Initial Results from the Boreal Ecosystem-Atmosphere Experiment, BOREAS

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BOREAS is a four-year, regional-scale experiment to study the forested continental interior of Canada. The objective of BOREAS is to improve our understanding of the interaction between the earth's climate system and the boreal forest at short and intermediate time scales, in order to clarify their role in global change.

During the winter, spring and summer of 1994, five field campaigns were conducted. About 85 investigation teams including nearly 300 scientists participated, including forest ecologists and ecophysiologists, atmospheric physicists, boundary-layer meteorologists, hydrologists, biochemists, atmospheric chemists and remote sensing specialists. Data from the field campaigns is being placed into a central archive at the Goddard Space Flight Center for immediate access by all participating scientists, and eventually by the outside scientific community.

Analysis of the data began in mid-summer as the data were being collected and continues at a rapid pace. The findings so far have been significant in terms of their implications for global change. The boreal ecosystem, occupying roughly 17 percent of the vegetated land surface and thus an important driver of global weather and climate, absorbs much more solar energy than is assumed by operational numerical weather prediction models. Albedo measurements in BOREAS shows that this forest absorbs nearly 91 percent of the sun's incident energy. Additionally, while it is known that much of the boreal ecosystem consists of forested wetlands, numerous lakes, bogs and fens, tower and aircraft measurements during 1994 show that the atmosphere above was extremely dry; humidity and deep boundary layer convection (3000 m) mimicked conditions found only over deserts. Physiological measurements of the trees during BOREAS show that this atmospheric desiccation was a result of the forest's strong biological control limiting surface evaporation. The data further show this tight control was linked to the low soil temperatures and subsequently reduced rates of photosynthesis.

BOREAS measurements also focused on net ecosystem carbon exchange. Data acquired during the late spring and summer, showed the boreal forest to be a net carbon sink. However, no measurements were taken in the early spring following thaw, and in the late fall, where the balance between photosynthesis and respiration is poorly understood. During 1996 additional data will be acquired to resolve the annual carbon budget and how it might depend on interannual climate differences.

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1 Introduction

The boreal ecosystem girdles the Earth above about 48 degrees north latitude and covers about 17 % of the earth's land surface (Whittaker 1975). It consists primarily of aspen and coniferous forests and is second in areal extent only to the world's tropical forests.

The role of the boreal ecosystem in influencing global climate and weather patterns is not well understood. It is well accepted now that variations in the ratio of sunlight reflected to that absorbed by land surface vegetation is a major driver of local and global atmospheric circulation. Light reflected back to space has little effect on atmospheric dynamics. On the other hand, light absorbed by vegetation, either heats the surface, in turn heating the lower atmosphere (sensible heat), or is released as evaporation (latent heat) which eventually condenses into clouds; the ratio of heat energy release to evaporative energy release can have very different effects on the dynamics of the lower atmosphere.

The role that the boreal ecosystem plays in global carbon dynamics, is also just emerging. Theoretical studies suggest that these forests play a strong role in cleansing the earth's atmosphere of excess carbon dioxide, by removing nearly 20 % of the annual emissions from fossil fuel combustion yearly (Tans et al. 1990). The exact mechanisms involved and the spatial contributions to this sink are as yet unknown, but the implication is that carbon is being stored in either living tissue or in the soil.

Other studies suggest however, that the areal extent and composition of the boreal forests might be greatly affected by rapid climatic change resulting from global warming (Davis and Botkin 1985, Solomon and Webb 1985) altering the vast stores of carbon accumulated since the last ice age. Such changes would alter the rate at which the boreal ecosystem accumulates or releases carbon thus accelerating or mitigating global warming. Such changes may also have feedback effects on the near-surface climatology, i.e. temperature, humidity, precipitation and cloudiness fields (Sato et al. 1989).

BOREAS was instigated to improve the understanding of the above interactions in order to clarify their roles in global change. BOREAS is a large scale, international investigation focused on improving our understanding of the exchanges of radiative energy, sensible heat, water, CO_2 and trace gases between the boreal forest and the lower atmosphere. A primary objective of BOREAS is to collect the data needed to improve computer simulation models of the important processes controlling these exchanges so that scientists can anticipate the effects of global change on the biome, in particular the effects of altered temperature and precipitation patterns.

2 Experiment Design

As shown in the accompanying graphic, BOREAS employed a multi-scale experiment design (see Fig. 1), permitting physiological, ecological and other information obtained at the leaf, plot and study area level, to be translated, via remote sensing and process models, to regional, and ultimately global scales.

