by David Herring

▶ 2

It's early summer 1994, 12:34 p.m. local time, and the Canadian Twin Otter research aircraft is flying 20 meters (about 65 feet) above the boreal forest canopy near Prince Albert, Saskatchewan. Scientists are busy measuring the exchanges of gas and heat between the forest and the lower atmosphere when the plane flies into an unseen vortex of intense, heat-induced winds—a "dust devil," as these phenomena are called in desert regions of the southwestern United States. Instruments aboard the aircraft clock the wind shift across the wall of the vortex at nearly 20 meters per second (45 miles per hour) and the updraft at the center of the vortex at 11 meters per second (25 miles per hour). Without warning, the strong winds catapult the Twin Otter upward and sideways in a few seconds. Fortunately, the pilot is able to stabilize the aircraft and return the plane and crewmembers safely to the ground, albeit a little shaken up. That summer the Twin Otter flew into eight such vortices in four months (MacPherson and Betts, 1997).

The boreal forest canopy as seen from the top of a tower about 30 meters above the ground. To measure the fluxes of heat and gases exchanged between the forest ecosystem and the lower atmosphere, the BOREAS team mounted sensitive instruments on these towers at multiple sites in the Canadian boreal forest. Measurements from these flux towers were complimented by measurements made aboard the Twin Otter research aircraft flying at roughly this altitude. (Photograph courtesy BOREAS project)

As an integral part of NASA's Boreal Ecosystem-Atmosphere Study (BOREAS) measurement strategy, a team of researchers, including Alan K. Betts from Vermont, used instruments aboard the Twin Otter and on forest towers to measure interactions between the forest and the lower atmosphere. During each season from 1994—97, data were collected on the exchanges of heat, momentum, carbon dioxide, ozone and water vapor to gain insights into the ongoing "dialogue" that occurs between the boreal ecosystem and the atmosphere. Their goal is to understand how changes in air temperature, moisture and carbon dioxide levels may impact the boreal ecosystem and what role the boreal forest plays in global-scale climate changes.

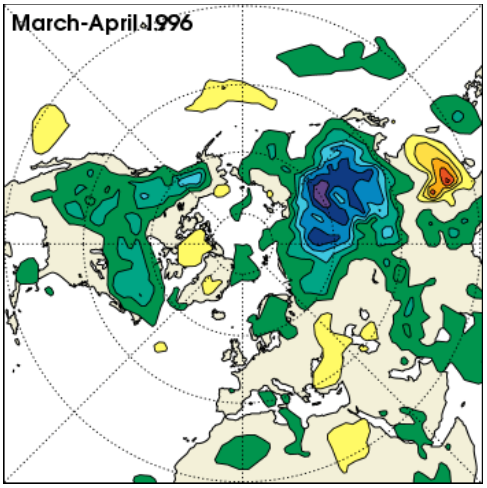
One of Betts' primary research objectives was to quantify the amount of heat emitted and light reflected by the boreal forest. The vortices of hot air that occasionally sent his colleagues on the Twin Otter "thrill rides" reinforced what other measurements were showing—the boreal forest stores and releases significantly more heat to the atmosphere in the spring and early summer than scientists previously thought.

▶ Everyone Complains About the Weather

The data used in this study are available in one or more of NASA's Earth Science Data Centers.

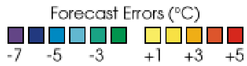
1 ◀ ▶ 3

Everyone Complains About the Weather...
Betts and his BOREAS colleagues observed that, in the spring, daily weather forecasts significantly underestimated air temperatures over the boreal forest, sometimes by as much as 10—15°C (18—27°F) (Viterbo and Betts, 1999). Additionally, the BOREAS team found that predictions of cloud cover over the boreal region were often far off the mark. Everyone complains about the weather, but how could the forecasts be so wrong so often?



