et al.* [1994] extended the boreal forest northward based on palaeobotanical data. They found that increased vegetation accounted for a 1.6°C increase in mean annual air temperature for land areas between 60°N and 90°N, with a maximum increase of about 4°C in March and April. These changes were the result of reduced snow cover, and a lower albedo associated with evergreen trees protruding above the snow cover instead of snow covered tundra.

2.2.4 Global Change

A better understanding of the role of the boreal forest in global change processes is important, both because the boreal forest itself strongly affects the global climate, and because global warming is expected to manifest itself most strongly in mid to high northern latitudes. Important positive and negative feedback processes exist between changes in the boreal forest environment and changes in the global climate system. Many of these processes are only poorly understood, especially in a quantitative sense, making it difficult to provide realistic projections of the effects of global change on the boreal forest and of changes in the boreal forest on the global climate.

Observations show that maximum recent warming has occurred during the winter over the high mid-latitudes of the continents in the Northern Hemisphere [*Nicholls et al.*, 1996]. Most of the increase of the mean temperature has occurred as a result of increased daily minimum temperatures. Since 1950, the increase of land-surface minimum temperatures has been twice as large as the increase in maximum temperatures. Consequently, diurnal temperature ranges have decreased. This decrease in diurnal temperature range has been most pronounced over land areas in the Northern Hemisphere, particularly in the autumn. These changes have been found to correlate with increased cloud cover [*Nicholls et al.*, 1996].

Direct effects of increased temperatures and CO_2 concentrations on plant growth are reasonably well understood individually, but their combined outcome is unclear. As mentioned previously, extreme temperatures may be more limiting to plant processes than average temperatures. Consequently, decreased nighttime temperatures may allow plants to survive at higher altitudes and latitudes, and will lengthen the growing season for agricultural crops. However, premature budburst could lead to increased frost damage, and the chilling period could become too short for certain plant species to flower [*Kirschbaum et al.*, 1996a; *Melillo et al.*, 1996]. Higher temperatures could result in higher amounts of evapotranspiration, leading to water stress for plants. At the same time higher CO_2 concentrations may lead to an increased stomatal resistance, since plants will not have to open their stomata as much to exchange CO_2 with the atmosphere [*Melillo et al.*, 1996]. This effect would decrease the moisture stress to some extent, but could lead to higher leaf temperatures that can be detrimental to the plant [*Kirschbaum et al.*, 1996a].

Nutrient-limited environments such as the boreal forest are to some extent buffered against the effects of climate change. If the climate becomes less favorable for the current vegetation, nutrient availability will become less limiting, while if the climate becomes more favorable, the nutrient shortage will prevent the vegetation from taking advantage of the improved climate conditions.

Kirschbaum et al. [1996b] compare the results from model simulations using three different global vegetation models. Currently none of these models is able to simulate the transient behavior of forests in a changing climate, but instead they simulate the new vegetation-climate equilibrium under altered climate conditions. Because there is a good statistical agreement between the observed and predicted vegetation distributions, there is some measure of confidence in the vegetation distributions that they predict for different climate scenarios. For a $2\times CO_2$ equilibrium climate change scenario, two of the three models predict a large decrease in the extent of the boreal forest, despite a northwards migration of the arctic tree line. The third model predicts only a small decrease.

Bonan and Sirois [1992] show that these models may not always include appropriate sensitivities of plant growth to changes in environmental conditions, so care has to be taken when interpreting their results. Another reason to be careful is that although climate models are able to simulate many large scale climatic features reasonably well, simulation results for regional climate still leave much to be desired [*Kattenberg et al.*, 1996]. Regional biases in temperature and especially precipitation are large, which should have significant consequences for the equilibrium vegetation types predicted by the vegetation models.

Wein and De Groot [1996] suggest that fire may play an important role in vegetation succession in the boreal forest under a changed climate. Vegetation changes in the nutrient and energy- limited boreal forest are expected to be slow, but fire may literally clear the way for new, better-adapted species. In addition to clearing the forest, the fire also alters the nutrient availability and the energy balance at the surface. Increased temperatures and drier conditions are expected to increase the occurrence of forest fires.

2.3 Hydrological Perspective

2.3.1 Land Surface–Atmosphere Interactions

Most measurements of the interactions between the land surface and the atmosphere are point observations, which often have a high temporal resolution, but which represent only a small area. Consequently, they reveal little about the spatial variability of the observed process. For many applications, an insight in the spatial distribution of these land-atmosphere interactions is important, if only to determine the average quantity of mass, energy, or momentum exchanged over a certain area. Until recently, no measurement techniques existed that allowed routine observations of the spatial variability of exchange processes. This situation has changed somewhat with the advance of remote sensing techniques, although most of these techniques are still in an experimental stage.