BOREAS was designed to measure and verify what was known at the leaf and plot level about ecophysiology and the biophysics of nutrient cycling, and what was known at the mesoscale and global levels about surface/atmosphere interactions and atmospheric circulation dynamics. The design permitted knowledge at one scale to be

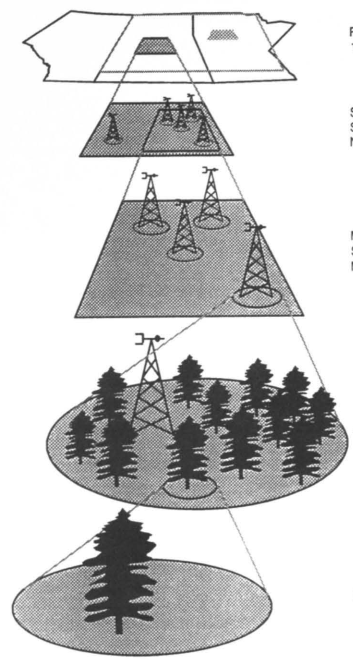

Fig. 1. Multiscale measurement strategy in BOREAS.

translated and compared to knowledge and data at different scales. The goal of experiment design was to permit understanding of the regional scale well enough to simulate various scenarios of global change, and their consequences; thus, BOREAS was not a program of strictly monitoring to observe change over a long period, but rather to develop the understanding necessary to simulate processes over a wide range of scales.

For example, general circulation models run at very coarse spatial resolutions on the order of hundreds of kilometers; thus, one required scale of investigation in BOREAS was the 1000 × 1000 km scale. Since it is impractical, even with aircraft, to measure these energy/water/carbon fluxes over areas larger than about 40 km, another scale of investigation is about 50 × 50 km. This scale is small enough to permit ground and aircraft characterization, yet large enough to test scaling hypotheses with models and remote sensing images. To verify the aircraft measurements of surface energy, water and carbon flux, and remote sensing estimates of biophysical parameters, measurements at a scale of about 1 km were utilized where towers were used to measure water, heat and CO_2 fluxes over relatively homogeneous patches. To characterize the ecophysiology, and biophysical characteristics these patches were subsampled with plots and within plots, measurements were made of site-level biomass density, leaf area index, light absorption, photosynthetic rate, litter decomposition and quality, soil moisture and temperature etc, all the variables needed to drive stand-level ecophysiological models.

A key tool that permits translation of this knowledge among scales is remote sensing, which in BOREAS was done at all scales from the leaf level using laboratory spectrometers, to the regional scale using satellite data such as the Na-

Team	Team Name	Number of Teams
AFM	Aircraft Fluxes, Meteorology	14
TF	Tower Flux	10
TE	Terrestrial Ecosystems	21
HYD	Snow and Hydrology	10
TGB	Trace Gas and Biogeochemistry	10
RSS	Remote Sensing Science	21

Fig. 2. BOREAS science teams.

tional Oceanic and Atmospheric Administration (NOAA) satellite series Geostationary Orbit Environmental Satellite (GOES) and the NOAA satellite series carrying the Advanced High Resolution Radiometer (AVHRR).

3 Implementation of the Experiment Design

To accomplish the measurements and modeling at the different scales required a large team of scientists, trained in the several disciplines involved. As shown in Fig. 2 over 85 teams were chosen through a competitive solicitation, and began work in 1993. These nearly 300 scientists were supported by a staff of about 11 people at the Goddard Space Flight Center (GSFC), who set up infrastructure, calibrated instruments, managed operations, did all the satellite data acquisition and analysis, and the very important job of building and maintaining a data system BOREAS Information System (BORIS) to distribute data to all BOREAS investigators as it becomes available. In BOREAS, every investigator has access to every other investigator's data, so BORIS serves the central function of acquiring the data from each investigator, putting it into a uniform format, working with the PI to document it, and putting it on line so that every one has access to it. In the end, the BOREAS data will be packaged, along with the documentation, and made available to the general science community.

In BOREAS many of the measurements were continuous or at least periodic. Some towers ran continuously, and some teams were in the field all summer. Certainly, satellite data were collected continuously. But to sustain an effort of this magnitude on a continuous basis is not possible, so periods were defined for intensive visits to the field by all investigators called intensive field campaigns. Experiment operations began in August of 1993 with an intensive field campaign (IFC) designed primarily to test equipment and operations procedures, but the major focus was the winter, spring, and three summer periods of 1994, of approximately two weeks each. The IFC's were spaced to catch the major phenological events, including a snow hydrology campaign in the winter, spring thaw, greenup, peak greenness, and beginning of senescence.

A variety of instrumentation was in place at the various scales. Beginning with the 1000 × 1000 km BOREAS region the existing operational meteorological network in Canada was augmented with nine automated meteorological stations acquiring the data needed to drive both the mesoscale and GCM models. In addition, satellite data was also collected or the entire region and aircraft transects flown between the Southern Study Area (SSA) and Northern Study Area (NSA) to characterize a transect between the two study areas.

