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Winter and spring thaw as observed with imaging radar at BOREAS

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Abstract. Measurements of the length of the growing season in the boreal regions, during which significant carbon exchange due to metabolic activity occurs, may improve current estimates of annual CO_2 fluxes at high northern latitudes. For coniferous, evergreen forest species, the summer frost free period bounds the growing season length and period of net carbon uptake. Spring soil thaw bounds the period of soil respiration and decomposition and thus carbon release. The balance of these two exchanges determines whether the boreal region is a net carbon source or sink. Imaging radar data can potentially be used to monitor these periods of soil and canopy thaw due to the sensitivity of radar to surface freeze/thaw state. In considering the use of imaging radar, two issues must be addressed. First, the temporal relationship between the time of freezing and thawing of the forest canopy and soil and the periods of photosynthetic and respiration activity must be ascertained. Second, the sensitivity of imaging radar to freeze/thaw processes in each of the forest components must be assessed. Of particular interest is the extent to which radar is selectively sensitive to tree and soil thawing. In 1994, in situ soil, stem and root temperatures, and stem xylem flux were measured over a complete annual cycle at the Boreal Ecosystem-Atmosphere Study (BOREAS) test sites in Canada. Imaging radar data from the European Space Agency Remote Sensing (ERS-1) satellite were also acquired throughout 1994. The in situ temperature data show clear transitions in soil and stem thawing related to the start of soil respiration and canopy photosynthesis, respectively. The imaging radar data show clear shifts in backscatter related directly to soil thaw, and possibly to canopy thaw, as two independent transitions. These results are compared to seasonal ecosystem model results for carbon exchange.

1. Introduction

In the boreal forest region and for coniferous forest species the summer frost free period bounds the growing season length [*Walter and Breckle*, 1991, 1986]. For both coniferous and deciduous trees, their growth potential is further limited by their mineral and water uptake. For the broader landscape the spring soil thaw bounds the period of root and soil respiration and decomposition. Estimating the onset and the duration of favorable soil temperature regimes is therefore of equal ecological significance as the temperature regime of the aboveground biomass. On the basis of imaging radar measurements collected in Alaska over the last 5 years, thawing of the landscape during spring results in a significant rise in radar backscatter. This change is due to an increase in soil and canopy dielectric constant as the water, highly polar in the liquid state, changes from the solid to the liquid phase.

In order to use imaging radar data for estimating periods of significant carbon exchange, two issues must be addressed. First, the relationship between tree and soil thawing and the beginning and end of photosynthetic and respirative activity must be ascertained. Secondly, the sensitivity of spaceborne imaging radar backscatter to freeze/thaw processes must be assessed. In particular, it is necessary to evaluate whether backscatter is selectively sensitive to tree and soil freezing and thawing, or dominated by one of these components.

To address these questions, in situ soil and stem temperatures and stem xylem flux were measured over a complete annual cycle in 1994 at the Boreal Ecosystem-Atmosphere Study (BOREAS) test sites in Canada [*Sellers et al.*, 1995]. European Remote Sensing (ERS-1) satellite imaging radar data were also acquired throughout 1994. In the winter phase of the ERS-1 mission, 3 day repeat image transect data provided detailed temporal sampling of some of the BOREAS sites. During the spring, summer, and fall phases of the mission a longer repeat orbit generated data over all sites every few weeks. The results for the winter and spring thaw for the mature black spruce site in the southern Prince Albert region are addressed in this paper.

1.1. Background

1.1.1. Boreal processes. Uptake and release of CO_2 by the boreal forest may account for up to 50% of the seasonal amplitude in atmospheric CO_2 at Point Barrow, Alaska, and about 30% of the seasonal amplitude at Mauna Loa [*D'Arrigo et al.*, 1987; *Keeling et al.*, 1996]. Recent carbon budget analyses indicate a net carbon sink in the terrestrial biosphere [*Siegenthaler and Sarmiento*, 1993]. On the basis of current estimates of oceanic carbon uptake, *Tans et al.* [1990], *Ciais et al.* [1995], *Dai and Fung* [1993], *Denning et al.* [1995], and *Friedlingstein et al.* [1995] conclude that a northern hemisphere terrestrial carbon sink of the order of 2.0–3.4 Gt C per year is required to

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balance the global carbon budget. While Tans et al. associate this sink with deciduous forests in temperate latitudes, *Bonan* [1991a, b] suggests that this sink may actually be a consequence of an imbalance in production and decomposition in boreal forests.

The role of boreal forests in the carbon cycle is particularly important because experiments with atmospheric general circulation models indicate significant northern hemisphere high-latitude climatic warming with doubled atmospheric CO_2 concentrations [e.g., *Schlesinger and Mitchell*, 1987]. The ecological implications of such a climatic change are not yet fully understood and are subject to various recent research activities [e.g., *Pregitzer et al.*, 1995], but the seasonal amplitude of atmospheric CO_2 concentrations in northern latitudes has increased with time, and this may reflect increased metabolic activity of ecosystems in northern latitudes due to warmer air temperatures and higher available CO_2 concentrations in the atmosphere [*Bacastow et al.*, 1985; *Gammon et al.*, 1985; *Houghton*, 1987; *Jacoby et al.*, 1996]. Change to a warmer, drier climate may release more than 1.75 Gt C per year to the atmosphere from boreal ecosystems [*Post*, 1990]. In addition to increasing metabolic activity, increased high-latitude temperatures may also extend the growing season. This could result in an increased annual carbon gain. Alternately, a decreased annual carbon gain due to a higher decomposition of soil organic matter, as well as increased periods of frost drought which may reduce net annual carbon sequestration, is possible.

Quantifying process rates in a warmer boreal region is also necessary for improving climate model representations of land surface processes. Primary global climate model inputs include surface energy, surface water, and seasonal cycles of vegetation. Timescales of interest are diurnal, seasonal, and interannual. To estimate these model inputs, the key measurables with remote sensing instruments are surface roughness, albedo, and canopy and soil resistance to water flux (G. Dickinson, personal communication, 1995). One approach is to obtain land surface classification maps from which these properties can sometimes be derived. A second approach is to measure these variables directly, independent of surface cover type. Estimates of the duration of the soil and canopy thaw period provide insight into all three model inputs (surface energy and water and seasonal cycles of vegetation) and bound the period when water flux through the soil is prohibited due to freezing conditions.

1.1.2. Remote sensing measurements. Remote sensing has great potential to provide parameters that can be used in climate and ecosystem models on appropriate temporal and spatial scales. A number of remote sensing instruments may be used to estimate growing season length, and it is likely that a combination of sensors will provide the most accurate information. The advanced very high resolution radiometer (AVHRR), for example, may provide good estimates of leaf-on period thus bounding the growing season length for deciduous species [*Justice et al.*, 1985; *Lloyd*, 1990; *Reed et al.*, 1994; *Schwartz*, 1992]. For coniferous species the growing season may be halted when air temperatures drop below $-2°C$ [*Waring et al.*, 1995]. For closed canopy forests, canopy temperatures are within a few degrees of air temperatures [*Luvall and Holbo*, 1989] and can potentially be estimated using thermal infrared emissions gathered by AVHRR. Access to these data is, however, limited by cloud cover.