Similarly, most surface-vegetation-atmosphere transfer schemes (SVATs) are very detailed in the vertical direction, with only a cursory treatment of the spatial variability of the modeled processes. One of the main challenges in research of land surface-atmosphere interactions is to integrate observations and understanding of processes at the point scale over larger areas in a rigorous and consistent manner. A better understanding of the hydrology of the boreal forest ecosystem is a prerequisite for integrating understanding of exchange processes at the plot and stand scale to the catchment scale, and eventually regional and continental scales. The availability of moisture, modulated by plant-physiological controls, largely determines the partitioning of available energy in latent and sensible heat. The presence or absence of snow changes the albedo of the land surface and consequently the surface energy balance.

Water balance studies based on observed river discharge data in the BOREAS study areas can help to provide a reliable estimate of the areal average latent heat flux over these basins. Such an areal average flux will provide an important constraint for other aggregation schemes and larger-scale regional hydrologic and atmospheric models.

2.3.2 The Boreal Winter

The hydrology of the boreal forest is largely characterized by the long, cold winter, which essentially stops vegetation growth for five to seven months of the year. *Harding and Pomeroy* [1996] describe a winter field experiment in which they compared the energy balance over a jack pine stand and a snow covered lake. The sensible heat fluxes above the snow free canopy and the snow covered lake showed opposite sign, with an upward flux over the canopy and a downward flux over the lake, largely because of the difference in albedo. However, when the canopy was snow covered, the sensible heat fluxes were of equal sign. In this case, the downward sensible heat flux above the canopy compensated for a large upward latent heat flux caused by sublimation of intercepted snow. As a result of interception and subsequent sublimation of snow in the canopy, snow accumulation under the canopy was 30% less than in adjacent clearings. Such large variations in the components of the energy balance over the different land surface types in the boreal forest complicate translation of understanding gained at the small (e.g. tower) scale to larger scales.

2.3.3 Evapotranspiration in the Boreal Forest

One of the important early findings from BOREAS was that despite the abundance of water, evapotranspiration is limited, even on warm days with low humidity, suggesting a strong biophysical control [*Sellers et al.*, 1995]. According to *Sellers et al.* [1995], evapotranspiration rates were less than 2 mm/day over the season, while sensible heat fluxes were often high, resulting in Bowen ratios[3] larger than one on many days. These high sensible heat fluxes lead to the development of deep convective boundary layers over the BOREAS region.

Hogg and Hurdle [1997] studied sap flow in trembling aspen, the most abundant deciduous tree in the North American boreal forest. One of their two study sites was the mature aspen site in the BOREAS southern study area, while the other site was located about 100 km further south. For both locations, they found that sap flow increased linearly for vapor pressure deficits (VPD) from 0 to 1 kPa, but that it remained constant for vapor pressure deficits greater than 1 kPa. Thus, an inverse relationship exists between the vapor pressure deficit and stomatal conductance for deficits above 1 kPa. Based on the sap flow measurements they estimated the maximum transpiration rates at the mature aspen sites at 0.4 mm/hr. One reason for the conservative water use by the aspen, might be the need to maintain a minimum water potential inside the leaves to prevent irreversible damage due to dehydration. In that case the resistance between the soil and the plant, and thus the rate at which water can be extracted from the ground, might determine the maximum transpiration rate [*Hogg and Hurdle*, 1997]. A similar response of stomatal resistance to vapor pressure deficits was found by *Saugier et al.* [1997], who studied transpiration at the branch, tree, and stand level at the mature jack pine site in the southern study area. Low transpiration rates were attributed to high stomatal resistances and low leaf area indices.

As part of the NOPEX project, *Grelle et al.* [1997] studied the evapotranspiration components in a mixed spruce (Norway spruce (*Picea abies*)) and pine (Scots pine (*Pinus silvestris*)) boreal forest in Sweden during the 1995 growing season. They found that although tree transpiration accounted for most of the total evaporation (65%), evaporation from interception storage (20%) and from the forest floor (15%) were important as well. Comparing their results to other evaporation experiments they concluded that the fraction of total evaporation that originates directly from the forest floor varies widely, but in all cases formed an important part of the forest water balance. They estimated the maximum interception storage for their site at 3.3 mm, for forests stands with leaf area index values between 3 and 5.

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[3]The bowen ratio is the ratio of the sensible heat flux to the latent heat flux.