At the study area level, two approximately 50 × 50 km study areas were located on the northern and southern edge of the boreal ecotone to capture a wide range of conditions for the driving variables (see Fig. 3). To characterize the study area energy, water and CO_2 flux, aircraft were used to fly flight lines at the edges of the study areas, and in grids over the study areas, using eddy correlation probes which permitted a computation of the area-averaged surface flux over a region, as well as the flow in and out the

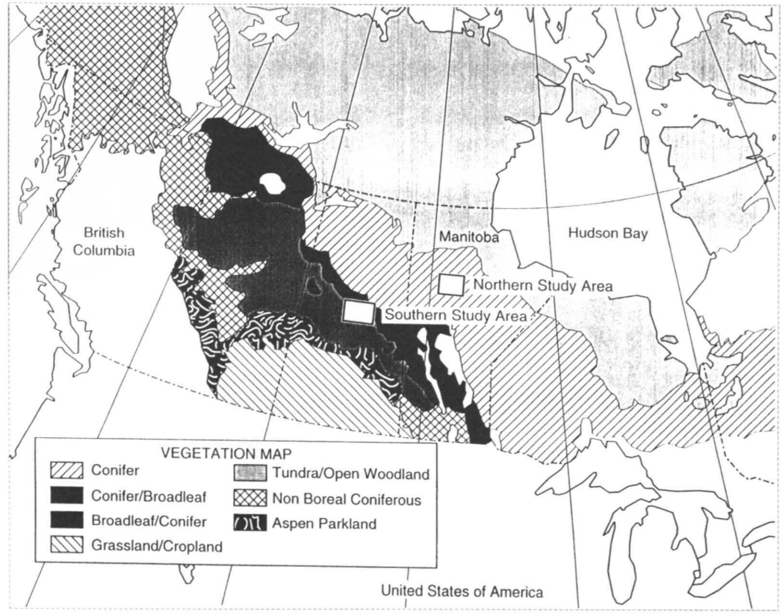

Fig. 3. Map of Canada showing location of the two BOREAS Study Areas and the major vegetation formations of the biome.

sides and boundary layer top of a three-dimensional box covering the area. A large part of the project operational management responsibility was to schedule these aircraft between the two study areas, and within the study areas, where often as many as eight aircraft operated at similar altitudes.

In each study area three boreal forest dominants were characterized by plot level measurements: black spruce, jack pine and aspen. Within each of these classes both mature and young regenerating stands were instrumented, as well as two wetland fens, one in the NSA and one in the SSA. Because the nine tower sites could not capture the range of variability in the region, an additional 70 auxiliary sites were also allocated, stratified by species type, productivity and age. In these approximately 100 × 100 m sites biometry and optical techniques were used to measure biomass density, leaf area index, NPP, litter fall etc. While the models will be tuned primarily on the tower flux sites, the auxiliary sites will be used as independent test sites for model predictions.

In the NSA, where trace gas studies were concentrated, a number of beaver pond sites and a collapsed palsa were also instrumented to measure methane flux.

At all these sites a remote sensing science program was implemented to characterize the optical properties from the leaf level, using lab spectroradiometers, to the canopy and stand level using tower and helicopter mounted spectrometers, to the study area and regional level using aircraft and satellite platforms.

To fund and obtain the international cooperation required for a project of this scale required the collaboration of several US and Canadian agencies and other organizations from around the world. The US National Aeronautics and Space Administration (NASA) and the Canadian Center for Remote Sensing CCRS led the study, with support also from the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation and Canadian agencies, the National Science and Engineering Research Council of Canada, Environment Canada, Agriculture and Agri-Food Canada, Canada Forest Service, and the National Research Council of Canada. There is also significant support from research agencies in the United Kingdom and France.

4 Operations

In August 1993, many of the BOREAS investigators and staff were in the study areas as part of an operational test, IFC-93. This 21-day IFC was used to test the experiment infrastructure and investigator's instruments as well as to refine coordination and communication procedures. All of these experiences were pooled to rewrite the four volume experiment plan which served as the basis for running operations in 1994. During IFC-93 and the 1994 field campaigns, operations were coordinated out of two centers, one in the NSA and one in the SSA. Each center was equipped with ground-to-ground and ground-to-air radio links, telephones, fax machines, etc. to maintain real-time management of the airborne operations and related surface work. Nightly BOREAS Operations Group meetings analyzed the results of the days completed operations and set up the next day's activities. Weekly science meetings provided a useful forum for sharing scientific results and reviewing recent progress. In addition to Landsat and SPOT images, data were acquired from GOES; AVHRR and ERS-1 (European Resource Satellite) over the BOREAS region throughout the field year.