This map shows the average errors in the European Centre for Medium-Range Weather Forecasts at 850mb (roughly equivalent to an altitude of 1500m) for March and April of 1996. The predictions, made five days in advance, were compared to actual measurements. The 1996 model did not include the adjustments to forest albedo.

(Figure from Viterbo, P. and A.K. Betts, 1999: The impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. J. Geophys. Res. (In press, BOREAS special issue). Courtesy A.K. Betts)



The scientists noticed a pattern that confirmed their earlier suspicions: the temperature forecasts were farthest off in late spring when snow was on the ground and grew more accurate after the snow melted. From summer through fall, the weather models matched actual measurements more closely (Betts et al. 1998). But the following year, come springtime, the forecasts again became increasingly inaccurate until snow melted. Why were the weather forecasts so inaccurate every spring?

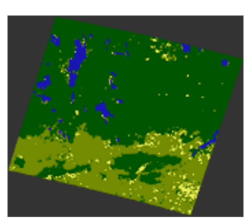
...BOREAS Did Something About The Forecasts

Comparing actual BOREAS data with two different forecast models—one developed by the National Centers for Environment Prediction (NCEP), and the other developed by the European Centre for Medium-Range Weather Forecasts (ECMWF)—the BOREAS team found that the models were overestimating albedo (the amount of light reflected by the surface). The models assumed that in the springtime, the boreal landscape is still covered by snow and therefore has a high albedo (reflects most of the sunlight). In reality, Betts observes, while snow is still typically on the ground in May, it lies under the forest canopy, which is green and therefore has a low albedo (absorbs most of the sunlight).

Trees in the Boreal forest shade the snow underneath them. The effect is more significant than it is in southern latitudes because the sun is so low in the sky, creating very long shadows.

How could meteorologists have made this mistake? Betts explains that in mid-winter the models were fairly accurate because the angle of the sun is low relative to the horizon (about 20 degrees), days are shorter, and the amount of incoming sunlight is small. Occasionally after snowfall, snow also remains in the canopy for a few days and reflects more sunlight. Yet in May, when the sun angle is higher and days are longer, there is more sunlight and no snow in the canopy to reflect it. Consequently, the canopy in dense forest regions intercepts most of the incoming sunlight, while the snow on the ground below is shaded.

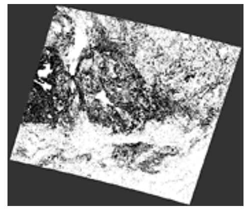
"Fresh snow on grass reflects about 80 percent of the sun’s light and absorbs 20 percent," Betts states. "The more sunlight that is reflected back up into the atmosphere, the cooler the surface temperatures. On the other hand, conifer trees (e.g., spruce and pine) reflect only 10 percent of the sun’s energy and absorb the rest, warming the surface and transferring the heat back to the atmosphere."



Yet the global forecast models used by NCEP and ECMWF treated the boreal forests in the spring as if they were snow-covered grasslands with an albedo of 60—80 percent, instead of forests with snow under the trees with an albedo of 10-20%. The models estimated that the boreal forest absorbs 100 Watts per square meter in the daytime, while BOREAS measurements show that the forest is actually absorbing between 300—400 Watts per square meter (Betts et al., 1998). According to Betts, when the new albedo measurements made by the BOREAS team were entered into the models, there was a large improvement in the accuracy of the temperature forecasts in Spring.

"Actually, this problem was known by meteorologists for some time," Betts notes. "Yet we didn't realize the magnitude of the problem until 1996. We have been trying to update the models for several years, but it wasn't until after the BOREAS field program of Spring, 1996 that we succeeded in inserting these new data into the global forecast models."

▶ The Green Desert
◀ Should We Talk About the Weather?