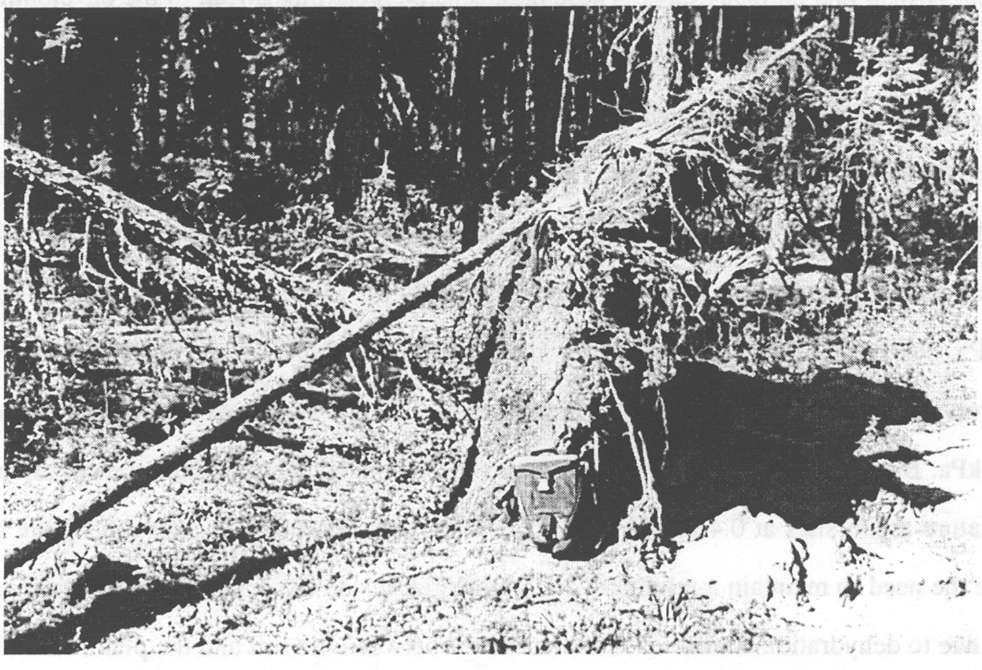

Figure 2.4: Root mass of a black spruce, demonstrating the small depth of the root zone.

2.3.4 The Organic Surface Layer

Most of the forest floor in the boreal forest is covered by a moss and lichen layer. According to *Bonan and Shugart* [1989] 80–90% of the above-ground biomass in cold and wet black spruce stands may be contained in the moss layer. This organic layer influences both the moisture and thermal characteristics of the forest floor. Its presence increases soil moisture, decreases soil temperatures because of its high water content and low thermal conductivity, and reduces nutrient availability. Most of the roots of trees and shrubs (especially in the black spruce forests in the BOREAS region) are located in this organic/moss layer (Figure 2.4). Mosses lack roots and vascular systems and are dependent on moisture taken up directly through the leaf surfaces. In addition, moss leaves do not have stomata, and thus respond differently to moisture stress than do higher plants.

Price et al. [1997] describe a study of the water fluxes through the canopy and the moss layer at two sites near the northern limit of the boreal forest during summer 1994. One site was just outside the BOREAS northern study area, while the other was near the mature black spruce flux tower site within the northern study area [see also *Haddeland and Lettenmaier*, 1995]. They found that about 23% of the total rainfall during their study was intercepted by the black spruce canopy, and evaporated directly from canopy storage. For individual storms the interception amount varied from about 60% for small events, to about 15-20% for large events with more than 30 mm of precipitation. Stemflow amounted to less than 1% of bulk precipitation, and could be neglected. About 21% of the throughfall was retained by the moss carpet, and subsequently evaporated. Maximum evaporation rates from the forest floor were more than 1 mm/day, with more typical rates about 0.5 mm/day. Water fluxes through the moss layer were large immediately after a storm event, but the amount of drainage between storm events was small. Canopy interception and moss evaporation accounted for about 41% of total precipitation during the measurement period.

The organic forest floor layer not only affects the hydrologic regime, but also plays an important role in the thermal balance of the surface and the underlying mineral soil [*Bonan and Van Cleve*, 1992]. Because of it low bulk density and the low thermal conductivity, the organic material acts as an effective insulator, resulting in lower soil temperatures and higher permafrost tables. The seasonal moisture regime of the organic layer aids in the formation and maintenance of permafrost. In the summer the surface layer dries out, and the low thermal conductivity of the organic material limits the amount of the warming of the soil. In the autumn and winter, decreased evapotranspiration leads to wetter conditions in the organic layer, resulting in a higher thermal conductivity, and consequently enhanced cooling of the underlying soil. As a result there is a net transport of heat from the soil to the atmosphere in the fall and winter, which is favorable for the formation of permafrost.

