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Editor's Corner

Steve Platnick
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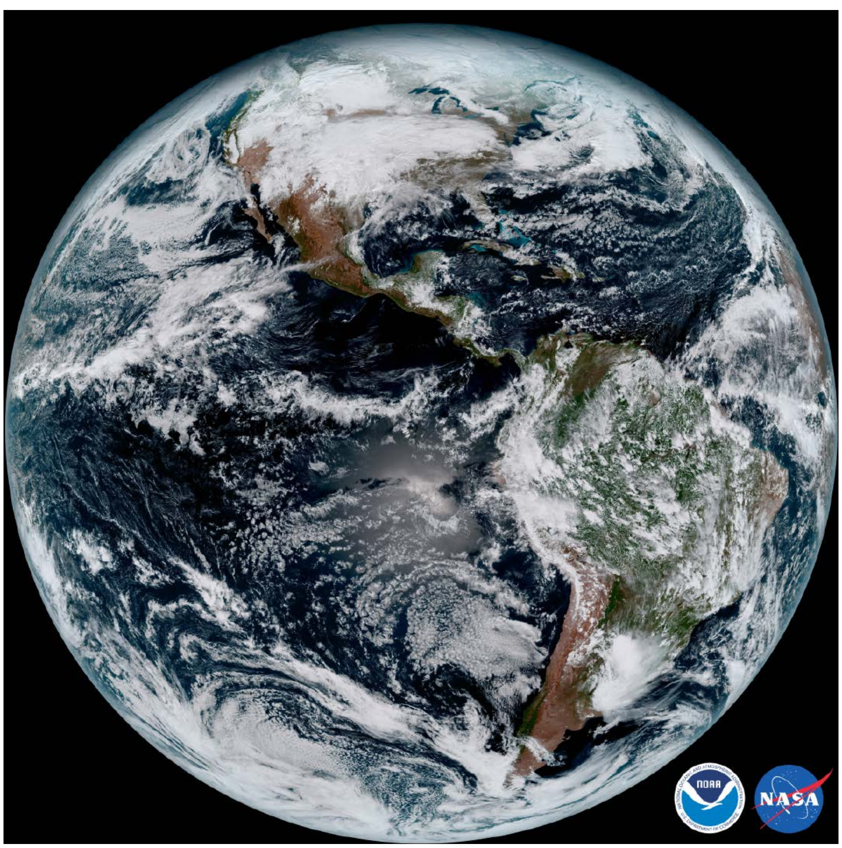
I am very sad to report that **Piers Sellers** passed away on December 23, 2016 from pancreatic cancer at the age of 61. Piers, who often referred to himself as the "human satellite," came to GSFC in 1981 as a biospheric scientist and served as the first Project Scientist for the NASA Earth Observing System's Terra mission (then called AM-1). He was selected to join the NASA Astronaut Corps in 1996 and went on to fly in space three times—including six spacewalks. In 2011, after concluding his tour of duty as an Astronaut, Piers returned to GSFC where he served as the deputy director of the Sciences and Exploration Directorate and the director of the Earth Science Division. The perspective Piers gained by observing the Earth from the vantage point of space made him all the more excited to resume his original mission to understand Earth's climate—and to communicate the science to the public. In a *New York Times* opinion piece from January 2016 Piers wrote of his spaceflight experience: "From this God's-eye-view, I saw how fragile and infinitely precious the Earth is. I'm hopeful for its future." The passion Piers brought to his work—especially after his cancer diagnosis—was an inspiration to all who were fortunate enough to work with him over the years. His humor, optimism, intellect, and tireless energy will be sorely missed. My condolences to Piers' family, friends, and many colleagues around the world. Please turn to page 4 to read *In Memoriam,* describing Piers' distinguished career.

continued on page 2



Among the "first light" images released from GOES-R (GOES-16) was this full-disk visible image of the Western Hemisphere at 1:07 PM EST on January 15, 2017. It was created using several of the 16 spectral channels available on the satellite's sophisticated Advanced Baseline Imager. The image, taken from 22,300 mi (~33, 588 km) above the surface, shows North and South America and the surrounding ocean.

Image credit: NOAA and NASA

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive*.

Among his many accomplishments, Piers was one of the visionary leaders of FIFE and BOREAS—two of NASA's first field campaigns designed to improve our understanding of the biosphere in the Earth system. The year 2017 marks the 30th anniversary of the beginning of FIFE'87. On October 6-7, 2016, a "reunion meeting" took place at NASA's Goddard Space Flight Center (GSFC). Dubbed *How FIFE/BOREAS Changed the World*, the meeting agenda was designed to look back at what these two experiments accomplished—and in some cases are still providing—and to consider how they changed the world for Earth science studies. Please turn to page 6 of this issue to learn more about these two pioneering field experiments.

NASA ended 2016 on a high note, with the successful launch of the Cyclone Global Navigation Satellite System (CYGNSS)—described in detail in our previous issue.[1] The mission launched on December 15, 2016, at 8:37 AM Eastern Standard Time, from Cape Canaveral Air Force Base in Florida aboard a Pegasus-XL launch vehicle into a low-inclination, low-Earth orbit over the tropics. CYGNSS is the first Earth Venture Mission (EVM-1)[2] to launch, and features a constellation of eight small satellites that will receive both direct and reflected signals from Global Positioning System (GPS) satellites. The direct signals pinpoint CYGNSS observatory positions, while the reflected signals respond to ocean surface roughness, from which wind speed maps are created. Kudos to principal investigator **Christopher Ruf** [University of Michigan] and the entire CYGNSS Team. To learn more about the CYGNSS "first light" science data, see the News story on page 51 of this issue, or visit *http://cygnss-michigan.org*.

Previously we reported on the successful launch of GOES-R (now GOES-16) on November 19, 2016.[3] "First light" images from the Advanced Baseline Imager (ABI) were released on January 23. Included among them is a composite color full-disk visible image of the Western Hemisphere captured on January 15, 2017—see front cover.

[1] To learn more about CYGNSS, read "Eight Microsatellites, One Mission: CYGNSS" in the November-December 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 6**, pp. 4-13].

[2] Earth Venture class missions are broken down into Suborbital (EVS), Instrument (EVI), and Mission (EVM). Learn more about the three categories and see a list of missions at *https://science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder*.

[3] See the Editorial of the November–December 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 6**, pp. 1-2].

Created using several of the ABI's 16 spectral channels, the full-disk image offers an example of the satellite's capability compared with previous GOES imagers. One ABI imaging mode provides a full-disk image every 15 minutes, a continental U.S. image every 5 minutes, and smaller mesoscale images every 30 seconds for one region or every minute for two regions. Another mode simply produces a full-disk image every 5 minutes. ABI spatial resolution ranges from 0.5 to 2 km at nadir (depending on spectral channel).

In May 2017 NOAA plans to announce the planned location for GOES-16, and by November 2017 GOES-16 is expected to be in either the GOES-East or GOES-West position. The next spacecraft in the series, GOES-S, is scheduled to launch in Spring 2018,[4] and is currently undergoing a full set of environmental, mechanical, and electromagnetic tests at Lockheed Martin's Littleton, CO facility. After initial on-orbit checkout GOES-S (GOES-17) will be moved into the operational position not occupied by GOES-16.

For more information refer to *https://www.nasa.gov/feature/goddard/2017/goes-16-sends-first-images-to-earth*. A gallery of other first light images can be found at *www.nesdis.noaa.gov/content/goes-16-image-gallery*.

Meanwhile, as EVM-1 (CYGNSS) prepared to launch this past year, 15 proposals submitted in response to the EVM-2 announcement were being reviewed. In early December, NASA HQ announced that the Geostationary Carbon Cycle Observatory (GeoCARB) was selected as the winner. The mission will monitor plant health and vegetation stress throughout the Americas, and probe the natural sources, sinks, and exchange processes that control carbon dioxide, carbon monoxide, and methane in the atmosphere.

GeoCARB will launch on a commercial geosynchronous communications satellite. The intent is for GeoCARB to employ otherwise unused launch and spacecraft capacity to advance science and provide societal benefits. By demonstrating that it can be flown as a hosted payload on a commercial satellite, GeoCARB will strengthen NASA's partnerships with the commercial satellite industry and provide a model that can be adopted by NASA's international partners to expand these observations to other parts of the world.

The principal investigator for GeoCARB is **Berrien Moore** [University of Oklahoma]. Other mission partners include the Lockheed Martin Advanced Technology Center; SES Government Solutions Company; the Colorado State University; GSFC; ARC; and JPL. Congratulations to the GeoCARB team on being selected as NASA's newest Earth Venture mission. To learn more about GeoCARB see the News story on page 50 of this issue.