The last field campaign ended in September of 1994, and the first science workshop was held in December and the initial summary of results is presented in Sellers et al. (1995). Even at this early stage in the experiment, a fascinating picture is emerging of the energy, water and carbon dynamics of the boreal ecosystem and its strong coupling to the boreal soils and forest species types.

5 Results

A fundamentally new realization from BOREAS is that the composition of the boreal forests and soils may be as much a determinant of boreal climate as the boreal climate is of the nature of the boreal ecosystem. In addition, the parameters of the interaction between the boreal ecosystem and the atmosphere are quite different than previously believed.

Much of the boreal forest of central Canada grows on a nearly flat terrain composed of mineral soils deposited by glaciers and lakes during the last ice age. These soils are overlain by a thin layer of live and decomposed moss to which the tree's root systems are largely confined. Because annual precipitation exceeds evaporation, the moss layer and soil surface generally stays saturated, even throughout the summer. With an abundant water supply and the warm summer temperatures of central Canada, trees should be capable of sustaining large growth rates, and a correspondingly large capacity to transpire water to the atmosphere, humidifying the atmospheric boundary layer.

Instead, BOREAS tower and aircraft measurements of evaporation and heat release showed that the forest behaves more like a desert than a wetland. The transpiration rates observed from the coniferous forests were low on most days (< 2 mm/day) throughout the growing season. Figs. 4 and 5 show time-series of midday evaporative fractions (latent heat flux divided by the sum of the latent and sensible heat fluxes) and CO_2 fluxes, respectively, as reported by some of the TF sites during the intensive field campaigns. Again, we see some very low evaporative fractions (corresponding to high Bowen ratios) over most of the sites most of the time. These are associated with much lower CO_2 fluxes than are commonly observed over temperate forests (Verma et al. 1986). The exception to this generalization are the aspen and fen sites which after a rapid leaf-out in IFC-1 maintained the highest evapotranspiration and carbon draw down rates of all the sites. By contrast, the SSA Old Jack Pine site and the SSA Old Black Spruce site reported mean growing season evapotranspiration rates of around 1.3 to 2.0 mm/day, respectively. These two sites more or less bracket the

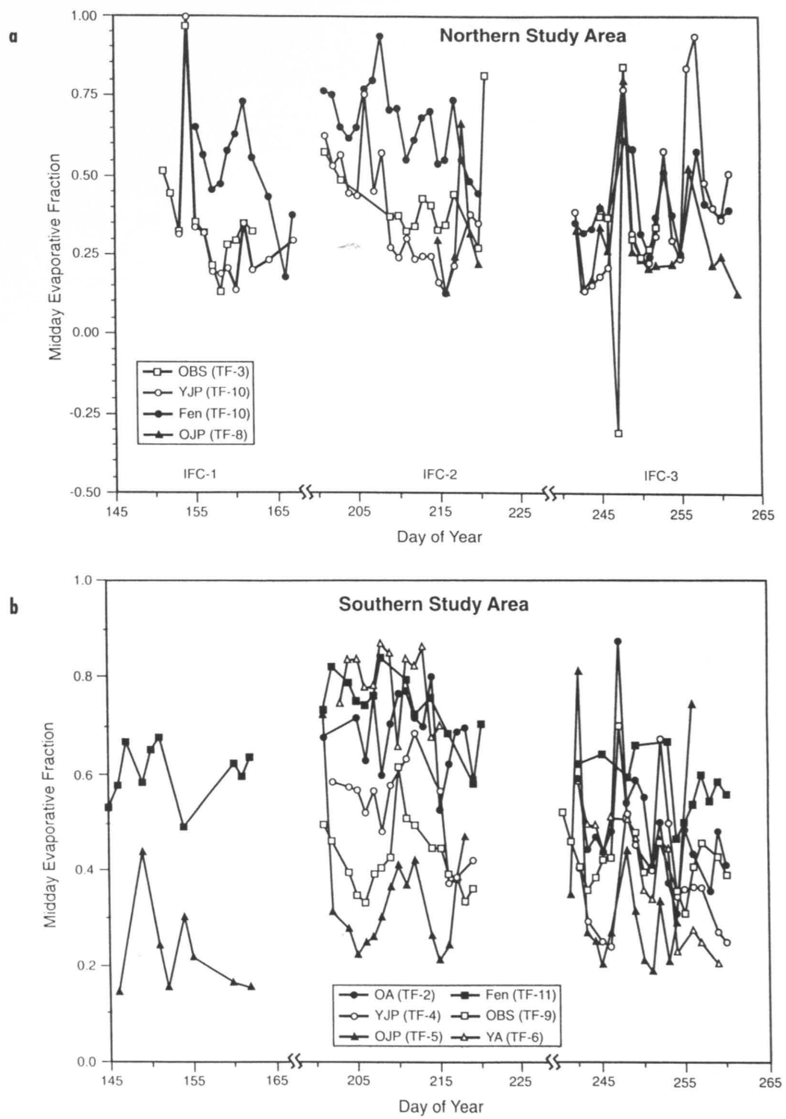

Fig. 4. Time-series of evaporative fractions (LE / (H + LE)). These were calculated from preliminary analyses of flux measurements averaged over a one-hour period centered on midday for each day of the IFC. (a) Northern Study Area, (b) Southern Study Area.