A third technique is to bound the length of the growing season by monitoring freeze/thaw transitions using imaging radar data. At microwave frequencies, freezing results in a large decrease of the dielectric constant of soil and vegetation because the crystal structure in frozen water prevents the rotation of the polar water molecules contained within the soil and vegetation. Microwave backscatter is controlled by both the canopy structure and the microwave dielectric properties of the scattering material. Current spaceborne imaging radars, ERS-1 and ERS 2, are limited in their temporal sampling due to their narrow (100 km) swath widths, however, Canada's RADARSAT (launched in October 1995) and ESA's Envisat (to be launched in 1998) operate with very wide swaths (500–1000 km) in a scanSAR mode providing the required temporal sampling frequencies of a few days.

Studies using truck-mounted scatterometers have shown that radar backscatter from frozen ground and frozen vegetation is much lower than the radar backscatter from thawed ground and vegetation [*Ulaby et al.*, 1982]. *Wegmuller* [1990] measured a 3–4 dB drop in radar backscatter from bare soils during day-night freeze/thaw cycles at a measurement geometry similar to that of the ERS radars. Backscatter change resulting from freezing and thawing was first observed in image data in a series of L band (23 cm) aircraft radar data sets that were acquired over the Bonanza Creek Experimental Forest, a Long-Term Ecological Research site near Fairbanks, Alaska, in March 1988 [*Way et al.*, 1990, 1994]. Data were acquired with the Jet Propulsion Laboratory airborne imaging radar on several different days over a period of 2 weeks. The airborne data were augmented with in situ measurements of the dielectric and moisture properties of the snow and forest canopy. During the time period over which the imaging radar data were collected, temperatures ranged from unseasonably warm (up to 9°C) to well below freezing ($-8°$ to $-15°C$), and some of the free water in the trees changed from a liquid to a solid phase. The imaging radar data demonstrated that the radar return is sensitive to these changing environmental factors at L band with a 4–6 dB increase (depending on microwave polarization and canopy type) in the radar cross section of the forest stands.

With the launch of ERS-1 in 1991, an intensive study of the fall freeze transition was carried out in Alaska [*Rignot et al.*, 1994]. ERS-1 C band (5.7 cm wavelength) images were acquired of the Tanana River floodplain forests. Canopy and soil temperatures and meteorological data were collected in three representative stands: black spruce, white spruce, and balsam poplar. The data show that a 3 dB drop in backscatter occurs during the transition of trees from a thawed to a frozen state. The results of this work were applied on a landscape scale by *Rignot and Way* [1994]. Transects which crossed Alaska from north to south of low-resolution (200 m) ERS-1 radar data were collected from August to November 1991. Forests and tundra imaged in the first transect collected in August were assumed to be completely thawed based on meteorological data. Successive transects were referenced to this first transect. Vegetation in a pixel was considered to freeze if the backscatter decreased by 3 dB. Freezing, as observed in the image transects, was consistent with meteorological data collected along the transects; the data show that as is expected, freezing occurred first in the high-latitude and high-altitude regions.

1.2. BOREAS

To further study boreal freeze/thaw transitions, ERS-1 imaging radar data were collected over the BOREAS region in 1994. BOREAS is a large-scale international field experiment with a goal of improving our understanding of the exchanges of

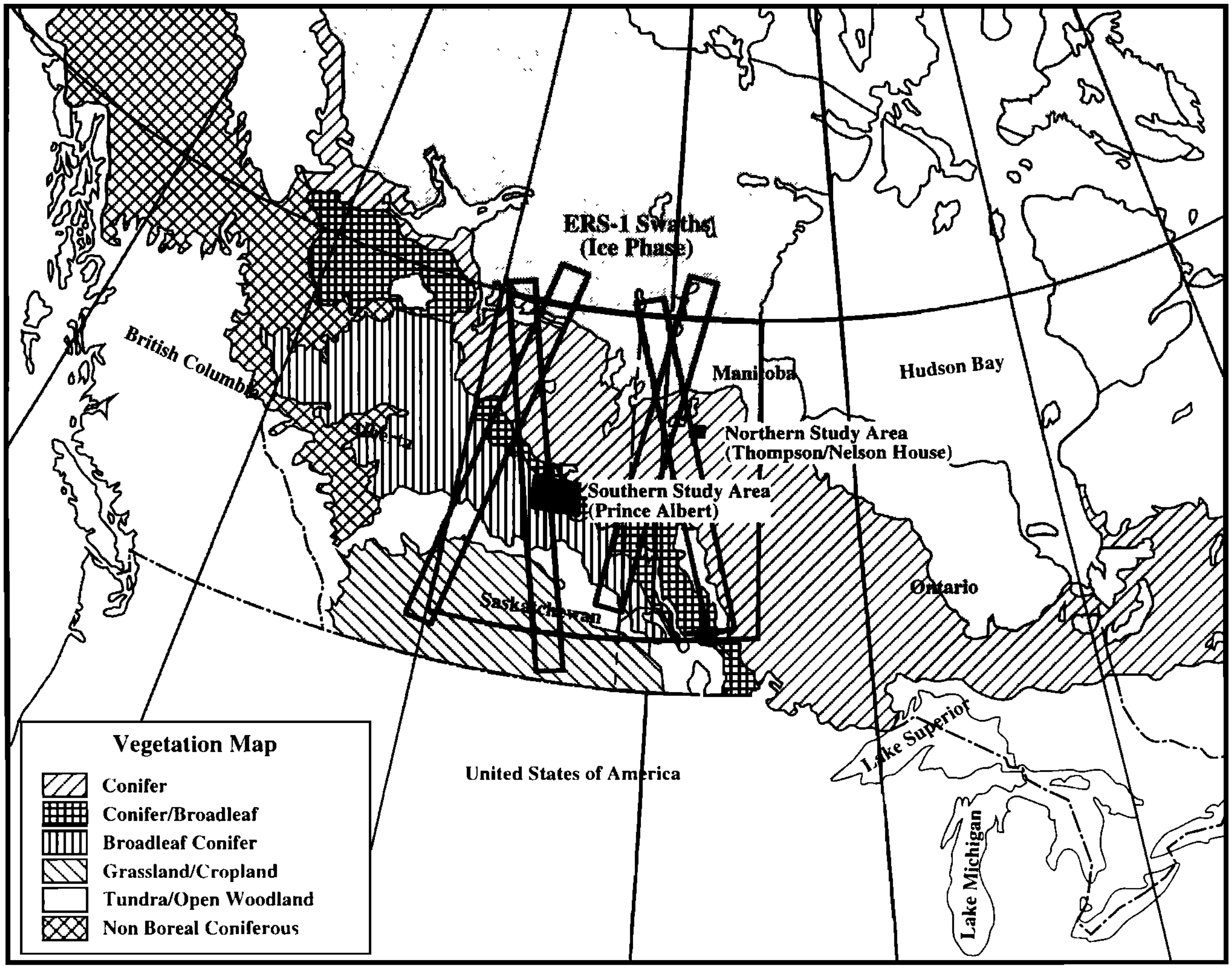

Figure 1. Map of Canada showing the BOREAS region, northern and southern study areas, and major vegetation types. Also shown are ERS-1 swaths (ascending-night and descending-day) which cross the BOREAS 1000 × 1000 study area.

radiative energy, heat, water, CO_2, and trace gases between the boreal forest and the lower atmosphere [*Sellers et al.*, 1995]. An important objective of BOREAS was to collect the data needed to improve computer simulation models of the processes controlling these exchanges so that the effects of global change can be anticipated.