Finally, this issue includes details about NASA's recent outreach activities at the UNFCC's COP-22 meeting and the 2016 AGU Fall Meeting—see page 24 of this issue. These events, organized by the Science Communication Support Office, showcase NASA science plans and stories on the Hyperwall and Dynamic Planet (see photo on page 24). These two display technologies provide a unique means to communicate science face-to-face with colleagues, stakeholders, and the public. To see where NASA's Hyperwall is headed next, follow the team on Twitter *@NASAHyperwall*. ■

[4] There will be two more in the "GOES-R" series: GOES-T and GOES-U are planned for launch in 2019 and 2024, respectively.

Undefined Acronyms Used in Editorial and Table of Contents

ARC	NASA's Ames Research Center
AGU	American Geophysical Union
BOREAS	Boreal Ecosystem–Atmosphere Study
CERES	Clouds and Earth's Radiant Energy System
COP	Conference of Parties
FIFE	First ISLSCP Field Experiment
GOES	Geostationary Operational Environmental Satellite
GRACE	Gravity Recovery and Climate Experiment
GSFC	NASA's Goddard Space Flight Center
ISLSCP	International Satellite Land Surface Climatology Project
JPL	NASA/Jet Propulsion Laboratory
UNFCCC	United Nations Framework Convention on Climate Change

In Memoriam

Piers J. Sellers, a renowned climate scientist and former NASA astronaut, passed away at age 61 on December 23, 2016, due to pancreatic cancer.

Piers J. Sellers **Photo credit:** NASA

Piers most recently served as the deputy director of the Sciences and Exploration Directorate at NASA Headquarters and acting director of the Earth Sciences Division at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. Piers arrived at GSFC in 1981 from his native Great Britain and dove into pioneering research on the use of satellites and computer models to study photosynthesis on a global scale. In the 1990s Piers served as the first project scientist for the Terra mission (then called AM-1), the first satellite in NASA's Earth Observing System and a "flagship" of the agency's Earth-observing fleet. After 14 years as an Earth-based NASA scientist, Piers changed course in 1996 when he joined the NASA astronaut corps with an eye toward working in space. His dreams were made real when he participated in missions to the International Space Station in 2002, 2006, and 2010, where he performed six spacewalks and various space station assembly tasks. In addition to helping build the space station, he gained a perspective on Earth that would infuse his talks to the public for the rest of his life. In 2011 Piers returned to GSFC where he provided leadership and guidance to the center's cadre of more than 2000 scientists. In this role, he once again took up his mission to study the changing climate and share his views with audiences worldwide.

Early in his career, Piers focused on the challenges of understanding and simulating the complex interactions between Earth's atmosphere and biosphere—the collection of the planet's plant life. In the mid-1980s he led the work that created the first realistic computer model of how the biosphere interacts with Earth's climate. He would go on to mine deeply this line of research, breaking new ground, and helping build the foundation for what the science community now understands.

Piers on one of his six spacewalks (STS-121, EV1). **Photo credit:** NASA

"It took years and years, but at the end of it we came up with a complete theoretical understanding of how it goes from a single leaf, with its little chloroplasts doing photosynthesis, to what that looks like from space, and then how to integrate the whole thing to find out the photosynthetic power of the planet," Piers said in a 2016 interview.

While Piers could dazzle a crowd with stories of seeing Earth from space as an astronaut, he was equally enthusiastic when discussing the excitement of scientific breakthrough. "It was enormous fun," he said. "It was the most fun I ever had. It was a huge scientific adventure."

Piers' five most impactful scientific journal articles—collectively outlining his Simple Biosphere Model (SiB), updates to it (SiB-2), and insights into how forest canopies conduct photosynthesis—have been cited in 7697 peer-reviewed papers. The work has had enormous impact on the current understanding not only of how the planet works, but also of how Earth will respond to rising carbon dioxide concentrations in its atmosphere.

"Piers did seminal work," said **Colleen Hartman** [GSFC—*Director of the Sciences and Exploration Directorate and Acting Center Director for Science at GSFC*]. "It completely changed the paradigm of how to use satellite data and made it so much more useful for applications in the real world and for understanding our changing climate. Purely on the science, he would be an icon."

After learning of his cancer diagnosis, Piers took on a much higher public profile when a January 2016 op-ed piece he wrote for *The New York Times* resonated deeply with people around the world. The piece described how his diagnosis affected his approach to examining our changing climate. It captured both the depth of his thinking on the topic and his pragmatic optimism.

"There is no convincing, demonstrated reason to believe that our evolving future will be worse than our present, assuming careful management of the challenges and risks," Piers wrote. "History is replete with examples of us humans getting out of tight spots. The winners tended to be realistic, pragmatic, and flexible; the losers were often in denial of the threat."

In the final year of his life, Piers gave dozens of interviews about his grounded yet hopeful perspective, culminating in an appearance in the documentary film, *Before the Flood*, released this fall. The message resonated, Hartman said, because of its authenticity.

On June 2, 2016, **NASA Administrator Charles Bolden** presented Piers with the *Distinguished Service Medal*—the highest honor the agency can bestow.

"When I was a kid, I watched the Apollo launches from across the ocean, and I thought NASA was the holy mountain," Piers said during his acceptance speech. "As soon as I could, I came over here to see if I could climb that mountain." And climb it he did, and then some. He accepted the award on behalf of everyone in attendance and all the people he has worked with throughout his 34-year career at NASA. "I owe this agency everything," he said.

Remembering Piers, Bolden said, "Piers devoted his life to saving the planet. As a climate scientist, his work in computer modeling of the climate system, satellite remote sensing studies, and field work using aircraft, satellites, and ground teams broke new ground in our understanding of Earth's systems. His legacy will be one not only of urgency that the climate is warming but also of hope that we can yet improve humanity's stewardship of this planet. His cancer diagnosis became a catalyst for him to work even harder on efforts to save the planet from global warming for the benefit of future generations. Piers was an eternal optimist whose positive energy inspired all those who had the good fortune to know him. His laughter, humor, and lighthearted spirit are as much a part of his legacy as his work."

Longtime friend and colleague Compton "Jim" Tucker spoke with Piers near the end. He said that Piers' final request was for "no moping" at events remembering him. Instead, he asked that we celebrate his life and accomplishments.

The Earth Observer staff would like to dedicate this issue to Piers who, among so many other accomplishments, led two groundbreaking field research campaigns—FIFE and BOREAS—described in great detail in the article on page 6 of this issue.

This *In Memoriam* drew information from several sources, including:

NASA Administrator Remembers NASA Scientist, Astronaut Piers Sellers

https://www.nasa.gov/press-release/nasa-administrator-remembers-nasa-scientist-astronaut-piers-sellers

Piers Sellers: A Legacy of Science

https://www.nasa.gov/feature/goddard/2016/piers-sellers-a-legacy-of-science

Cancer and Climate Change (The New York Times): *https://www.nytimes.com/2016/01/17/opinion/sunday/cancer-and-climate-change.html?_r=0*

Sellers Awarded Distinguished Service Medal: *https://www.nasa.gov/feature/goddard/2016/reaching-the-summit-at-nasa-piers-sellers-receives-distinguished-service-medal*

Piers Sellers Media Resources: *http://svs.gsfc.nasa.gov/12275*

Image gallery: *https://www.flickr.com/photos/nasa_goddard/sets/72157669808364751*

Recollections of FIFE and BOREAS: Historical Perspective and Meeting Summary

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Robert E. Murphy, NASA Headquarters (retired), remurphy@scientiaphoto.com
Piers Sellers, NASA's Goddard Space Flight Center[1]

Introduction

Field campaigns are a critical component of NASA's Earth Observing System (EOS). Such experiments are designed to test and evaluate various scientific hypotheses governing interactions between the Earth's surface and atmosphere, and form the basis of algorithms used in computer models that simulate Earth's weather and climate. Field experiments are thoughtfully designed and carefully planned to acquire data to test and evaluate hypotheses contained within these model's codes. This typically requires synchronous observations taking place at several-to-many locations, over a range of spatial scales, and at multiple levels of the atmosphere. The *in situ* measurements obtained include surface states as well as rates of energy, gas, and heat exchange within the atmosphere. Exchanges of carbon, water, and heat (or *fluxes*) are measured at a range of altitudes within the atmospheric boundary layer. For example, measurements of radiative energy exchange are required at scales of meters (feet) to kilometers (miles) from ground level to space—usually defined as 100 km (~62 mi). Geophysicists, meteorologists, and oceanographers have been doing field experiments since the International Geosphere Year (IGY) in 1957-'58; however, the biosphere was not included in this type of multisite strategic approach until just a few decades ago—in 1987.