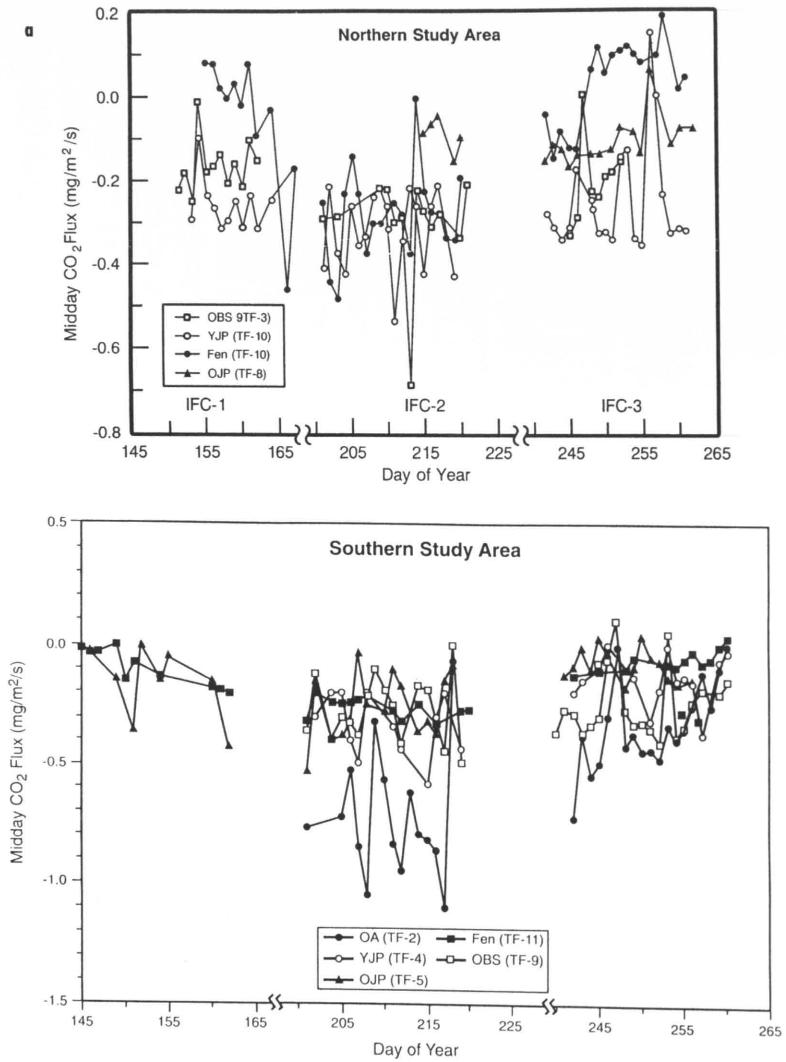

Fig. 5. Time-series of total (above canopy) CO_2 flux. These were calculated from preliminary analyses of flux measurements averaged over a one-hour period centered on midday for each day of the IFC. (a) Northern Study Area, (b) Southern Study Area.

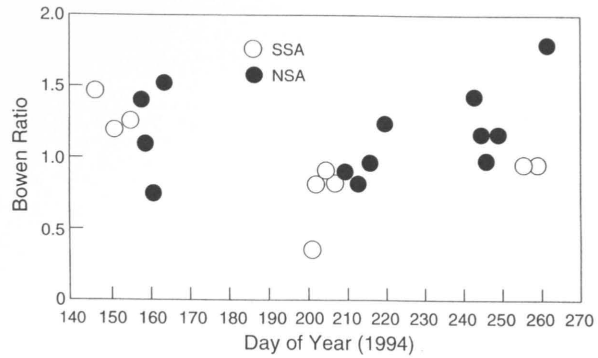

Fig. 6. Seasonal pattern of Bowen ratios for the SSA and NSA grid patterns as flown by the Twin Otter in BOREAS.

range of wet (black spruce) and dry (jack pine) conditions over most of the BOREAS sites and present us with a new and unexpected picture of the partitioning of energy at the surface in this region. These data are consistent with those measured from eddy-correlation aircraft flying patterned grids over the study area.