From August 1993 to the end of 1994 a variety of monitoring measurements were gathered over a 1000 × 1000 km BOREAS study region that ranges from 50°N to 60°N latitude and 95°W to 110°W longitude and which covers much of Saskatchewan and Manitoba, Canada (Figure 1). Imbedded in this region are two study areas: the southern study area (SSA), which is 11,170 km^2 and is located north of Prince Albert, Saskatchewan, between 53.53°N and 54.40°N latitude and 104.00°W and 110.00°W longitude; and the northern study area (NSA), which is 8000 km^2 and lies west of Thompson, Manitoba, between 55.80°N and 56.00°N and 98.25°W and 98.67°W. Within each study area were several "tower sites" that were designed to measure energy and mass fluxes of carbon and water in the dominant and representative boreal vegetation types (Figure 2). Each tower site was established in a region of a homogeneous vegetation type and low relief (~1 km^2). Together, the nine tower sites represent the major boreal forest types in this region of Canada. Both the north and the south study areas included tower sites with mature black spruce (*Picea mariana*, Mill.), mature jack pine (*Pinus banksiana*, Lamb.), young jack pine, and fens. The southern study area also includes a mature aspen (*Populus tremuloides*, Michx.) site. In this paper, we focus on the SSA black spruce because it is the only instrumented coniferous stand for which continuous ERS-1 data are available due to the orbital coverage patterns. In 1994 the SSA black spruce/feathermoss forest ecosystem was a 155 year old stand with tree heights ranging from 0 to 10 m, a stem density of 4330 trees/ha, and a basal area of 30 m^2/ha. The percent canopy cover was 55% (see Figure 3), and the organic layer was 5–20 cm in depth. The center latitude and longitude are 53.985°N and 105.12°W, respectively.

The BOREAS project included six field campaigns that provided intensive in situ and remote sensing data sets. Comprehensive surface-atmosphere flux data were supported by ecological, trace gas, and hydrological measurements and visual, infrared and radar remote sensing observations. Two of the towers were operated from the winter of 1993 to the winter of 1994; the other tower sites started operation in May 1994 and concluded in September 1994 (Figure 4). Although the tower in the SSA black spruce stand was not operated during the

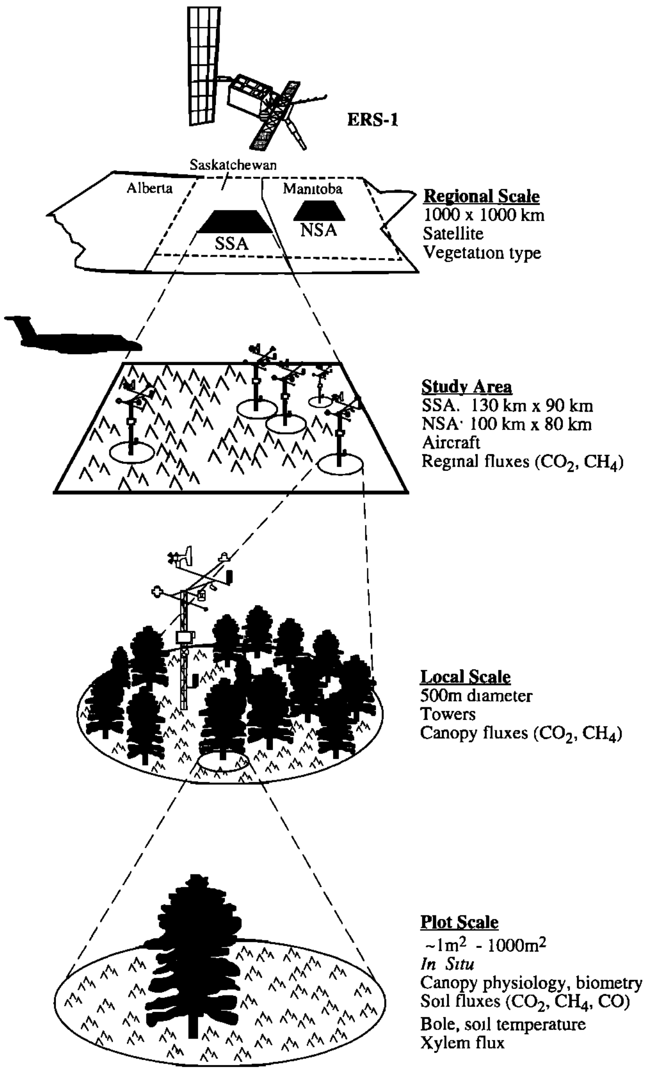

Figure 2. Tower flux measurements include wind speed and direction, photosynthetically active radiation (PAR), air temperature, relative humidity, global short-wave radiation, canopy radiation temperature, precipitation using a rain bucket on the tower and an ultrasonic snow depth sensor on the ground, air pressure, canopy air temperature, and soil temperature at 0.1 and 0.5 m.

spring thaw, the NSA black spruce tower did operate for the full annual cycle [*Goulden et al.*, this issue]. Tower flux measurements from the NSA black spruce stand were used to validate a daily carbon balance model [*Frolking et al.*, 1996] which was then applied to the SSA black spruce stand [*Frolking*, this issue] and compared to the radar backscatter results in this paper.

2. Approach and Measurements

ERS-1 imaging radar data were collected for each overpass of the BOREAS region. This paper focuses on the winter-spring thaw transition in the black spruce at the southern BOREAS site, and nighttime transects crossing the 1000 × 1000 km region at the SSA site. The tower flux data were augmented with in situ temperature and xylem flux data. Soil and canopy thaw transitions and the start of photosynthetic activity were monitored with the in situ measurements and compared with backscatter transitions in the ERS-1 data.

2.1. ERS-1 Imaging Radar

ERS-1 is the first of two identical polar orbiting Earth-viewing satellites launched by the European Space Agency (ESA) [*Duchossois*, 1986]. ERS-1 was launched in June 1991 and is continuing to operate through 1997. The ERS-1 synthetic aperture radar (SAR) is part of the Advanced Microwave Information (AMI) package, a unit with shared electronics for the radar and a scatterometer. The imaging radar is C band (5.7 cm wavelength; 5.25 GHz frequency) with vertical transmit and vertical receive (VV) polarization, and it illuminates the Earth's surface at an incidence angle of 23° from nadir. The swath width is 100 km with 30 m resolution for four looks. The data are also processed at a low resolution of 200 m for landscape-scale studies.

ERS-1 flies in a Sun synchronous orbit of 97.5° inclination and a morning equator crossing of 1030. The altitude for ERS-1 ranges from 775 km, providing a 3 day repeat coverage for the commissioning phase, or first 3 months of the mission and for the winter ice phases, to 781 km, providing a 35 day repeat for global access, to 783, providing a 168 day repeat for a geodetic portion of the mission. In 1994, ERS-1 was in a 3 day repeat until March 26. The orbit was then shifted to the first geodetic phase on April 10 with an equator crossing optimized for the spaceborne imaging radar (SIR-C/X-SAR) shuttle mission which flew in April 1994. On April 17 and October 1 the equator crossings were shifted, still maintaining a 168 day repeat. Table 1 summarizes the ERS-1 orbit for 1994.

Data from ERS-1 are transmitted to a number of ground receiving stations, including the National Aeronautics and Space Administration Alaska SAR Facility (ASF) at the University of Alaska Geophysical Institute in Fairbanks [*Weller et al.*, 1983; *Carsey*, 1988]. There the data are collected, processed, calibrated, and distributed. Scene-to-scene calibration stability is 0.3 dB [*Freeman et al.*, 1993]. No onboard recording capability is included, therefore, only regions in view of the ground receiving stations are accessible to ERS-1.