The first field campaign to include the coupled biosphere–atmosphere as part of a coordinated measurement strategy was the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment [FIFE], with deployments in 1987 and 1989 to the Konza Tallgrass Prairie near Manhattan, KS—see *The FIFE and BOREAS Study Areas* on pages 8–9—to measure surface properties (e.g., vegetation and vegetation status, soil moisture) and fluxes of heat, moisture, and trace species. The surface flux measurements were used as ground truth for the development and evaluation of algorithms to estimate fluxes from satellite observations. FIFE'87 had four, two-week deployments[2] involving 5 satellites, 10 aircraft, and some 150 people. Researchers returned to Kansas two years later for a second round of experimentation on the Konza Prairie—FIFE'89. Measurement approaches were refined based on the results of FIFE'87 so as to resolve scientific questions that arose during subsequent algorithm development to estimate fluxes from satellites.

The logos for FIFE and BOREAS. **Image credit:** NASA

Even as scientists analyzed data collected during FIFE, plans were underway for an even more ambitious (and better-funded) experiment: the joint U.S.-Canadian Boreal Ecosystem–Atmosphere Study (BOREAS),[3] with preparatory activities in 1993 and field deployments in 1994 and 1996. Whereas FIFE took place on the plains of Kansas, BOREAS was executed over the more-remote southern and northern extremes of north-central Canada—the boreal forests.

[1] Regrettably, Piers Sellers passed away on December 23, 2016, from pancreatic cancer. An *In Memoriam* for Sellers appears on page 4 of this issue.
[2] These deployments were timed so they captured different parts of the growing season.
[3] U.S. participants in BOREAS included NASA, the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA); Canadian participants included the National Science and Environmental Research Council (NSERC), National Aeronautics Council (which provided the Twin Otter aircraft), and Agriculture and Agri-Food Canada.

The primary objectives of BOREAS were to determine how the boreal forest interacts with the atmosphere (via gas and energy fluxes), how much carbon is stored in the forest ecosystem, how climate change will affect the forest, and how changes in the forest affect weather and climate. BOREAS integrated ground, tower, airborne, and satellite measurements of the interactions between the forest ecosystem and the lower atmosphere. BOREAS moved beyond FIFE in two important ways. The FIFE ecosystem was relatively small and simple, and the physics of the remote sensing of the simple grassland was well understood. On the other hand, in addition to being a much larger region, the BOREAS ecosystem was far more complex and remote sensing of the complex forest canopy and undergrowth was much more difficult than that of the simple grassland of the Konza. There were two smaller study areas where observations took place, each further subdivided into observation sites—see *The FIFE and BOREAS Study Areas* on pages 8–9. Once the BOREAS experiment was completed, the Canadian government took over the infrastructure that had been built. The Boreal Ecosystem Research and Monitoring Sites (BERMS) study began in 1996, operated and funded by Environment Canada (EC). Some of the BOREAS sites are still in use today as part of Fluxnet-Canada, discussed later in this article.

FIFE and BOREAS helped to move scientific understanding of Earth's systems from a good idea to a concrete reality in the late 1980s, and further laid the groundwork for understanding how the individual components of Earth's systems (e.g., atmosphere, biosphere) work and interact with one another.

The year 2016 marked the twenty-ninth anniversary of the beginning of FIFE'87 and the twentieth anniversary of the conclusion of BOREAS. On October 6-7, 2016, a gathering of interested parties convened for a reunion meeting at NASA's Goddard Space Flight Center (GSFC), called *How FIFE/BOREAS Changed the World.* The meeting agenda was designed to look back at what these two experiments accomplished—and in some cases are still providing—and to consider how they literally changed the world, as new perspectives on Earth system science (as it is now called) were developed.

If we are to understand how FIFE/BOREAS changed the world, however, we first need to get some sense of the world that existed before these experiments took place, particularly in the realm of NASA's biospheric science studies; we provide that perspective here. We also briefly summarize the history of FIFE and BOREAS, along with historic perspectives and anecdotal accounts from participants in FIFE and BOREAS, as shared during the GSFC meeting.[4]

FIFE and BOREAS helped to move scientific understanding of Earth's systems from a good idea to a concrete reality in the late 1980s, and further laid the groundwork for understanding how the individual components of Earth's systems (e.g., atmosphere, biosphere) work and interact with one another.

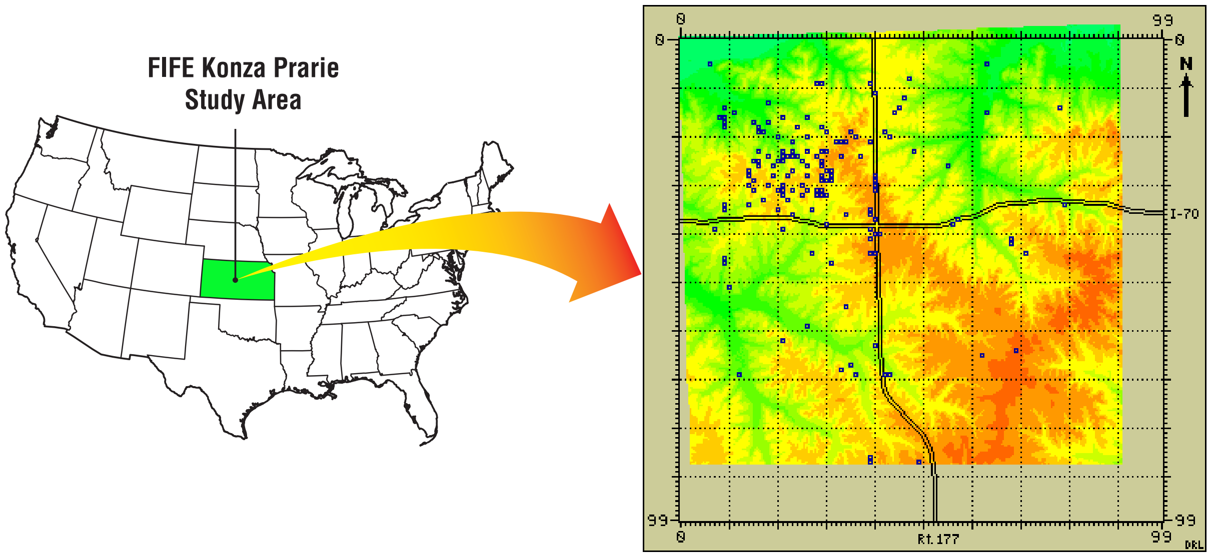
[4] All presentations from the meeting can be viewed and downloaded from *http://cce.nasa.gov/cce/boreas_fife/boreas_vids/BOREAS_Vids.html*.

FIFE - BOREAS Reunion Meeting particpants at GSFC on October 6, 2016. **Photo credit:** Bill Hrybyk [GSFC]