For example, the National Research Council Twin Otter flux aircraft flew a total of 22 double-grid patterns (9 in the SSA, 13 in the NSA), during the 1994 IFCs. These patterns consisted of a series of nine 16-km parallel tracks with a spacing of 2.0 km. Three of the flux tower sites were contained within this grid. Many of the Twin Otter grid patterns were flown in coordination with the University of Wyoming King Air, which flew a 32 × 32 km grid that encompassed both the Twin Otter grid and another of the flux tower sites (Old Black Spruce). The Twin Otter was flown at an altitude of approximately 35 m, while the King Air operated at 60 m. On each occasion, the grid was flown twice, with the second pass flown in the opposite direction to the first. This procedure ensures that each pair of legs flown are time-centered on the same reference time, a technique designed to remove time trends from the data. Fig. 6 shows the Bowen Ratio (H/LE) computed from the sensible (H) and latent (LE) heat flux measured by the Twin Otter and averaged over all 18 runs of each double grid pattern.

Two points are worth noting: first, the SSA is generally associated with lower Bowen ratio values (i.e. higher latent heat fluxes) over the period and; second, the values are consistently high, that is the area-averaged daytime sensible heat flux is greater than the latent heat flux (Bowen ratio greater than one). These data were acquired under a wide range of radiation conditions, from smoky and cloudy through to clear-sky. Bowen ratios were consistently higher under clear-sky conditions. These high Bowen ratios suggest significant stomatal control by the vegetation. Other data collected in the experiment support this and indicate that under warm, clear-sky conditions, the stomata of coniferous trees tend to close down in response to the associated high atmospheric vapor pressure deficit, presumably a self-protective mechanism to prevent desiccation of the foliage and embolisms in the conducting tissue. By mid-morning stomata were responding to falling humidity as the atmospheric boundary layer expanded and dried from solar heating. The boundary layer expansion was accelerated by the evaporative shutdown of the vegetation. This positive feedback between the vegetation physiology and lower atmosphere resulted in deep convection by mid-morning, creating boundary layer heights greater than 3000 m, similar to those observed over deserts.

The key to understanding this somewhat unexpected picture of an atmospherically arid wet-

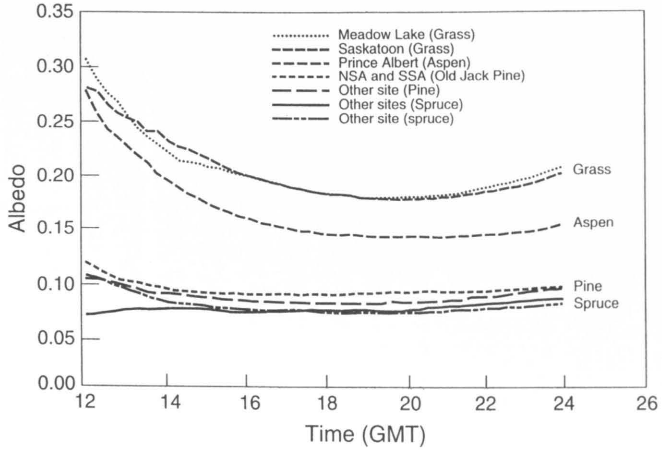

Fig. 7. Surface albedos for different vegetation covers found in the BOREAS region. The data were obtained from the BOREAS automatic meteorological station (AMS) network.

land ecosystem appears to lie with the low photosynthetic capacity observed for the boreal vegetation. Measurements showed that the boreal species have considerably less photosynthetic capacity than temperate forests to the south. This is reflected in low rates of annual carbon dioxide exchange with the atmosphere, and associated low carbon fixation rates. Low photosynthetic capacities in turn may be related to the limited root volumes of the forests and low soil temperatures with correspondingly low rates of nutrient cycling. Because transpiration of water from boreal vegetation is strongly coupled to photosynthetic rates, the boreal soils themselves and the adaptation of boreal vegetation to these harsh conditions, may provide a key to understanding boreal climatology and the effects of future climate change.