2.3.5 Carbon Exchange Between the Boreal Forest and the Atmosphere

Water availability, soil moisture distribution, and soil temperature are also controlling factors in the exchange of CO_2, an important greenhouse gas, between the boreal forest and the atmosphere. *Frolking et al.* [1996] used a one-dimensional, daily time step carbon balance model to investigate the temporal variability of carbon dynamics in a spruce/moss boreal forest environment. They showed that annual ecosystem productivity was particularly sensitive to the timing of the onset of spring, which is characterized by the disappearance of snow, and thawing of the soil layers. Model results indicated that ecosystem productivity tended to be highest in years with early springs and relatively wet summers and lowest in years with late springs and relatively dry summers.

Methane (CH_4), produced by anaerobic microbial decomposition of organic matter, is another important greenhouse gas whose emissions were monitored as part of the field phase of the BOREAS project. Methane emissions from a boreal fen in the southern study area showed a strong relationship with the temperature of the peat layers and the average height of the water table during the 1994 growing season [*Suyker et al.*, 1996]. For different parts of the growing season, peat temperature and water table height, either alone or in combination, were able to explain between 68% and 94% of the observed variation in methane emissions. Methane emission increased with increased peat temperature, both reaching their peak in early August. The relationship between the water table depth and methane emissions was more complicated, with abrupt changes in the water table followed by a more gradual change in methane emissions after a time lag of 12 days. Similar results have been reported by investigators in other boreal forest areas, for example *Kettunen et al.* [1996] in a study of boreal peatlands in Finland, and *Moosavi et al.* [1996] in a study of boreal peatlands in Alaska.

2.3.6 Drainage Network

The limited topographical relief in most of the boreal forest area (Figure 2.5), combined with the geology and geomorphology of the landscape, leads to a complicated mosaic of lakes and wetlands (Figure 2.6). Many northern peatlands lack a clearly defined drainage network, and flow is often very diffuse. In the BOREAS area considerable effort was expended on defining the boundaries of the White Gull Creek Basin in the southern study area by R. Soulis and N. Kouwen from the University of Waterloo, Canada. This effort suggests that the boundary of the basin may well change with changes in local ground water table. Topographic gradients in the smaller NW2 and

Figure 2.5: View of the black spruce forest in the northern study area.

NW3 basins in the northern study area are steeper, and consequently these basins are somewhat better defined.

Hydrologic response of the White Gull Creek Basin is slow. During the period July 13–19, 1994, about 120 mm of precipitation fell on the White Gull Creek Basin, with most of that falling on July 18–19. However, the peak runoff measured at gauge SW1 (drainage area about 603 km^2), was only 25.4 m^3/s, measured on July 21, 1994. During the weeks following the storm, observed areal average runoff amounted to only 35.6 mm (July 13–August 5, 1994), while the total amount of precipitation during this period was 128.3 mm.

Omernik and Bailey [1997] argue that for areas where watersheds are difficult to define the basic unit for analysis, resource assessment, and management should not be the watershed, but the ecoregion. An ecoregion is a region within which the mosaic of ecosystem components is different from that of adjacent regions. In essence this is the approach followed in defining the

Figure 2.6: Lake and surrounding forest in the southern study area.

BOREAS region and study areas, whose boundaries do not coincide with watershed boundaries. However, in order to study the water balance of a region it is necessary to account for the fluxes across the boundary of the region. For water balance studies the watershed remains the analysis unit of choice, since fluxes across the boundary can be neglected.

2.3.7 *White Gull Creek Basin*

The White Gull Creek basin upstream of Highway 106 formed the largest gauged area in the southern study area with an approximate drainage area of 603 km^2. The main stream gauge (SW1) was equipped with an all-season recorder, installed and operated by Environment Canada. White Gull Creek drains extensive wetland areas in a gently undulating to moderately rolling terrain east of Candle Lake, Saskatchewan. Three of the flux towers in the southern study area (mature black spruce, mature jack pine and young jack pine) were located within the boundaries of the White

Gull Creek basin, while a fourth (fen) was located just southeast of the watershed. The surface geology is characterized by Pleistocene and recent glacial deposits on top of Cretaceous bedrock. Vegetation consists mainly of black spruce in poorly drained areas, and jack pine on well-drained and sandy soils. Mixed stands of aspen and white spruce are common on well-drained glacial deposits.