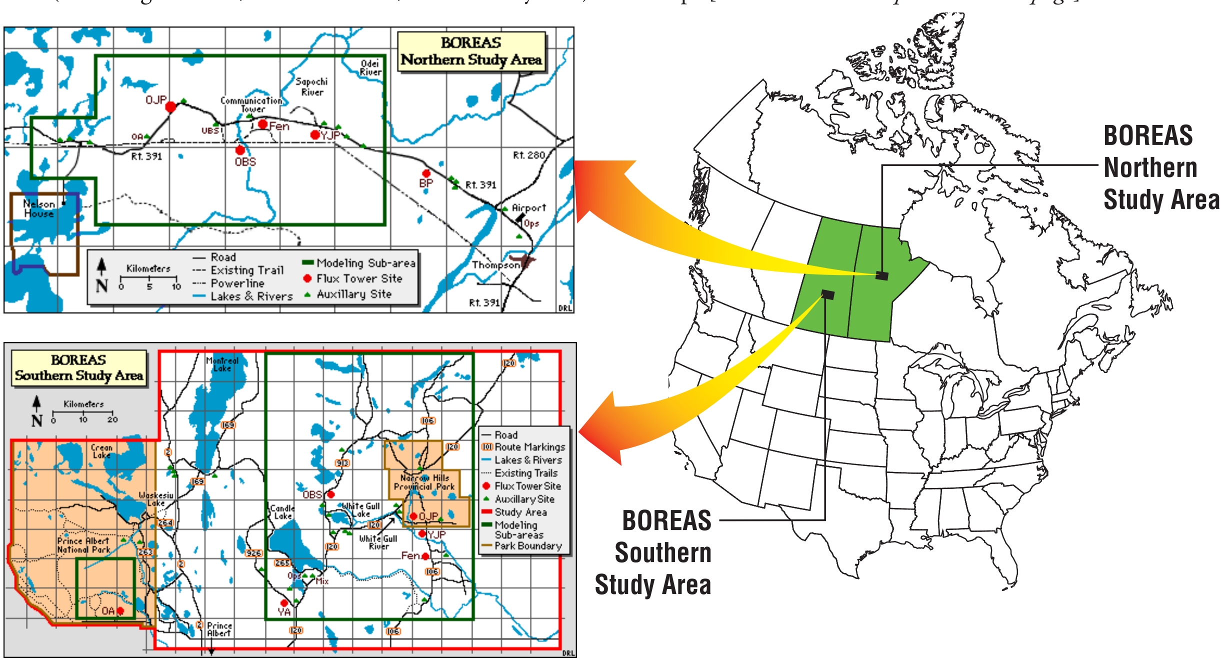
The FIFE and BOREAS Study Areas*

The goals of FIFE and BOREAS were to develop and test methods for upscaling biophysical understanding from meter scales to geographic scales—where carbon, climate, and weather models operate. They were also to develop and test satellite remote sensing algorithms for inferring the surface drivers of these models—e.g., albedo, temperature, soil moisture, and vegetation type. The specific objectives of the field phases of FIFE and BOREAS followed directly from those goals. The challenge was to design feasible experiments.

FIFE focused on the Konza Prairie study area, a 15 x 15-km (~9 x 9-mi) inhomogeneous rolling terrain site of the Konza Preserve near Manhattan, KS—see map [*below*]. The area was small enough to sample with existing resources, but large enough to acquire sufficient samples of satellite data and sample the turbulent structure of the planetary boundary layer with aircraft. It also had convenient access to aircraft (Fort Riley) and logistical support (Kansas State University in Manhattan).



BOREAS was more ambitious, with observations taking place over a larger 1000 x 1000-km (~621 x 621-mi) region with two distinct study areas in northern Canada—the **Northern Study Area** and the **Southern Study Area**—each with multiple sites (modeling subareas, flux tower sites, and auxillary sites)—see maps [*below—with descriptions on next page*].



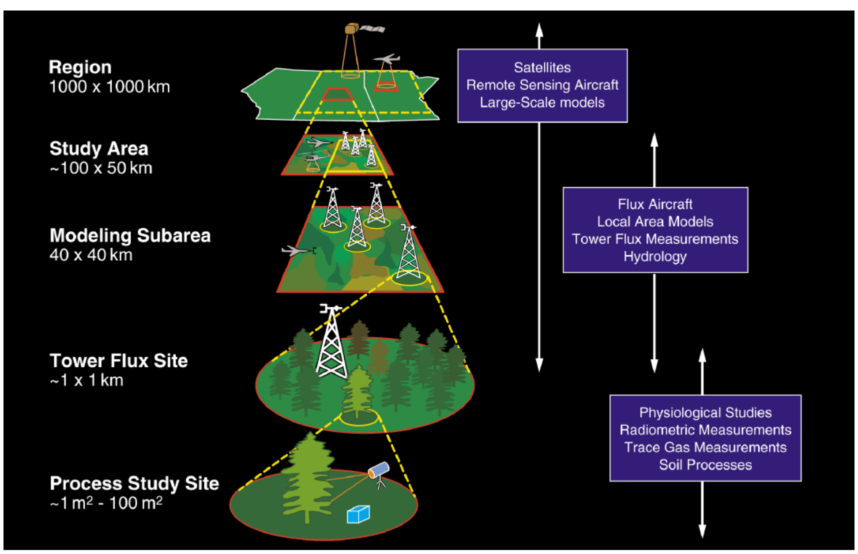
The **Northern Study Area** (NSA) was a 100-km x 80-km (~62-mi x 50-mi) area around Thompson, Manitoba. The NSA had five main sites and several auxiliary sites. They were:

- Beaver Pond (NSA-BP)—*flux tower*† on a small lake;
- Fen (NSA-Fen)—flux tower in a swampy wetland area;
- Old Black Spruce (NSA-OBS)—flux tower in an area of old growth black spruce (wet soil);
- Old Jack Pine (NSA-OJP)—flux tower in an area of old Jack Pine (dry soil);
- Young Jack Pine (NSA-YJP)—flux tower in an area of young Jack Pine (dry soil);
- BOREAS Operations (NSA-Ops)—BOREAS Ops center, Thompson Airport;
- Upland Black Spruce (NSA-UBS)—canopy access tower in a small stand of spruce (auxiliary);
- Old Aspen (NSA-OA)—canopy access tower in a large stand of old Aspen trees (auxiliary).

The BOREAS **Southern Study Area** (SSA) was a 130-km x 90-km (~81-mi x 56-mi) area around Prince Albert, Saskatchewan—about 780 km (~485 mi) from the NSA. The SSA had six main sites and several auxillary sites in and around the Prince Albert National Park (PANP) and Narrow Hills Provincial Forest. They were:

- Fen (SSA-Fen)—flux tower in a swampy wetland area;
- Old Aspen (SSA-OA)—flux tower in an area of old growth aspen trees;
- Old Black Spruce (SSA-OBS)—flux tower in an area of old growth black spruce (wet soil);
- Old Jack Pine (SSA-OJP)—flux tower in an area of old Jack Pine (dry soil);
- Young Aspen (SSA-YA)—flux tower in an area of young aspen trees;
- Young Jack Pine (SSA-YJP)—flux tower in an area of young Jack Pine (dry soil);
- BOREAS Operations (SSA-Ops)—BOREAS Ops center, Snodrifters Lodge, Candle Lake;
- Southern Airport—Prince Albert Airport; and
- Mixed Growth Site (SSA-Mix)—Terrestrial Ecology (TE) canopy tower in a mixed forest (auxillary).

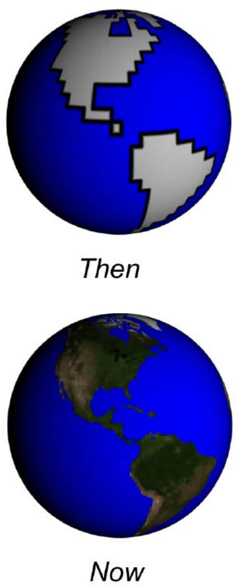
The diagram [*below*] illustrates the multiscale measurement strategy used during FIFE and BOREAS with measurements going on from synoptic (regional) scales down to the level of individual trees and leaves (i.e., at the process level).



* To learn more details about these study areas and see some images and pictures, visit *https://daac.ornl.gov/FIFE/FIFE_Location.html*, *https://daac.ornl.gov/BOREAS/bhs/Sites/SSA.html*, and *https://daac.ornl.gov/BOREAS/bhs/Sites/NSA.html*.

† Flux towers monitor physical and chemical properties of atmosphere-related processes, such as humidity, wind, and reactive nitrogen at several levels. They also measure *net ecosystem exchange*—the amount of gas that is exchanged between the atmosphere and the ecosystem.

How FIFE and BOREAS Changed the World



Logo for *How FIFE/BOREAS Changed the World* meeting. **Image credit:** NASA (concept by Piers Sellers).

The World before FIFE[5]

As intimated earlier, Earth system science did not spring full-blown into existence. The steps to organizing this literally global enterprise were small and somewhat hesitating—droplets of discovery slowly coming together throughout the 1960s and 1970s to form separate streams of scientific endeavor that, in the early 1980s, began to coalesce into the Earth-spanning interdisciplinary effort we know today. At that time there were a number of NASA workshops initiated to "address the feasibility of developing a major NASA research initiative to document, to understand, and if possible, to predict long-term (i.e., between 5 and 50 years duration) global changes that can affect the habitability of Earth."[6] The consensus arising from these workshops was that while this would be a worthwhile endeavor, there would be significant knowledge gaps that would need to be closed before proceeding—in particular, with regard to interactions between the atmosphere and Earth's surface, about which virtually nothing was known. Models at the time were at the "hand-waving stage"[7] when it came to their representation of many parameters crucial to understanding Earth's climate, e.g., radiative energy, water vapor, and carbon fluxes; surface albedo; atmospheric water content; and the roles of clouds—all highlighted as necessary foci to understand Earth's systems and climate.