ERS-1 data are accessible over the majority of the BOREAS region from the ASF receiving station. During the 1993/1994 ice phase, the transect that crossed the Prince Albert site was

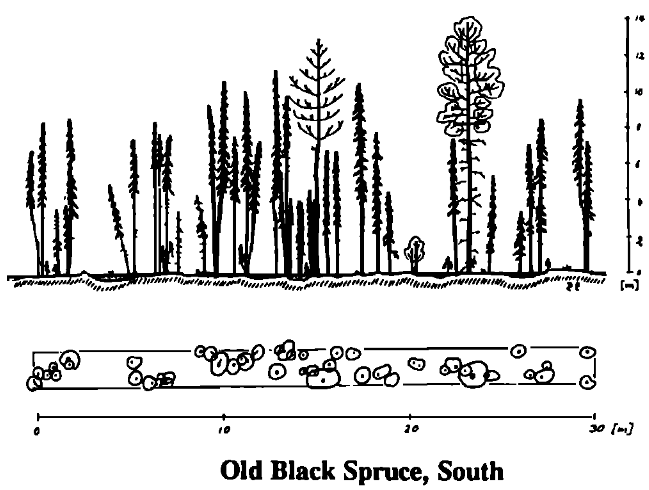

Figure 3. Cross-section sketch of southern black spruce stand.

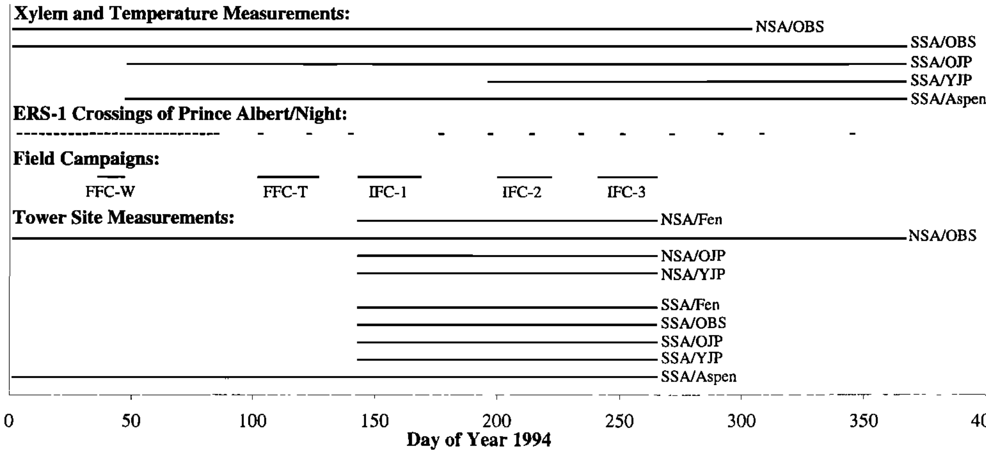

Figure 4. Duration of xylem and temperature measurements and tower measurements; timing of focused field campaigns for winter (FFC-W) and thaw (FFC-T) and intensive field campaigns (IFC-1, IFC-2, and IFC-3); and times of ERS-1 crossings (for the period of January 1 to March 26, crossings are every three days; beyond March 26 the orbit shifted to a 168 day repeat).

a nighttime ascending pass; no passes intersected the northern study area during this portion of the mission (see Figure 1). For this paper, we therefore focus on the night passes that cross the SSA. Additional data are available for the entire BOREAS region and for the day crossings starting in 1991. ERS-1 data continued throughout 1996 and beyond, and data from ERS 2, which was launched in 1995, will continue for 3–5 years from launch.

For each transect that crosses the SSA, low-resolution data were processed for the full transect, and full resolution data were ordered for the scenes that cover the tower sites. Each scene is a 100 km × 100 km square. The low-resolution data sets are mosaicked along track and displayed in a temporal series (Figure 5). The length of the mosaic is a function of the number of scenes available for each orbit of the ERS satellite. The early mosaics are shorter in length because ERS data were not acquired along the entire transect at that time. The scenes acquired between day of year (DOY) 4 and 78 corresponded to the 1994 ice phase of the ERS-1 satellite which provided exact repeat-pass data over the same sites every 3 days. Later acquisitions of ERS-1 data over the BOREAS study sites corresponded to a 168 day repeat cycle; the BOREAS sites could still be imaged about every 2 weeks but at a different location within the radar swath, therefore limiting the possibilities to automatically coregister the data on a pixel-per-pixel basis.

The full resolution scenes are used to extract backscatter signatures from the tower stands; these values are averages of at least 400 pixels collected from a uniform portion of the stand area. Figure 6 shows three of the full resolution ERS-1 scenes for the Prince Albert region immediately preceding and following the first thaw (DOY 60 and 63, respectively) and for summer (DOY 213). Figure 7 shows the backscatter values for the southern black spruce stand. The standard deviation in all cases is less than 0.3 dB.

Table 1. ERS-1 Orbit Parameters for 1994

Phase	Start Date	End Date	Repeat Cycle, Days	Notes
Ice	Dec. 23, 1993	March 26, 1994	3	
SIR-C	April 10, 1994	April 17, 1994	168	
Geodetic I	April 17, 1994	Sept. 26, 1994	168	node shift
Geodetic II	Oct. 1, 1994	present	168	node shift

2.2. In Situ Measurements

In situ tree and soil temperature and tree xylem sap flow were collected in the SSA black spruce for a full annual cycle starting on October 25, 1993 and ending in May 1995. Data were collected automatically by data loggers (DL-2, Delta-T Devices Ltd., Burwell, England) at each site. During summer the data storage rate was between 10 and 30 min (each data point representing the average of a continuous series of measurements collected on 30 s intervals), and during winter the data storage rate was slowed to 1 hour intervals to conserve memory. Line power supply (110 VAC) to the system was buffered by a DC charge controller, connected to 12 V/64 Ah lead batteries. This allowed continuation of all external power dependent measurements (xylem flux and micrometeorology sensors) for 5–10 days in case of temporal line power supply loss.

2.2.1. Temperature. Tree bole and soil temperatures were measured with linearized high-resolution thermistors (Siemens M841/S1/3K). The linearization algorithm accuracy was better than 0.1°C from −40° to +60°C. The sensors were installed in several trees in the tree boles at xylem depth, at approximately 2 m above the ground and in the adjacent soil at the depth of the rooting zone and in the upper 5 cm. The results are shown in Figure 7 for the 25 cm probe. Soil temperature data for this probe are missing beyond DOY 100 due to degradation of soil temperature sensors during freeze/thaw. The sensor at 5 cm depth failed early in the year, and no data are available.