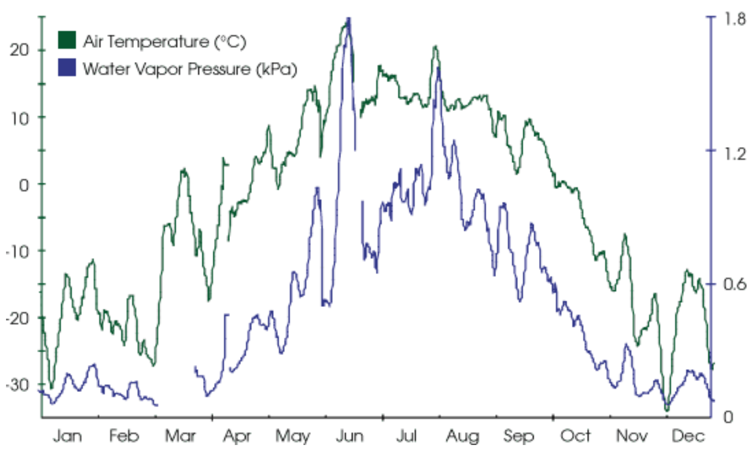


Even though the entire area shown in these two images is snow covered, the satellite-derived snow cover map (bottom image, white indicates snow) shows many of the forested areas (dark green in the top image) to be snow free. The forest canopy, which is free of snow, shields the snowpack from both sunlight and overhead observations. All of the grassland (yellow), water (blue), and mixed forest/agriculture (light green) land is indicated correctly as snow covered.

2 ◀ ▶ 4

The Green Desert

"When you fly over the boreal forest, it appears to be a very wet ecosystem—lush and green," observes Forrest G. Hall, physicist and BOREAS project scientist at NASA's Goddard Space Flight Center. "You see so many lakes and fens, and in the spring the ground is covered by melting snow. But the atmosphere is very dry, more closely resembling that over a desert than you would expect over a wet forested region."



The above graph shows air temperature and water vapor pressure during 1995 above the canopy of the northern BOREAS old black spruce site. The air is relatively dry all year long. In contrast, summer water vapor pressure near Washington, DC (a humid area) may peak at 2.5 kPa when the temperature is 25°C.

(Graph by Robert Simmon, based on data from Sutton, Doug, Mike Goulden, and Steven Wofsy. 1998. BOREAS TF-03 NSA-OBS Tower Flux, Meteorological, and Soil Temperature Data. Available online from the ORNL Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.)

The lower atmosphere is so dry, in fact, the BOREAS team nicknamed the boreal ecosystem "the green desert." Afternoon humidity in May is often as low as 30 percent there, whereas tropical forests have an average afternoon humidity of 60 percent. According to Betts, the atmospheric boundary layers that form over the boreal forest often resemble those boundary layers that form over the southwestern United States. They can become very deep (up to 8000 feet, or 2500 meters) and very turbulent. ["Boundary layer" refers to the part of the atmosphere closest to Earth's surface; it is typically very turbulent as large amounts of heat, aerosol particles, and trace gases are mixing in it and passing through it.]

"There is very little evaporation (in the boreal ecosystem) in the spring and summer," Betts observes. "An enormous amount of sunlight is being absorbed by the forest canopy and then emitted back into the atmosphere as heat. Consequently, it can get very warm there—up into the 80s Fahrenheit (30 Celsius) in early June."

But, ironically, while the boreal air in springtime is hot and dry like a desert's, the ground under the coniferous forests is still frozen, a foot or two down. So, while the forest canopy is absorbing tremendous amounts of sunlight and storing it as heat, water cannot evaporate from the trees as long as their roots are frozen (Betts et al., 1999). Likewise, while the lakes in the region have all melted in late spring, they are still very cold—too cold to release much water.

Soil which remains frozen year round is called permafrost, and is often found in the far north. Even though summer air temperatures in the boreal forests are quite warm, the upper layers of soil insulate the deep soils, preventing them from thawing. Over time, several meters of permafrost can eventually accumulate. (Image courtesy Canadian Soil Information System)

Typically, evaporation, or the release of water vapor from the surface up into the atmosphere, provides forest ecosystems with a means of cooling off or regulating temperature. As sunlight warms the surface, evaporation from bodies of water and from the water vapor released by trees cools the surface. But in the boreal ecosystem, where very little evaporation occurs in the spring, most of the sun's energy is absorbed and re-radiated back up into the lower atmosphere as heat; hence the deep, dry and very turbulent boundary layer.