As all this played out (in the early 1980s), it became increasingly apparent that biology (not just physics) played a key role in regulating the Earth system. (In fact, biology controls about one-third of the energy exchanges between the land surface and the atmosphere.) At that time, AgRISTARS (defined in the *Timeline* on page 13), a large interagency program using empirical techniques to monitor agricultural productivity, was coming to a close, and a small portion of those resources, together with some of the scientific leadership, became available for "reprogramming." Additional intellectual vigor entered through the National Research Council's new Post-Doctoral program and from other existing NASA programs (e.g., the Earth Resources Branch at GSFC) and the Biospheric Sciences program was born. Research initially focused on the role of biologic processes on climate models and later expanded to include carbon flux measurements.

Harbingers of FIFE and BOREAS: ISLSCP and HAPEX-MoBilHY

By the early 1980s, a programmatic framework for global biospheric studies was in place. Now, all that was needed was a mechanism to make it all happen, and the International Satellite Land Surface Climatology Project (ISLSCP—the "I" in FIFE) would provide that mechanism. Conceived of in 1983, the idea behind this large-scale program was to study the land biosphere in terms of its relevance to Earth's climate. This would require a series of field experiments to develop and improve general circulation models (GCMs) and to develop satellite-based methods to initialize and validate these models on regional and global scales to answer increasingly interesting and important Earth-system science questions. ISLSCP provided a practical framework to do this. The field studies and model development being proposed under ISLSCP provided the opportunity for biospheric sciences to become an essential part of NASA's climate program. ISLSCP held its first meeting in 1984, and planning for FIFE began. The French Centre National de Recherche Meteorologique (CNRM) was also involved in ISLSCP and invited NASA to participate in the HAPEX-MoBilHy[8]

[5] While many specific details could not be preserved due to editorial requirements, the presentations given by **Bob Murphy**, **Piers Sellers**, **Forrest Hall**, and **Joe Berry** at the *How FIFE/BOREAS Changed the World* meeting and additional information provided by co-authors Hall and Murphy form the basis for this introductory material. Some material in those presentations has therefore been omitted from the summaries, provided here.

[6] This quote is an amalgamation from two sources: *Global Change Impacts on Habitability*, NASA/Jet Propulsion Laboratory D-95 (1982); and *Earth Observations from Space: History, Promise, and Reality,* National Academy of Science (1995).

[7] See Piers Sellers's "Reflections on the Early Days of EOS: A Biased and Unexpurgated History" in the January-February 2009 issue of *The Earth Observer* [**Volume 21**, **Issue 1**, pp. 4-8].

[8] HAPEX-MoBilHy stood for Hydrologic Atmospheric Pilot EXperiment–Modelisation du Bilan Hydrique. The campaign's goal was to measure the hydrological budget and evaporation flux at a resolution of 10 km^2 (~4 mi^2)—i.e., the scale of a general circulation model grid square at the time. A follow-on experiment was HAPEX-Sahel, which was undertaken in western Niger, in the west African Sahel region from 1990 to 1992, and sought to understand how interannual changes to the land surface of that region impacted the general circulation in general—and on drought in particular.

field experiment—an activity of the World Climate Research Programme (WCRP)—which took place in 1986 over a 100-km x 100-km area near Toulouse. The NASA team had only a small remote sensing component during HAPEX-MoBilHy, nevertheless they learned much from participating in development of ground measurement strategies that they would use during FIFE. For example, one effective observational strategy used during HAPEX–MoBilHy was the implementation of a *special observing period (SOP)*, or alternatively *intensive observing period (IOP)*, during which researchers obtained detailed measurements of atmospheric fluxes and remote sensing observations of Earth's surface properties using instrumented aircraft. This was the basis for FIFE and BOREAS later implementing a similar intensive field campaign (IFC) measurement strategy—see **Figure 1**.

IFC Operations: Flexible Response

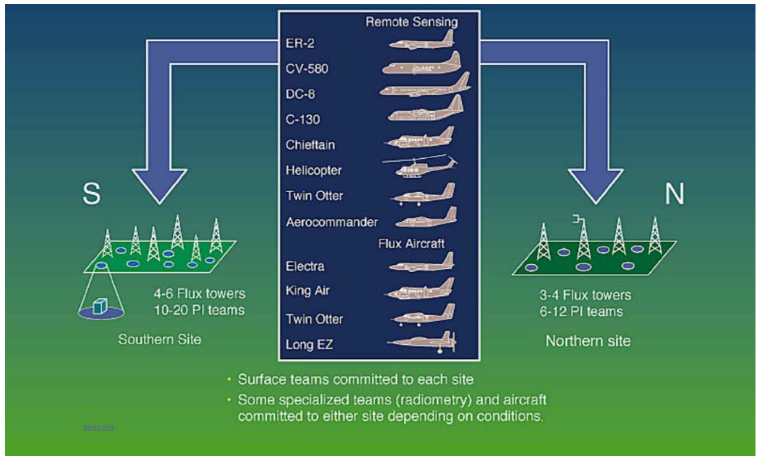


Figure 1. An illustration of how the Intensive Field Campaign (IFC) was implemented during BOREAS, with observations going on simultaneously at the Northern and Southern Study Areas. **Image credit:** NASA

FIFE, BOREAS, and NASA's EOS

There was synergy and excitement at early planning meetings for FIFE as this great concept came together, along with the availability of talented individuals who could make it happen. FIFE was to be a multiscale experiment that would take measurements from the small scale (where biologists understood plant behavior) to the large scale (where remote sensing specialists could describe the aggregate result of the those small-scale processes). The idea was to both *upscale* knowledge from the leaf to satellite levels for prediction, and *downscale* from satellite maps of area to leaf level for validation—see **Figure 2**. Such an enterprise required careful planning and execution. The organizers (primarily **Piers Sellers** and **Forrest Hall,** both from GSFC) worked with the newly selected science team drawn from universities, NASA field centers, government laboratories, and the private sector to develop a detailed *FIFE Science Plan* and *FIFE Experiment Plan* that provided detailed guidance for accomplishment—see **Figure 3**. A similar plan would guide BOREAS.

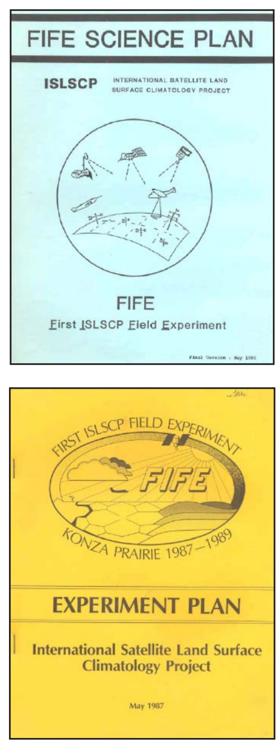


Figure 3. Covers for the *FIFE Science Plan* and *FIFE Experiment Plan*. A similar set of documents guided BOREAS. **Image credit:** NASA (covers hand-drawn by Piers Sellers)

Around the same time FIFE was underway, the concept for NASA's Earth Observing System (EOS) began to take shape; the first EOS Announcement of Opportunity was published the same year that FIFE'89 took place. The tumultuous and inspiring tale of its evolution has been told in bits and pieces in other places and will not be recounted

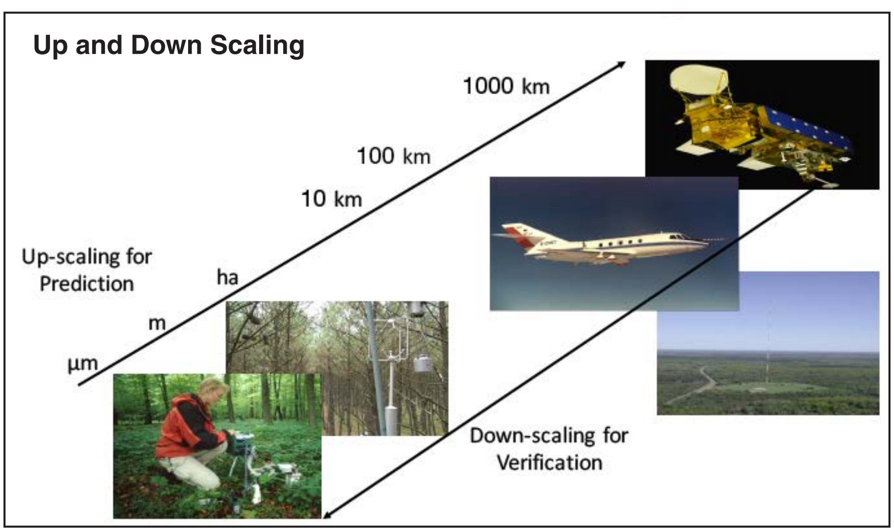


Figure 2. Diagram showing the upscaling (for prediction) and downscaling (for validation) done during FIFE and BOREAS. **Image credit:** Forrest Hall

here;[9] in this context, it suffices to say that EOS went through a series of revisions to the design of the proposed spacecraft during the early-to-mid 1990s—just as BOREAS was being planned and implemented.