2.4 Data Collection and Data Processing

2.4.1 Hydrological Investigations

The BOREAS hydrology group (HYD) consisted of eight science teams, who were responsible for snow and hydrology investigations. The science teams focused on soil moisture, snow processes and snow remote sensing, catchment hydrology, and hydrological modeling. The objectives of the hydrologic investigations were to characterize the storage of moisture, in both liquid and solid state, at and near the land surface, as well as the moisture fluxes to and from the land surface [*BOREAS Science Team*, 1994]. Five of the eight science groups focused on snow processes, three of which were mainly involved with the estimation of snow cover and snow depth from remote sensing observations. One science group focused on soil moisture, while the remaining two groups dealt with catchment hydrology, both from a modeling and data collection point of view.

Snow related measurements included field measurements of snow depth, snow water equivalence, profiles of density and temperature, and incident radiation on the snow pack. These measurements were only made during part of the FFCs. During the summer of 1994, soil moisture profiles were measured at selected flux tower sites, using neutron probe and TDR instruments. Streamflow measurements were made at year-round gauges operated by Water Survey of Canada (WSC) on White Gull Creek in the southern study area and the Sapochi River in the northern study area. Precipitation measurements were made using Belfort weighing gauges and tipping bucket gauges during the 1994–1996 growing seasons. In addition a rain radar was operated over the southern study area from May till September 1994 [*Schnur et al.*, 1997]. Moss gravimetric and canopy interception studies were performed near the mature black spruce site in the north.

Table 2.2: University of Washington participation in BOREAS field investigations

Period and Participant	Location	Purpose	Activities
June 1994 Bart Nijssen	SMSA	Support HYD-9 in general hydrologic data collection	Stream gauging; monitoring of lake and groundwater levels; monitoring of rain gauges
August-September 1994 Ingjerd Haddeland[a]	NSA-OBS	Moss interception and evaporation measurements	Moss gravimetric studies; canopy interception
April 1995 Bart Nijssen	NSA-OBS	Support HYD-3 during snow studies. Work focused on attenuation of shortwave radiation by the tree canopy	Measurements of radiation, snow depth, snow density, and biophysical characteristics such as stem density, stem diameter, and needle density
February 1996 Bart Nijssen	SSA-OBS SSA-OA	Support HYD-3 during snow studies. Work focused on attenuation of shortwave radiation by the tree canopy	Measurements of radiation, snow depth, snow density, and biophysical characteristics such as stem density, stem diameter, and needle density
August 1996 Bart Nijssen	SSA-OBS	Support HYD-8 during studies of the moss water balance	Moss gravimetric studies; monitoring of rain gauges

[a] see *Haddeland and Lettenmaier* [1995]

The hydrological measurement program during 1996 was more limited. Although no precipitation radar was operated, soil moisture profiles were again measured at a number of tower sites and the precipitation gauge network were re-activated. Additional moss evaporation studies were performed near the mature black spruce site in the south. The water balance study in Chapter 5 combines data from a large number of BOREAS science teams to investigate the hydrological behavior of the White Gull Creek basin. University of Washington participation in BOREAS hydrological fieldwork is documented in Table 2.2.

Chapter 3

POINT EVALUATION OF A SURFACE HYDROLOGY MODEL FOR BOREAS

This chapter has appeared as B. Nijssen, I. Haddeland, and D. P. Lettenmaier, Point evaluation of a surface hydrology model for BOREAS, *J. Geophys. Res.*, *102*, 29,367–29,378, 1997.

3.1 Introduction

One of the main objectives of the Boreal Ecosystem-Atmosphere Study (BOREAS) is "to improve the process models that describe the exchanges of radiative energy, water, heat, carbon, and trace constituents between the boreal forest and the atmosphere" [*Sellers et al.*, 1995]. This paper describes the application and evaluation of one such process model which simulates the surface water and energy fluxes. The data gathered by BOREAS investigators offer a unique opportunity to evaluate model performance, to examine which processes are important, and whether they are adequately represented by process models.

The Distributed Hydrology-Soil-Vegetation Model (DHSVM) is a surface hydrology model developed to infer the spatial distribution of runoff generation, and moisture and energy fluxes at spatial scales on the order of 100 m to 1 km and a sub-daily time scale. This is accomplished by simulating a detailed water and energy balance at each node in a digital elevation model (DEM), and predicting lateral redistribution of water in the subsurface zone. DHSVM was originally developed for areas with complex terrain, and has been applied successfully in mountainous regions in the western United States [*Arola and Lettenmaier*, 1996; *Storck et al.*, 1995; *Wigmosta et al.*, 1994]. In all of these applications the model has been employed as a fully distributed hydrological model, although *Arola and Lettenmaier* [1996] examined the effects of varying spatial resolution on total regional energy and moisture fluxes. Our ultimate purpose in the BOREAS