▶ Everyone Complains About the Weather
◀ Improving the Forecast Models

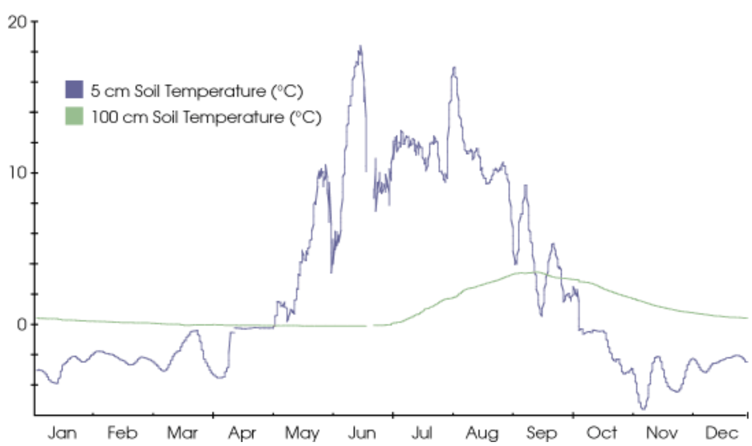
Improving the Forecast Models

3 ◀ ▶ 5

Moss covers the ground throughout the boreal forest, including the upland black spruce study area shown here. The moss inhibits water evaporation, helping keep the soil wet and the atmosphere dry and sometimes covering pools of standing water. (Photograph courtesy BOREAS project)

In order to construct accurate computer models of the boreal ecosystem, the BOREAS team must take many variables into account. One problem the scientists face is predicting soil temperatures and knowing when the soils thaw. Soil dynamics are not easy to track from year-to-year because there are thick layers of moss that insulate much of forest floor. Current models don't accurately represent the role moss plays in the hydrological (water) cycle in the boreal ecosystem.

Moss helps keep the deeper layers of soil frozen, as well as the roots of trees, well into the spring, thereby reducing water vapor. When it rains in the summer, the moss acts like a sponge and soaks up a lot of the water. About one-third of the total amount of water that is evaporated by the boreal ecosystem in the summer comes from moss within a few days after a rain.

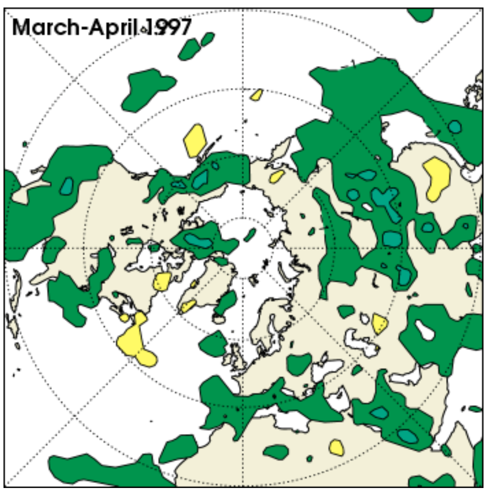


BOREAS measurements show that in the spring and summer, only about one-third of the solar radiation absorbed by the boreal ecosystem is used in evaporation, while about two-thirds is emitted as heat. But the ECMWF model computed that half of the radiation is used in evaporation and half is emitted as heat. The NCEP model computed that 70 percent of the solar radiation is used in evaporation and only 30 percent is emitted as heat. Consequently, these models were predicting more precipitation—as much as 50 percent more—than was actually being measured (Betts et al. 1998).