As the following summary of the meeting held this past October at GSFC makes evident, FIFE and BOREAS were truly interdisciplinary studies that required the insights and participation of ecologists, soil scientists, boundary-layer meteorologists, and weather and climate modelers—and thus the research projects conducted were perfectly suited to be conducted as EOS investigations, which emphasized interdisciplinary science. The FIFE/BOREAS community (i.e., the ISLSCP community) provided 8 of the 31 original EOS Interdisciplinary Scientists—the most prestigious and well-funded positions in the early days of that program. This was quite a remarkable achievement for a discipline that did not exist in the early 1980s!

"In retrospect, it's clear that the years of hard and painstaking work by the FIFE and BOREAS teams were absolutely critical in getting the Earth Observing System started, designed, and launched—and how remarkable and rare a success the EOS project was. Dixon Butler, Berrien Moore, Francis Bretherton, Shelby Tilford, Ghassem Asrar, Chris Scolese, Michael King, Diane Wickland, and Piers Sellers—as well as many others—deserve enormous credit for making EOS a reality."

—Forrest Hall

With this as background, we will now move into summaries of the meeting presentations, emphasizing the seminal changes that so significantly contributed to our current understanding of Earth system science and—as a result—how we view our home planet. Please note that the presentations given at the meeting were individual reminiscences of each speaker's experience during FIFE and/or BOREAS, and thus what appears in this summary is not a chronological account of these events. The *Timeline of Key Events Related to FIFE and BOREAS* on page 13 may be helpful to refer to while reading.

EDITORIAL ACKNOWLEDGMENT: Every speaker at the *How FIFE/BOREAS Changed the World* meeting reviewed a draft summary of their presentation, which resulted in a very detailed account of the meeting. The authors wish to thank all participants for contributing those detailed reviews. Unfortunately, in order to fit within page limits in *The Earth Observer*, some of that information had to be shortened or eliminated—including many entertaining and enlightening anecdotal accounts. We hope that what we have preserved conveys the fact that, in addition to being pioneering scientific endeavors, FIFE and BOREAS were intensely personal experiences. Those interested in reading the unabridged summaries should contact the first author of this article.

Meeting Presentation Summaries

Thursday, October 6

Opening Remarks: Changing the World

Piers Sellers [GSFC—*Deputy Director of the Earth Sciences and Exploration Directorate*[10]] welcomed everyone to the meeting and set the scene as July 20, 1994, as the team awaited the nightly BOREAS Operations briefing at a location near Candle Lake, Saskatchewan, Canada. The teams were preparing for IFC operations first at the Southern Study Area on July 21, 1994, then two days later at the Northern Study Area. He showed operational documents such as an Aircraft Flight Plan, a daily Team Participation Schedule, and a list of issues from the Mission Manager (Sellers) and Study Area Manager (Carla Evans). These documents gave a sense of the immense amount of logistical planning that was required to make this IFC happen.

Sellers proceeded to give what he called a "revisionist history" of FIFE and BOREAS and ways in which they changed the world and, in particular, how they served as impetus to move interdisciplinary Earth system science from the realm of possibility to the realm of reality. He ended with a discussion of the results of these two campaigns, which led to large integrated datasets (i.e., measurement from subsoil to

[9] *The Earth Observer* has done many previous articles chronicling the history of the EOS Program. One of the most comprehensive summaries is "The Earth Observer: 25 Years Telling NASA's Earth Science Story" in the March–April 2014 (25th anniversary) issue of *The Earth Observer* [**Volume 26**, **Issue 2**, pp. 4-13]. This article references a number of articles in the *"Perspectives on EOS"* series that ran from 2008 to 2011, which have been compiled into *The Earth Observer Perspectives on EOS Special Edition*, and can be downloaded at *http://eospso.nasa.gov/sites/default/files/eo_pdfs/Perspectives_EOS.pdf*.

[10] Please note that, unless otherwise specified all affiliations listed in brackets are the speaker's current (or most recent if retired or deceased) affiliation and, if applicable, title.

orbit), available on CD-ROMS (some of which are still being used today), and an abundance of publications, both discipline-specific and—later—interdisciplinary. These themes were repeated in many of the presentations that followed.

Remote Sensing During FIFE and BOREAS

Forrest Hall [GSFC, *retired*] recalled the humble beginnings of what led to FIFE, beginning with closet-like office space and simplistic computing capabilities. Hall led the remote sensing part of FIFE/BOREAS because—as he put it—"Piers headed up pretty much everything else." Hall traced how remote sensing capabilities evolved from the time he moved from NASA's Johnson Space Center (where he had worked on LACIE and AgRISTARS—defined on timeline, *right*) to GSFC in 1985 throughout FIFE and BOREAS. He discussed plans for FIFE, including a diagram of the scenario that Piers conceived for choosing *golden days* and *silver days* (used during FIFE and BOREAS) to prioritize measurements for data analysis.[11]

Hall summarized results obtained during FIFE'87 showing Normalized Difference Vegetation Index (NDVI) maps of the region and describing efforts to measure sensible heat. He and his colleagues developed remote sensing algorithms using data from FIFE to produce seasonal, annual, and decadal maps of vegetation type and biophysical properties at regional and global scales. They also developed a quantitative methodology for using vegetation indices to monitor surface energy, water, and carbon fluxes, as well as a physical understanding of what vegetation indices were measuring and their dependence on extraneous effects such as atmospheric and sun angle variations—all foundational approaches to interdisciplinary, multiscale, Earth system science.

Hall next mentioned some of the lessons learned during aircraft experiments during FIFE and BOREAS and how they laid the foundation for EOS data product algorithms and influenced Decadal Survey[12] and Venture Class[13] mission concepts. The data collected revealed, for example, that three-dimensional vegetation structure could be inferred using lidar (GEDI), radar, and passive optical remote sensing (MODIS), and that hyperspectral imagers can map vegetation, photosynthetic, and non-photosynthetic structure (HyspIRI).[14] These investigations also laid groundwork for future field campaigns [e.g., BERMS, LBA,[15] and Arctic Boreal Vulnerability Experiment (ABoVE)[16]].

Impacts on Numerical Weather Forecasting

Alan Betts [Atmospheric Research] worked on analyzing aircraft data during FIFE (obtained mostly by instruments on the de Havilland Canada DH-6 Twin Otter aircraft)

[11] At the end of FIFE'87, the participating scientists reviewed the preliminary datasets and mission logs and identified the best day in each IFC as a *golden day*, assigning it the highest priority for data processing and submission. Other days known to have good datasets were identified as *silver days* and given slightly lower priority for data processing. The process was repeated after FIFE'89 and the BOREAS field deployments.

[12] The National Academy of Science's 2007 Earth Science Decadal Survey was the first-ever comprehensive study of the Earth sciences that could benefit from spaceborne observations; it identified science priorities and a proposed time sequence of missions: Tier 1, Tier 2, and Tier 3. To learn more, visit *https://decadal.gsfc.nasa.gov/about.html*. A 2017 Decadal Survey is presently in formulation—see *http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm*.

[13] Earth Venture class missions are broken down into Suborbital (EVS), Instrument (EVI), and Mission (EVM). For more about the three categories and a list of missions, see *https://science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder*.

[14] GEDI stands for Global Ecosystem Dynamics Investigation Lidar, an Earth Venture Instrument mission planned for launch in 2020; MODIS stands for Moderate Resolution Imaging Spectroradiometer on NASA's Terra and Aqua satellites; and HyspIRI stands for Hyperspectral Infrared Imager, a Tier 2 Decadal Survey mission currently in formulation.

[15] The Largescale Biosphere–Atmosphere Experiment in Amazonia (LBA) took place from 1995 to 2005 and was led by Brazil. While the timeframe is mostly beyond the scope of this article, LBA can essentially be thought of as a follow-on to BOREAS, this time focusing on tropical forests.

[16] NASA's Terrestrial Ecology Program is conducting ABoVE, a major field campaign in Alaska and western Canada, for 8 to 10 years, starting in 2015. ABoVE seeks a better understanding of the vulnerability and resilience of ecosystems and society to the changing environment.