2.2.2. Xylem sap flux. Xylem sap flux density was measured in the stems of nine trees at each site at 1.8–2.0 m above the ground with a thermal constant energy input method [*Granier*, 1987] (Figure 8). The temperature difference between the stem xylem and the center of a heated cylindrical probe (diameter 2 mm, length 20 mm) inserted in the hydroactive xylem (constant heat dissipation 200 mW) was measured every 30 s. Figure 9 shows the xylem flux density for the southern black spruce. Xylem flux density can be calculated for periods when there are no freeze/thaw phase transitions in the xylem. During freeze/thaw transitions, heat conductivity

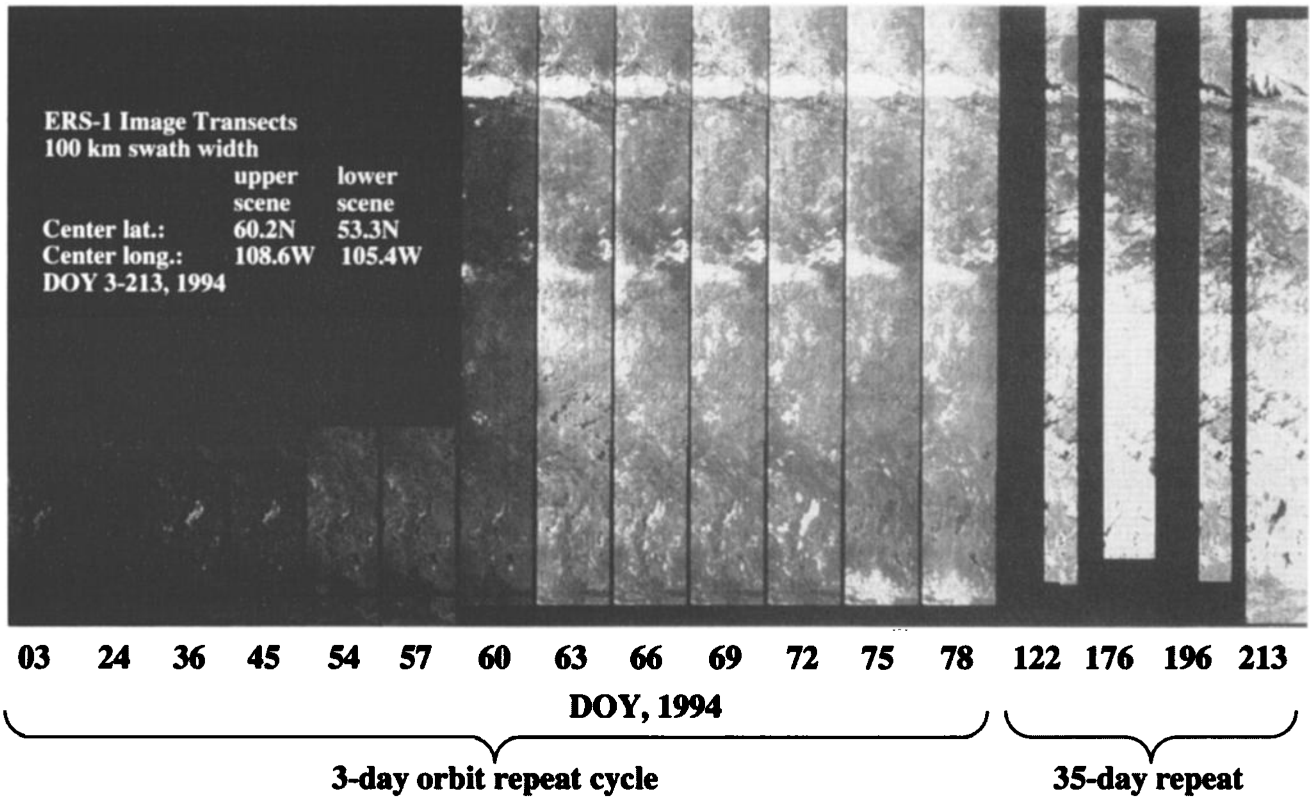

Figure 5. Transects across the BOREAS region which also intersect the Prince Albert site collected by ERS-1 for 1994 through the fall. Transects crossing the Prince Albert site occur every three days during the first part of the year and every few weeks for the duration of the year when the ERS-1 orbit is a 168 day repeat. The swath width for the transects is 100 km, and the resolution used is 200 m. A rise in backscatter on a landscape scale is apparent between DOY 60 and DOY 63 and between DOY 78 and DOY 122. In some areas of the transects, backscatter does not rise. For example, lakes show variable shifts in backscatter depending on whether the lake is frozen on the surface or to the bottom (see lake in bottom quarter of transect, which is black on DOY 213 and white on DOY 72), and agricultural areas at the bottom of the transect, which are dark up through DOY 72 and then shift from bright to dark depending on the surface cover.

changes in the unheated xylem much faster than in the heated areas, thus prohibiting a flux density estimate. Therefore the plots in Figure 9 start at DOY 138 when these transitions are no longer present in the early morning and late evening. Also shown is the xylem flux temperature gradient which indicates that no flux occurred preceding DOY 60. Some xylem flow may have started as early as DOY 60.

2.2.3. Meteorological measurements. A meteorological measurement setup was established at each tower stand, and the data were collected by the BOREAS Core Project and are part of the BOREAS Information System (BORIS) data set. Of particular interest for this work are the air temperature above the canopy and precipitation. These measurements were initiated at the black spruce stand in May, therefore, we show meteorological data from the nearby old jack pine stand. Rainfall was measured using a tipping bucket mounted on the tower. The results for air temperature, snow depth, and precipitation are shown in Figure 7. The results for precipitation are shown in Table 2 for each ERS overpass.

3. Analysis

The backscatter for the southern black spruce (Figure 7) shows a rise in backscatter between DOY 60 (March 1) and 63 and a second rise between DOY 80 (March 21) and 100 (April 6). A peak in backscatter on DOY 176 (DOY 175 in local time) is related to a rainfall event that occurred at the time of overpass (see Table 2); a rise in backscatter will occur with a wet canopy. Note that there were no simultaneous rain events for the other ERS overpass times. The magnitude of the first rise in backscatter on DOY 60 is between 1 and 1.5 dB with the second rise being approximately 2 dB relative to the midwinter values. On a landscape basis the transects shown in Figure 5 display the same two major rises in backscatter. Also noticeable are backscatter changes due to lake thawing and changing field conditions in the agricultural regions near Prince Albert at the bottom of the transects (see caption to Figure 5).

The measured soil and bole temperatures show a first thaw on DOY 60. Both the soil layer and the bole warm to a temperature of 0°C. The soil, acting as a large thermal buffer, remains near 0°C from DOY 60 to at least DOY 100. Air temperatures dropped back below freezing, indicating a freeze/thaw phase transition was in progress in the top soil layer from DOY 60 to DOY 100. The bole temperatures, however, continue to follow the air temperature, again dropping well below −20°C after the first thaw. This indicates that the water contained in the boles did not complete a phase transition and remained in a frozen state after the first thaw. On DOY 100, air temperature rises sufficiently to produce the persistent