Another somewhat unexpected result is the very low albedos measured for the surface of the boreal forest. Fig. 7 was produced from analyses of the short wave radiation measurements made by the mesoscale network of automatic meteorological stations (AMS). Each AMS is equipped with upward and downward looking radiometers which allows for the direct calculation of albedos for the different vegetation covers found in the BOREAS region. The European Center for Medium Range Forecasting (ECMWF) model assumes that the boreal winter-time albedo prior to snowmelt is that of a bare snow-covered surface, i.e. about 0.8. However, the BOREAS AMS measurements show that during the winter, the coniferous canopy cover obscures the snow background almost completely, reducing the albedo of snow cover by an order of magnitude to about 0.08. The erroneous value for winter-time albedo in the ECMWF model causes large errors in the ECMWF predictions of surface air temperature by as much as 18 °C. During the non-winter months the ECMWF albedos are also higher than those measured in BOREAS. The grassland areas in the 1000 × 1000 km BOREAS study region show albedos of between 0.19 and 0.26, depending on solar angle, while the coniferous covers (Jack Pine and Spruce) show almost constant albedos of between 0.07 and 0.11 during the day. The fully foliated aspen cover with a total (canopy plus understory) leaf area index of between 4 and 5 has intermediate values. The variation in albedo with solar angle is a function of the heterogeneity of the surface cover and hence the amount of shadowing in the canopy: the spire-shaped crowns of the black spruce canopies generate a large proportion of shadowed area while the relatively diffuse deciduous and grass canopies behave more like classical turbid media with regard to radiative transfer and are therefore characterized by relatively strong variations in albedo with solar angle.

Table 1. Aerial fractions of landcover type as estimated from classification of composited AVHRR data over the BOREAS 1000 × 1000 km region.

Landcover type	% of total
Wetland conifer	27.0
low density	(5.0)
medium density	(14.5)
high density	(7.5)
Upland conifer	5.5
Mixed coniferous/deciduous	22.7
coniferous dominated	(8.1)
coniferous, deciduous codominant	(8.7)
deciduous dominated	(5.9)
Bare/very sparsely vegetated	6.5
Recent burn (< 5 years)	4.4
Visible regeneration from fire/logging	16.2
Open water	13.3
Unidentified	4.4

These and later findings should have significant implications for our understanding of how this important ecosystem influences weather, climate and other global processes. In an earlier similar study of the grassland prairies of the US called FIFE (Sellers and Hall 1992, Hall and Sellers 1995), scientists showed that more correctly accounting for the stored soil moisture and evaporative heat release in operational weather forecast models, permitted much more accurate predictions of the 1993 floods that inundated portions of the US Central Plains. Current weather models do not realistically represent the boreal ecosystem; thus it is anticipated that the BOREAS results, when incorporated into operational forecast models, will greatly improve weather forecasts in the short term, as well as longer term climate simulations.

As mentioned in Section 3, to permit scaling the results from the plot level to regional and global levels, the BOREAS experiment design incorporated a remote sensing science component that utilized ground, aircraft and satellite remote sensing to provide a self-consistent set of vegetation biophysical properties (landcover type, LAI, biomass density, Fapar, etc.) at all geographic scales. These properties, along with their desired spatial and temporal precision were defined and prioritized by the scientific questions at stake in BOREAS. While the ultimate use of the remote sensing products will be as drivers of the carbon/energy/water process models at the various scales, a number of interesting findings have already emerged.

Beginning at the 1000 × 1000 km scale, AVHRR analyses by Steyaert et al. (personal communication) have shown the boreal biome in the BOREAS study area to be dominated by wet land and upland conifer (Table 1). The classes wetland conifer, upland conifer and coniferous dominated mixed class, occupy nearly 40 % of the region. Conifers in these classes are characterized by shallow rooting systems, and in general can be expected to display the same seasonal behavior observed for the black spruce and jack pine flux tower sites; i.e. low evaporation and carbon storage rates. Another interesting observation from Table 1 is that only about 14 % of the study region is deciduous forest, and is located mostly in the southern edge of the region. Finally, nearly 11 % of the region is relatively recently disturbed (< 25 yrs), primarily from naturally occurring forest fires. A majority of this disturbance occurs in the mid to northern reaches of the study region, which is sparsely settled and fire suppression is not practical. Open water will also play a significant role in regional energy balance since over 13 % of the region is in lakes. While these results are preliminary, they are being carefully evaluated by comparison to TM analyses over the BOREAS southern and northern study areas. The TM classifications are in turn thoroughly evaluated by comparison to auxiliary site data, thus permitting data collected at the plot scale to be extrapolated to the total BOREAS study region.

In addition to the optical remote sensing analyses, ERS-1 C-band imaging radar data were collected continuously during 1994 and will continue to be collected in 1995 on 3-day repeat intervals. Preliminary analyses show a large shift in backscatter between winter frozen and summer thawed conditions. The spring thaw transition shows a sharp rise in backscatter with the first early thaw and less pronounced shifts for subsequent freeze/thaw transitions. These data are being correlated with the onset of transpiration as indicated by in situ tree xylem flux measurements and other observations, see also Rignot and Way (1994).

6 Conclusions

In terms of data acquisition, and early science results, the 1993–1994 BOREAS field year must be considered a success with the collection of comprehensive surface, airborne and satellite data sets.