Timeline of Key Events Related to FIFE and BOREAS

1972
- First "remote sensing" experiments with Landsat-1 data

1974
- Large Area Crop Inventory Experiment (LACIE) ***1974-1978***

1978

1979
- Agriculture and Resources Inventory Surveys through Aerospace Remote Sensing (AgRISTARS) ***1979-1985***

1983
- ISLSCP Conceived

1984
- First ISLSCP Meeting
- Biospheric Sciences Branch created at GSFC

1986
- HAPEX-MoBilHy

1987
- FIFE'87

1988
- KUREX'88

1989
- FIFE'89*; -EOS AO*

1990
- HAPEX-Sahel ***1990-1992***

1991
- KUREX'91

1992

1993
- BOREAS preparatory

1994
- BOREAS

1995
- LBA begins ***1995-2005***

1996
- BOREAS
- BERMS

1999
- Launch of first EOS "flagship" mission—Terra

and realized they could be used to evaluate the European Centre for Medium Range Weather Forecasts' (ECMWF) weather forecast model. Betts was delighted to receive enthusiastic support from Tony Hollingsworth, then Director of Research at ECMWF. The timing was fortuitous for ECMWF: The improved version of the land-surface model went into testing in July 1993 and hit "pay dirt" immediately as it greatly improved forecast skill for the historic flooding that took place in the Midwest U.S. that summer.

The improved ECMWF model was used for daily forecasts for BOREAS, and BOREAS data were subsequently used to correct forest snow albedo in Canada and Eurasia. Data from both BOREAS and BERMS later played a big role in improving ECMWF's 45-year reanalysis of global atmosphere and surface conditions that ran until August 2002. Betts said that FIFE and BOREAS were transformative for modeling, and provided significant ground truth for evaluating forecast models; he noted that the FIFE dataset was used to test every land surface model for a decade. In summary, BOREAS/BERMS led to new forest models and several generations of snow models—information still being transferred into Earth-science models today.

FIFE and BOREAS were transformative for modeling, and provided significant ground truth for evaluating forecast models; the FIFE dataset was used to test every land surface model for a decade.

Physiology: Leaf to Orbit

Joe Berry [Carnegie Institution for Science] described a series of scientific investigations that took place around the same time FIFE was under way. He began by describing the pioneering work of Compton "Jim" Tucker at GSFC, who developed NDVI using AVHRR[17] data in 1979, and Inez Fung, then at NASA/Jet Propulsion Laboratory (JPL), who studied global atmospheric carbon dioxide (CO_2) concentrations. Berry showed the iconic "flying carpet plots," (from a 1986 article in *Nature* that Tucker, Fung, and others, co-authored) that show how CO_2 and NDVI varied over space and time. Around the same time as Tucker and Fung's research, Sellers was working to incorporate his Simple Biosphere (SiB) land-surface parameterization into a GCM. Berry began an effort to improve the SiB model's representation of evapotranspiration, based on an earlier model of photosynthesis developed by Graham Farquhar and Susanne von Caemmerer, who were both at the Australian National University. Berry and Tim Ball, Berry's graduate student at Colorado State University (CSU), used that model to predict the stomatal response, later used by Sellers and his GSFC colleague, Jim Collatz, in an improved version of the canopy model: the Simple Biosphere Model-II (SiB-II).

Ultimately, all these areas of study came into play when two of the original EOS Interdisciplinary Science Projects merged to form *The Greening of the Colorado State University GCM*, which was discussed in a 1996 issue of *Journal of Climate*. This was the first time models of larger-scale processes were coupled with models of smaller-scale process. The project took place in parallel with FIFE and BOREAS, which meant there were plenty of new field data to test the updated models.

Aircraft Flux Measurements during FIFE and BOREAS

Raymond Desjardins [Agriculture and Agri-Food Canada, Science and Technology Branch] showed how FIFE and BOREAS aircraft observations contributed to improving flux-measuring systems. These experiments improved our understanding of mass and energy fluxes between Earth's surface and its atmosphere. He demonstrated how the data collected by flying long [30-m (~98-ft)] transects over the boreal forest helped quantify the contribution of mesoscale transfer to the lack of energy budget closure on flux measurements.

Desjardins described several key measurement techniques that were new at the time, and also showed how integrated observations are essential for understanding land-atmosphere interactions. He stated that additional information will be extracted from these data. He noted that if he were to do an experiment like FIFE or BOREAS today, he would recommend fewer tower/aircraft comparisons, more focus on budget studies, and taking measurements over long transects.

[17] AVHRR stands for Advanced Very High Resolution Radiometer, which has flown on NOAA's Polar Orbiting Environmental Satellite series.

FIFE and BOREAS Soil/Atmosphere Flux Models

Dave Schimel [JPL] noted the irony in Piers Sellers asking him to discuss modeling. He noted that he always thought of FIFE as "scaling from chiggers to C-130s"—chiggers being a key operational issue in those days.[18] He invited participants to step into "the modeling Wayback Machine" by describing the now-dated technology used at the time, and then focused in on the state of the art of models prior to FIFE. In the mid-1980s it was accepted that "you could not scale from leaf to canopy" because there was no scaling rule to simplify modeling each leaf, and there was no way to choose between alternate scaling theories. Testing scaling theories and models required measuring photosynthesis or respiration at large scales and—until FIFE—this had never been done.

Early empirical field observations over the Konza Prairie led to the discovery of a relationship between light interception and nitrogen limitation, which led to emergence of a scaling rule that related light absorption, canopy nitrogen, and photosynthetic capacity—the first step to scaling from leaf to canopy. That rule was immediately incorporated into the nascent SiB-II. However, the basic assumptions still needed verification. The pioneering sustained eddy covariance measurements taking during FIFE led to the answer—i.e., canopy-scale flux measurements. While now routine, work done on the Konza Prairie established biophysical and biogeochemical linkages that are still being absorbed into models.

Flux Observations at the BOREAS Northern Study Area Old Black Spruce (NSA-OBS) Site

Steve Wofsy [Harvard University] was introduced to models of the global carbon cycle through Inez Fung's work, discussed previously. He described how he thought Sellers and Hall had a "beautiful" concept for a campaign, and noted that Diane Wickland, in her roles as HQ program scientist and program monitor for FIFE and BOREAS, was willing to push the envelope beyond the norm at NASA, taking a risk in funding their concept. History has shown that her risk has more than paid off.

Wofsy showed pictures of the NSA-OBS site—see *The FIFE/BOREAS Study Areas* on pages 8-9 for context—and the people involved, noting the ground-level temporal and spatial variability in the boreal forest. Wofsy also connected the BOREAS study to the recent EVS-1 study, Carbon in the Arctic Reservoirs Vulnerability Experiment (CARVE), yet another "grandchild" of BOREAS—see *https://carve.jpl.nasa.gov* to learn more. Three years of aircraft flights over Alaska (2012–2014) resulted in hundreds of vertical atmospheric profiles, giving results that were foreshadowed by BOREAS. BOREAS provided the remote sensing context to link ecosystem scale observations to the global carbon cycle. BOREAS results also showed the critical importance of year-round monitoring of the *shoulder seasons* in between peak activity to understand the soil-climate-carbon nexus—and how to model it.

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Follow the (Surface) Water

Richard Cuenca [Oregon State University, Corvallis] gave a detailed description of the routine used to make soil moisture measurements during the first BOREAS campaign (1994) using a neutron probe. He also discussed visualization of soil water dynamics during BOREAS, using neutron probe data and then using continuous-recording dielectric probe data. He also described infiltration tests to parameterize soil water dynamics, describing winter operations under trying conditions to maintain and prepare the sites for summer campaigns.

[18] *Chigger* is one nickname for a class of arachnids called *trombiculid mites*; they are commonly found in moist grassy areas like fields and forests (which pretty much covers the terrain of FIFE and BOREAS). Adult chiggers don't bite but their larvae do. They can latch onto pants and shirts and seek out and attach to exposed skin. The bites, which can be very itchy, would most often be found in clusters around the waist or lower legs.

Cuenca went on to discuss the Airborne Microwave Observatory of Subcanopy and Subsurface Mission (AirMOSS) campaign (see *http://airbornescience.jpl.nasa.gov/campaign/airmoss*), which involved Mahta Moghaddam from the University of Southern California and Sassan Saatchi from JPL, who also worked together during BOREAS—see presentation below. He showed the AirMOSS sites, noting that some were used during BOREAS. He ended by commending Sellers and Hall for their vision and pioneering work to make these field campaigns a reality.