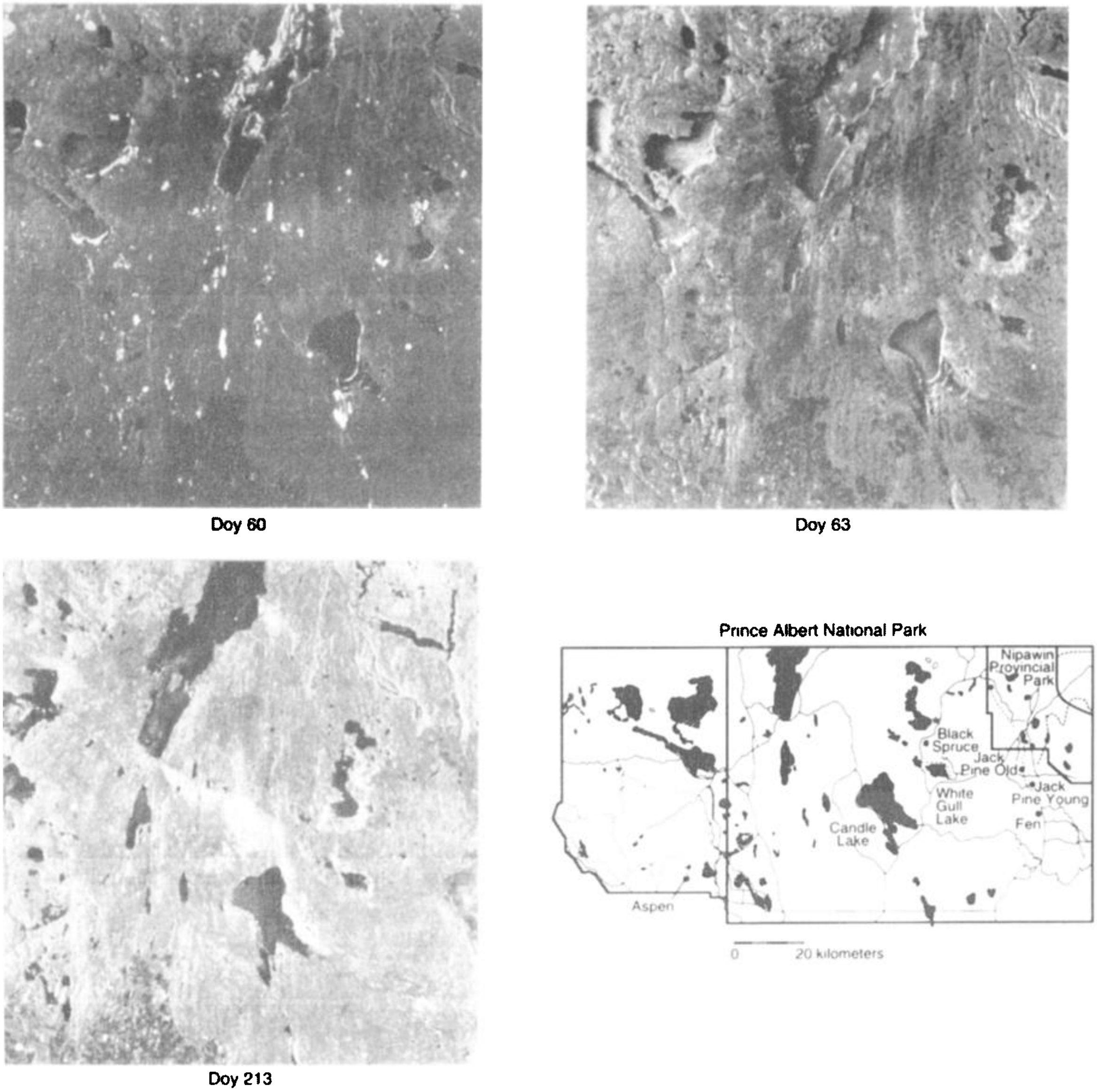

Figure 6. Full resolution (30 m) ERS-1 images for period preceding first thaw (DOY 60), just after first thaw (DOY 63), and summer (DOY 213). Also shown is a map for the Prince Albert region showing locations of tower flux stands.

transition to the liquid water phase in the boles. As air temperatures drop below freezing again, the boles now remain above or at 0°C. By DOY 138, both air and bole temperature remain above 0°C. At this time, we can calculate xylem flux without concern for errors due to freeze/thaw phase transitions. The xylem flux density data show significant xylem flow. The daily fluctuations in the xylem measurements reflect typical diurnal patterns of sap flow; flux drops to near zero at night or when the air temperatures approach freezing (e.g., see DOY 143). Before DOY 100, no xylem activity is observed. Between DOY 100 and 138 it is difficult to estimate xylem flux because solid-liquid phase transitions of the xylem water cause indeterminate shifts in the zero-flux baseline. The xylem temperature difference, shown in Figure 9 as a surrogate for the xylem flux measurements, indicates that no xylem flow occurred before DOY 100 as seen from the relatively unchanging temperature difference. Between DOY 100 and DOY 138, xylem flux is indicated; however, the magnitude is unknown.

The 1.5 dB rise in measured backscatter on DOY 60 is correlated with the observed in situ beginning of soil thaw on DOY 60. Unfortunately, the ERS-1 coverage frequency is not adequate beyond DOY 85 to allow a direct correlation with between the measured bole thaw and the second rise in backscatter. Although these responses are apparent, isolation of the source of the radar response to changes in dielectric properties of a single class of canopy component is limited since the ERS radar is a single-channel radar. In order to unambiguously interpret the sources of these temporal changes, a multichannel radar is required.

The ERS backscatter, an average of 400 pixels, was related to the stem temperature measured within an hour of the overflight. The ERS backscatter represents the composite effect of several types of surfaces in which water is thawing and freezing at different rates. Stem temperature is highly correlated to the temperature of other surfaces in an area, such as canopy and soil surface temperature, all of which change with air temper-

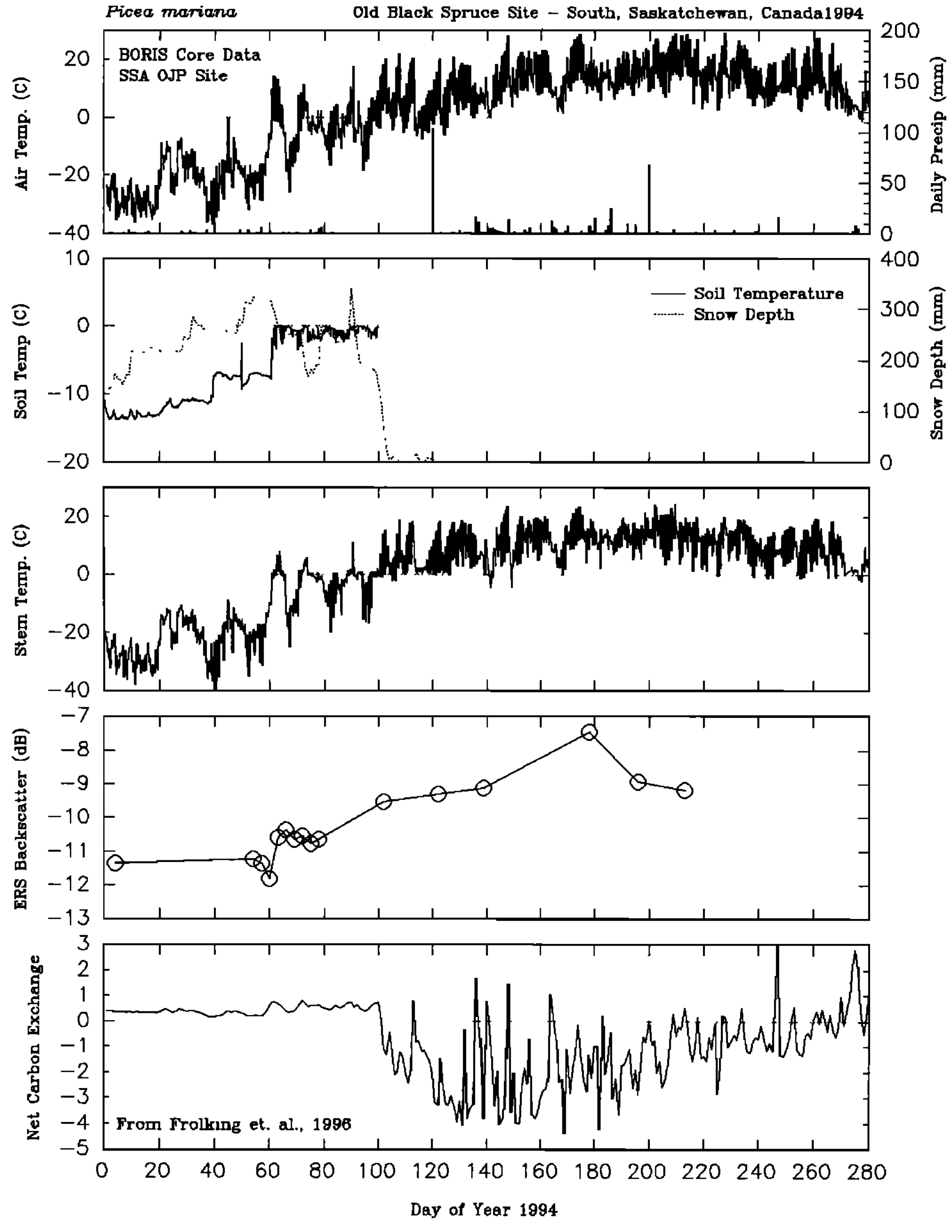

Figure 7. Above-canopy air temperature (C) and daily precipitation (mm) from BORIS core data acquired at the Prince Albert old jack pine site and soil (at 25 cm depth) and stem temperatures, ERS 1 backscatter (dB), and modeled carbon flux (g/m^2/d) from *Frolking et al.* [1996] for the Prince Albert black spruce site for 1994.