An unexpected picture of the energy, water and carbon dynamics of the boreal ecosystem is emerging, even at this early stage in the experiment. Observations show that the root zone of the wetland conifers, which comprise the bulk of these boreal forests, is very thin (< 40 cm deep) and is contained entirely within the live/decomposed moss (moss/humus) layer. As a result the boreal ecosystem often behaves like an arid landscape. Early in the growing season, the low soil temperatures inhibit the uptake of water by vegetation, while later in the growing season a combination of xylem (stem) resistance and vapor pressure deficit feedback responses act to strongly control the evapotranspiration rate. Most of the incoming solar radiation is intercepted by the vegetation canopies rather than by the moist underlying moss/soil surface which generally makes only a small contribution to the total sensible and latent heat fluxes. In addition, many areas have low water holding capacities so that much of the summer precipitation penetrates through the moss and soil to the underlying semi-impermeable layer and runs off. These strong controls on evapotranspiration result in the dissipation of much of the intercepted radiation as sensible heat. Consequently, a deep (> 3000 m) and turbulent atmospheric boundary layer can often develop over this ecosystem. These insights into the partitioning of the surface energy should have a significant impact on the development of climate and weather models, most of which currently characterize the boreal landscape as a freely evaporating surface.

Importantly, it would appear that the moisture level in the moss/humus layer does not get low enough to induce moisture stress in the overlying foliage. This implies that root zone moisture, a difficult variable to quantify over large spatial scales, does not exert a major control on the surface energy balance. Rather, the more important variables controlling photosynthesis and evaporation appear to be soil temperature in the spring, and atmospheric relative humidity and air temperature in the summer and fall.

This new understanding of controls on regional evaporation rates is relevant to the issue of whether the boreal ecosystem is a sink or source of carbon, but until the analysis is further along this question will remain unresolved. We have learned that sequestration of carbon by conifers, the largest component of the boreal ecosystem, is limited in the spring by frozen or cold soils, and in the summer by hot temperatures and dry air. In the fall, the conifers were observed to have the largest carbon uptake of the season; presumably as soils are warmed, the air temperatures are not so hot, and the air is not so dry. Leaf-level measurements suggest that the end of the growing season may be induced by flow air temperatures. Measurements show that at temperatures between –5 to –10 °C, black spruce needles do not photosynthesize. Measurements conducted throughout the winter indicate that the soils are a sustained source of respired CO_2 during the cold season.

Acknowledgements

As pointed out in the text, a large number of scientists, staffers participated in BOREAS. The results synopsized herein are the result of their hard work, creativity and dedication.

References

Davis, M.B. & Botkin, D.B. 1985. Sensitivity of cool temperate forests and their fossil pollen to rapid climatic change. Quaternary Research 23: 327–340.

Hall, F.G. & Sellers, P.J. 1995. FIFE in 1995. JGR FIFE Special Issue II, 100(D12). p. 25383–25395.

Rignot, E. & Way, J.B. 1994. Monitoring freeze-thaw cycles along North-South Alaskan transects using ERS-1 SAR. Rem. Sens. Env. 49: 131–137.

Sato, N., Sellers, P.J., Randall, D.A., Schneider, E.K., Shukla J., Kinter, J.L. III, Hou, Y-T. & Albertazzi, E. 1989. Effects of implementing the Simple Biosphere Model (SiB) in a general circulation model. J. Atmos. Sci. 46: 2757–2782.

Sellers, P.J. & Hall, F.G. 1992. FIFE in 1992. Results, scientific gains, and future directions. JGR FIFE Special Issue, 97(D17). p. 19091–19109.

— , Hall, F.G., Margolis, H., Kelly, R., Baldocchi, D., Hartog, G., Cihlar, J., Ryan, M., Goodison, B., Crill, P., Ranson, J., Lettenmaier, D. & Wickland, D. 1995. The Boreal Ecosystem-Atmosphere Study (BOREAS): An overview and early results from the 1994 field year. Bulletin of the American Meteorological Society 76(9): 1549–1577.

Solomon, A.M. & Webb, T. III. 1985. Computer-aided reconstructions of late-Quaternary landscape dynamics. Annual Review of Ecology and Systematics 16: 63–84.

Tans, P.P., Fung, I.Y. & Takahashi, T. 1990: Observational constraints on the global atmospheric CO_2 budget. Science 247: 1431–1438.

Verma, S.B., Baldocchi, D.D, Anderson, D.E., Matt, D.R. & Clement, R.J. 1986. Eddy fluxes of CO_2, water vapor and sensible heat over a deciduous forest. Boundary Layer Meteorology 26: 71–91.

Whittaker, R.H. 1975. Communities and ecosystems. 2nd edition. Macmillan Publishing Co., New York.

Total of 10 references