By introducing their new BOREAS data into the weather models, Betts says he expects to see significant improvements in forecasts of daily temperature, cloud cover and precipitation amounts. It typically takes a few years to develop and test these forecast model changes, Betts explains. When the changes that are being tested this summer are complete, he plans to go back and re-analyze both the old forecasts, the new forecasts, and the actual measurements to get a quantitative measure of how much the models have improved. He won't get the results of those analyses until the year 2000, but loftier goals await over the horizon.

This graph shows soil temperatures at 5 and 100 centimeters during 1995. The upper soil is insulated by snow in the winter, but warms quickly in summer. (Note: snowmelt is shown by the constant zero degree temperature during April.) In contrast, the deep soils remain near freezing through early summer, not warming up until the air temperature has already begun to drop. This prevents the trees from evaporating water at their full capacity.

(Graph by Robert Simmon, based on data from Sutton, Doug, Mike Goulden, and Steven Wofsy. 1998. BOREAS TF-03 NSA-OBS Tower Flux, Meteorological, and Soil Temperature Data. Available online from the ORNL Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.)



This map shows the average errors in the improved European Centre for Medium-Range Weather Forecasts at 850mb (roughly equivalent to an altitude of 1500m) for March and April of 1997. The model used in 1997 used a reduction in the forest snow albedo based on BOREAS data to improve the 5-day forecasts.

(Figure from Viterbo, P. and A.K. Betts, 1999: The impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. J. Geophys. Res. (In press, BOREAS special issue). Courtesy A.K. Betts)

"Today, global forecast models are evolving into Earth system models," Betts states. "New land measurements are improving land surface meteorological forecasts significantly, so that there will be another round of improvements to the models in 2001. Then, we will enter our revised understanding of the global carbon cycle into the Earth system models. Over the next 5-10 years, global forecast models will become fairly complete Earth system models."

▶ Full Circle
◀ The Green Desert

Full Circle

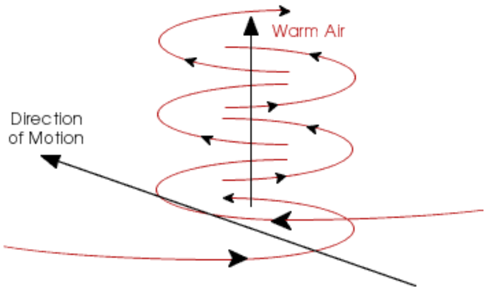
During their flights aboard the Twin Otter to measure the interactions between the boreal forest and the lower atmosphere, the BOREAS team encountered eight vortices during the summer of 1994—an average of one for every 1800 km (1100 miles) flown (MacPherson and Betts 1997). They ranged in diameter from 150 to 300 meters (500—1000 feet), and reached some 1500 meters (5000 feet) in height.

Functioning a little like "mini-tornadoes," these vortices provide a mechanism in low wind conditions for the surface to transfer enormous amounts of heat and carbon dioxide up into the atmosphere. The BOREAS team measured fluxes of heat and carbon monoxide anywhere from 30 to 60 times greater than average during these vortex events.

4 ◀

Small atmospheric vortices in arid regions, like this one in Australia, are called "dust devils." In the boreal forests there are few fine dust and sand particles to be lofted into the air by vortices, so they remain invisible, threatening low-flying aircraft. (Photograph by John Roenfeldt, courtesy Australian Severe Weather)

"The vortices are a kind of dry-air convection," Betts says. [Here, "convection" refers to the upward motion of warm air, which rises because it is less dense than adjacent cooler air, just as warm air rises above a wood stove.]



A column of rising warm air forms the center of a vortex, surrounded by spiraling winds. (Diagram courtesy Mars Pathfinder Project, Jet Propulsion Lab)

"There are a number of different ways in which the atmosphere organizes to transfer heat away from the surface," he adds. "The fact that the boreal ecosystem uses these vortices is an interesting curiosity—but very important when you're flying 20 meters above the forest canopy."

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◀ Improving the Forecast Models