ature but at different time constants. Despite these confounding influences, using stem temperature to assess changes in backscatter was expected to reflect three distinct regions: (1) below freezing, where backscatter is lowest and fairly constant; (2) above freezing, where backscatter is higher and may reflect variations in the hydration state of the forest; and (3) a transition from lower to higher values as different components of the ecosystem thaw. The latter region is indicated by a range of stem temperatures which include values below zero (when canopy components thaw) to values above zero (when the soil thaws). A logistic regression, particularly suitable to describe dependency of such a pattern between variables, in the form of

$$\text{backscatter} = d + (a - d)(1 + (c - 1\ Ts)b) - 1$$

where $a = -11.15$, $b = 7.78$, $c = 28.34$, and $d = -9.00$ are coefficients generated by the regression procedure; backscatter is in dB; and Ts is stem temperature in °C. The three regions expected, based on first principles, are clearly seen in Figure 10, which also shows a surprisingly strong relationship between ERS backscatter and an increase in "ecosystem surface temperature," as approximated by stem temperature.

4. Discussion

In general, low soil temperatures inhibit microbial activity and thus soil respiration. Frozen plant structures (roots and stems) prohibit water transport in plants and thus limit leaf-gas exchange due to the risk of desiccation, even if the photosyn-

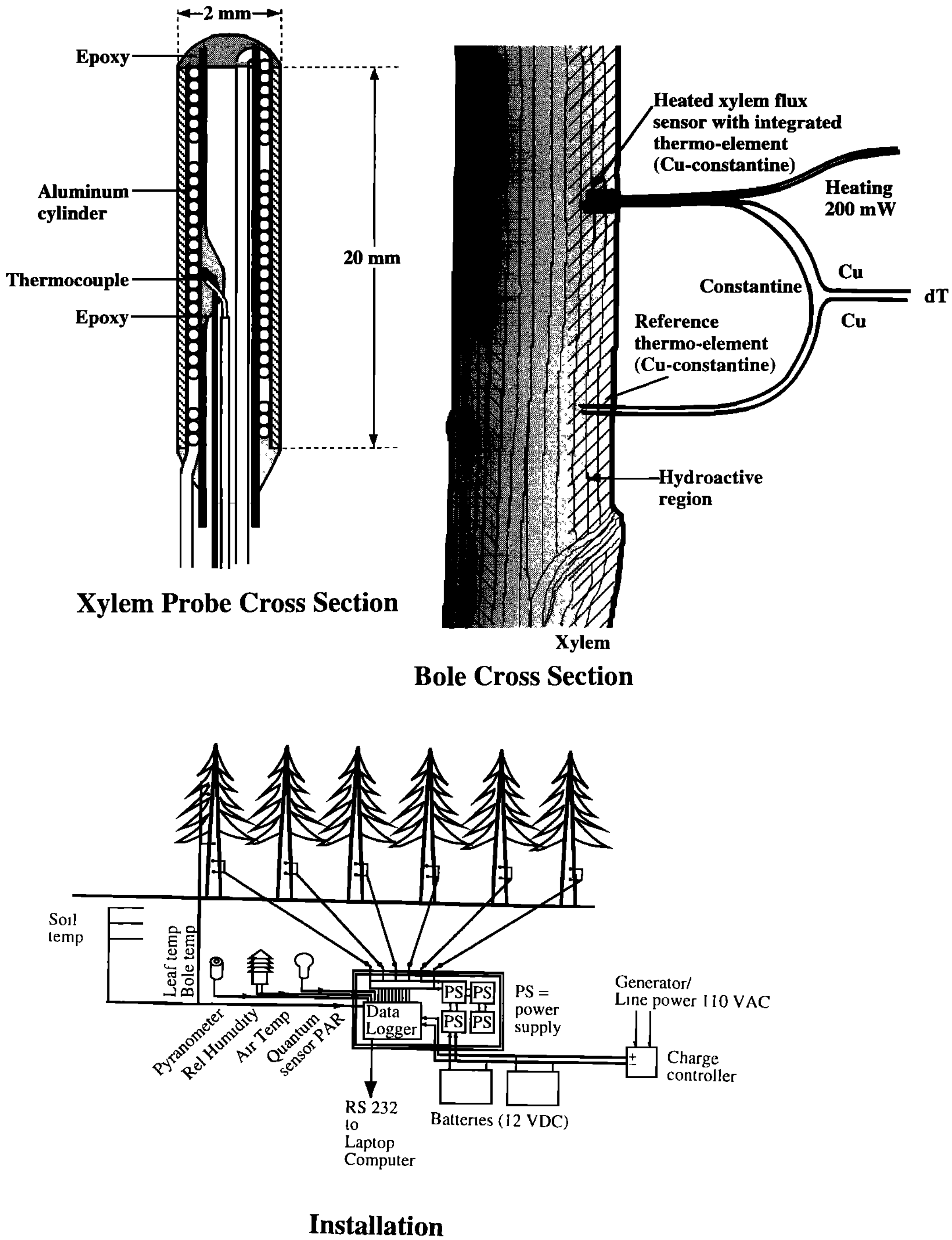

Figure 8. Xylem tip used to measure xylem flux, installation of xylem tips in hydroactive region of xylem, and installation at site.

thetic apparatus of plants is already functional in spring. The temporal dynamics of thawing for small-size aboveground plant components (leaves and twigs), structural and transport components of plants (branches and stems), and nutrient and uptake components (roots) are quite different. Roots are thermally in equilibrium with the soil and lag considerably behind the aboveground thawing of plant components.

During the spring thaw period of 1994, no tower flux data were collected for any of the coniferous species in the southern BOREAS sites but are available from the northern black spruce site. The close relationship between soil or bole thawing and marked changes in gas exchange patterns for carbon dioxide among the soil, trees, and atmosphere were demonstrated by *Goulden et al.* [this issue]. Carbon flux was modeled by *Frolking et al.* [1996] for the northern mature black spruce/moss forest, using daily weather conditions. The model results were then compared to the in situ CO_2 tower flux measurements. The model simulation of daily soil climate status, spruce photosynthesis and respiration, moss photosynthesis and respiration, and litter decomposition indicated that the northern black spruce ecosystem is actually a carbon sink since winter respiration (carbon loss from the ecosystem) during the snow-covered season was 58% of the net carbon gain during the growing season. A 10 year simulation of carbon exchange

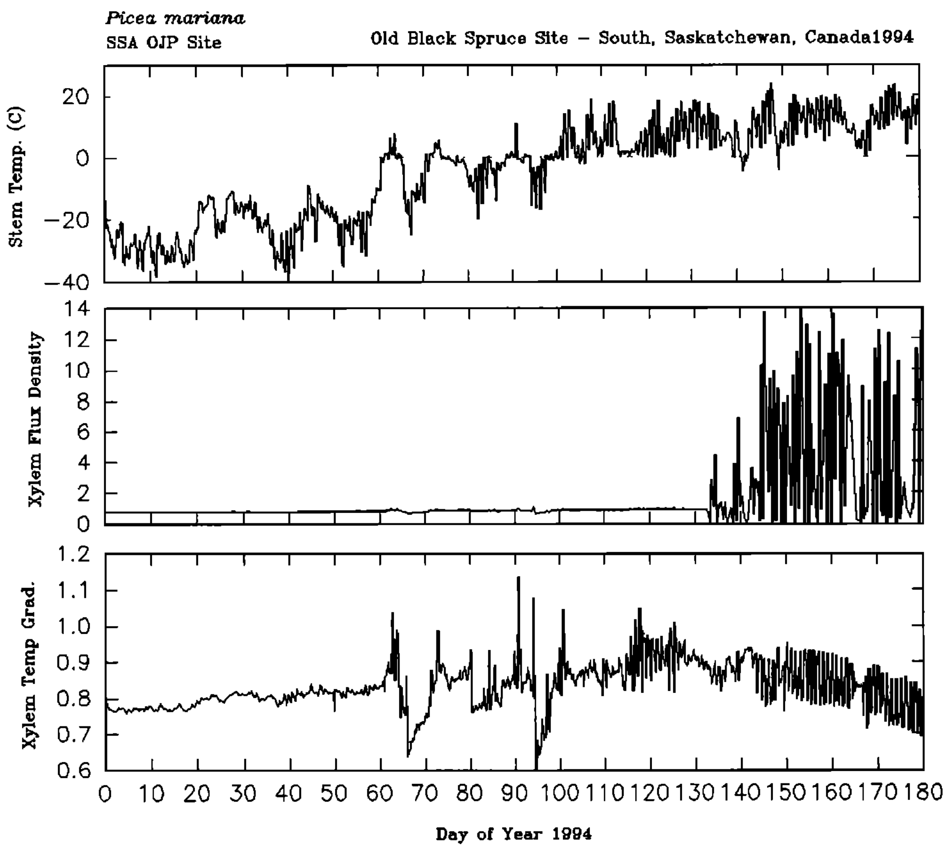

Figure 9. Stem temperature, xylem flux density (g^2/s^2) and xylem temperature gradient (mV) for the Prince Albert black spruce site for 1994.

showed a year-to-year variability of up to 5 weeks in heterotrophic respiration [*Frolking*, this issue]. This simulation indicates that the variability in amount and duration of CO_2 release, as a result of metabolic activity by cells that do not contain chloroplasts (like soil bacteria and most structural components of plants), was primarily due to the onset of spring thawing. To a lesser extent, the soil respiration was influenced by the occurrence and intensity of summer precipitation.

The controlling factors for the onset of metabolic activity in spring are the loss of snow cover (for the mosses), and soil thaw, and root water availability (for trees). The timing of fall freeze-up and snow had much less impact on plant productivity. The same model of *Frolking et al.* [1996] was run using daily weather conditions from the southern black spruce site (S. Frolking, personal communication, 1996, Figure 7). The results of the model show a significant increase in soil respiration on

Table 2. Precipitation at ERS Overpass Time (Local Standard Time)

DOY of ERS Overpass	Hour of ERS Overpass	Precipitation in Previous 12 Hours, mm	Time of Precipitation Measurement
2	2200	0.1*	2100
53	2200	0.0	
56	2200	0.2*	2145
59	2200	0.0	
62	2200	0.2*	2100
65	2200	0.6*	1100
68	2200	0.0	
71	2200	0.0	
74	2200	0.0	
77	2200	1.0*†	2145
101	2200	0.0	
121	2200	0.0	
138	2200	0.3	0700
175	2200	2.5	2130
195	2200	8.6	0000
212	2200	0.0	

*Precipitation fell as snow.
†Accumulated snowfall, 32 mm.

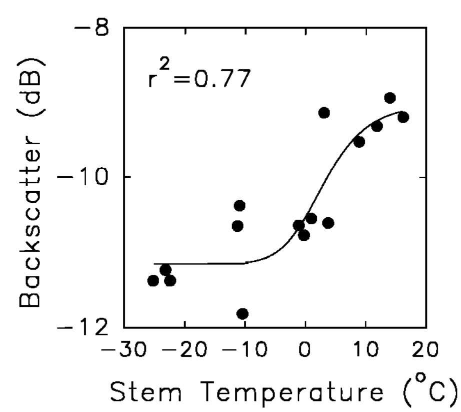

Figure 10. Plot of ERS backscatter versus stem temperature for the southern study area old black spruce. Line represents the results of a logistic regression (see text).

DOY 60, which is sustained for most of the rest of the late winter/spring transition. Net plant carbon gain starts at approximately DOY 100. The results of the model suggest a strong correlation between carbon flux patterns and soil freeze/thaw state. We demonstrated that the radar backscatter detects this freeze/thaw transition and thus provides a means to determine the actual time of this important status change of the vegetated land surface in spring.

5. Summary and Conclusions

The bole and soil temperature data at the southern black spruce site show the beginning of a transition from completely frozen soil to the onset of soil thaw on DOY 60, where soil thaw is defined as the time when soil water shifts from a frozen to a liquid phase. The water in the tree stems finally thawed on DOY 100 and remained at or above 0°C after this date. The xylem flux is fully active by DOY 138 and may begin as early as DOY 60. The ERS-1 data show a significant rise in backscatter between DOY 60 and DOY 63. The backscatter does not drop back to its winter value after this date even though the stem temperatures drop below 0°C. A second rise in backscatter also occurs in the spring; however, the temporal resolution of the ERS-1 data does not permit a direct correlation of this second rise with stem thaw. On the basis of these results, ERS-1 temporal backscatter changes are dominated by soil thaw and potentially by canopy thaw. The soil thaw is consistent with the start of soil respiration, which in 1994 starts as early as March at the southern BOREAS site.

In summary, radar provides an ability to observe thaw transitions of vegetated surfaces at the beginning of the growing season. Existing radar platforms have sufficient time resolution for repeated observations in order to detect ecologically significant interannual variations of these events. On the basis of the results of other BOREAS investigators, early spring soil thaw triggers an increase of respiration. Although the fluxes are small in March through June, the duration of this carbon loss from the ecosystem to the atmosphere is quite long and therefore a relatively large factor in the annual carbon budget.

It appears possible that a radar-based measure of thaw transitions serves as a surrogate for springtime phenology or as an onset of growing season. Radar also provides a reliable data source for estimating circumpolar carbon flux in boreal forests because the cloud cover and low Sun angles do not impede imaging. Landscape-scale freeze/thaw maps of the global boreal forest generated on a consistent, long-term basis would provide a useful measure of spatial and interannual variations in growing season length. This information could be used in carbon flux models either to validate the models or as a direct input. Imaging radar thus provides a method for virtually continuous daily global coverage of freeze/thaw status regardless of seasonal or atmospheric conditions. This phenology monitor could be the vegetation equivalent of monitors of global snow cover and sea ice that are being used to observe hydrologic responses to global change.

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