Follow the Carbon

David Fitzjarrald [State University of New York (SUNY) Albany, Arctic Slope Research Corporation] was fresh from the NASA Atmospheric Boundary Layer Experiment (ABLE), with projects in the Amazon forest, the Alaskan tundra, and Quebec boreal forest and fen, when he met Sellers and Hall in 1992. Sellers called this flux work "Boy Scout science," with defined steps and mid- and endpoints, whereas BOREAS was to be the "real science." Fitzjarrald demurred at this assessment, and felt his approach was more *aleatoric*, that is, prizing the serendipitous discovery common in field research.

Spirited but civil debate—a notable feature of BOREAS—led the very same FIFE people who early on argued against long-term flux measurements to lead the development of FLUXNET, a large international flux tower network.

BOREAS was structured to have the former ABLE participants and new Canadian colleagues in the NSA and FIFE veterans participate in a more-elaborate field operation in Saskatchewan. Fitzjarrald stated that among the durable results from BOREAS was recognition that long-term eddy flux measurements are required, supplanting the FIFE template of a series of short-term intensive field periods. Spirited but civil debate—a notable feature of BOREAS—led the very same FIFE people who early on argued against long-term flux measurements to lead the development of FLUXNET, a large international flux tower network.

Follow the Photons

Jing Chen [University of Toronto] began working on BOREAS as a postdoc. He described how photons in leaves can go to three different interrelated processes: non-photochemical quenching, chlorophyll fluorescence, and photochemical quenching—the main interest for his work. The *one big leaf* model for photon pathways gives a fair estimate of Net Primary Productivity, but work by John Norman, moving to two leaves (a sunlit leaf and a shaded leaf), improved results considerably. According to the fraction of vegetation photosynthesis model, discussed previously, photons are "more welcome" in shaded leaves. During and after BOREAS, researchers started "following the photons" in various ways and learned that the mechanistic photosynthesis model developed by Graham Farquhar and Susanne von Caemmerer (described previously) requires us to follow photons to both the sunlit and shaded leaves. Chen then proceeded to show how gaps in canopies are as important as gaps between measurement sites, and that remote sensing has a major role to play in filling both gaps.

Radar Derived Forest Biomass and Canopy and Soil Moisture in BOREAS

Sassan Saatchi [JPL] started his remote sensing work during FIFE'89, and got to know Sellers and Hall when he worked at GSFC from 1989 to 1991. Prior to BOREAS, vegetation canopy radar observations from space were conceived of but there was very little to connect them to the ground. Saatchi was part of the Airborne Synthetic Aperture Radar (AirSAR) team when they prepared to head to Canada in 1993, and described how the three-frequency microwave measurements provided information about soil and vegetation over the BOREAS study sites. Saatchi discussed the theoretical basis for the biomass algorithm developed during the experiment and how results and concepts were later incorporated into space missions—e.g., NASA's Soil Moisture Active/Passive (SMAP) mission, the joint NASA–ISRO[19] Synthetic Aperture Radar Mission (NISAR), and the AirMOSS.

[19] ISRO stands for the Indian Space Research Organization.

Friday, October 7

New Understanding of Atmospheric Turbulent Mixing

Jielun Sun [University Corporation for Atmospheric Research] described the pioneering work that she and her colleagues did during BOREAS to investigate the role of the CO_2 advection in explaining the "missing" nighttime CO_2.[20] Since then, many field campaigns have been conducted to study this effect. She went on to describe the only nighttime flight of the Twin Otter and the *ad hoc* boat measurements to try to measure the *chimney effect*[21] over Candle Lake. The data Sun's team collected during BOREAS also revealed significant differences between surface radiation temperature and aerodynamic temperature—differences that are important to understand in order to parameterize turbulent heat transfer from air–land interactions in models.

Sun demonstrated how BOREAS facilitated interdisciplinary work, which included both designed and *ad hoc* experiments. She concluded by showing some more-recent research into understanding turbulent mixing in air–land interactions that builds upon the knowledge gained during BOREAS.

Large-scale experiments like BOREAS are not just about scientific achievements but also about human synergy; twenty years later, the people involved in FIFE and/or BOREAS are still a community.

Flux Tower Measurements during BOREAS

Elizabeth Pattey [Agriculture and Agri-Food Canada] reported on how studying unmanaged forest and managed agroecosystems provide insight on atmospheric biogeosciences, thus supporting aircraft teams, atmospheric chemists, and Earth-observation scientists. She described how FIFE and BOREAS initiatives helped the micrometeorological community improve their flux measuring methodology and better understand and interpret their flux measurement datasets. The OBS site data, obtained used two tunable diode lasers for methane and nitrous oxide fluxes and a relaxed eddy accumulation system for measuring isoprene emissions, revealed that boreal forests—and OBS in particular—behave like an arid ecosystem, as they are very conservative in resource management. Other phenomena from these early studies presaged increased tower- and aircraft-based trace gas flux experiments. Researchers experimented with new ways to assimilate such data into vegetation models. Pattey reflected sentiments similar to those of previous speakers: Large-scale experiments like BOREAS are not just about scientific achievements but also about human synergy: She noted that twenty years later, the people involved are still a community.

Learning Ecosystem Atmosphere Studies from BOREAS

Ken Davis [Pennsylvania State University] was a physics undergraduate student when FIFE took place, and was a postdoc at the National Center for Atmospheric Research (NCAR) during BOREAS. He described his experiment [Airborne Fluxes and Meteorology (AFM)-13] on the NCAR Electra aircraft based in Saskatoon, Saskatchewan Province, Canada, with activities to "tie together" the BOREAS northern and southern study areas. Davis noted that point measurements (e.g., from flux towers) and global measurements are not sufficient, and that intensive campaigns that oversample ecosystem variability in important regions of the Earth system are necessary. Davis also called for renewed engagement between the climate modeling community and the field research community.

Capturing and Cataloguing Data: FIS and BORIS

Don Strebel [Versar, Inc.], speaking on behalf of co-authors **Fred Huemmrich** [University of Maryland, Baltimore County] and **David Landis** [Global Science & Technology, Inc.],

[20] In ecological studies, the "missing CO_2" refers to the mismatch between the known reasonable amount of CO_2 respiration from the ground and ecosystem at night and the relatively small CO_2 flux measured at towers. Because of the stable boundary layer developed at night, which reduces turbulent mixing, a significant amount of the CO_2 is transported horizontally and never reaches to the tower sensors.

[21] The *chimney effect* refers to cold air drainage flow over Candle Lake that carries nighttime respirated CO_2 from soil/canopies over the warmer lake water surface. The convective buoyancy then transports air with high CO_2 concentrations upward over the lake by turbulent mixing, forming a CO_2 transporting mechanism, or *chimney*, over the area.

The FIFE datasets were made widely available on CD-ROM, which at the time was state of the art technology. **Photo credit:** Don Strebel

described the pioneering information systems that connected investigators with data—essential to the success of FIFE and BOREAS. He described the creation and accomplishments of the FIFE Information System (FIS), with tools that are the functional equivalents of what we commonly use today, but were not then available.

FIS grew into NASA's first working interactive online data system, which successfully supported FIFE, formed the basis for the BOREAS Information System (BORIS), and reinvigorated a later version of NASA's Pilot Land Data System (PLDS).[22] In addition to the FIS staff, the collaborative effort drew upon the talents of many NASA scientists, contract support scientists, Konza Prairie Longterm Ecological Research (LTER) scientists, and the FIFE investigator teams.

The FIS Staff, ca.1988. [Standing, *left to right*] Scott Goetz, Gail Beckman, Babu Banerjee, Forrest Hall, David Landis, Jeff Newcomer, Rich Irish,Tom Eck. [Seated, *left to right*] Ned Horning, Ruth Kennard, Jaime Nickeson, Don Strebel. Others *not pictured* included Diana Van Elburg–Obler, Fred Huemmrich, Jim Ormsby, Steve Ungar, Jim McManus, Bob Lutz, Alan Nelson, Patrick Agbu, and Blanche Meeson, along with several interns. **Photo credit:** Don Strebel

In sum, FIS personnel (see photo above) built the Internet's first interactive scientific database, established the first practical data documentation standards, and published the first digital scientific data collection to meet the "20-year test" by publishing the FIFE data on CD Roms—see photo [*upper left*]. Still in use today and described as "the longest running FIFE experiment," this effort showed that formal data publication could preserve for at least 20 years data for access and use by a scientist unfamiliar with the datasets or their collection.

In sum, FIS personnel built the Internet's first interactive scientific database, established the first practical data documentation standards, and published the first digital scientific data collection to meet the "20-year" test by publishing the FIFE data on CD-ROMs.

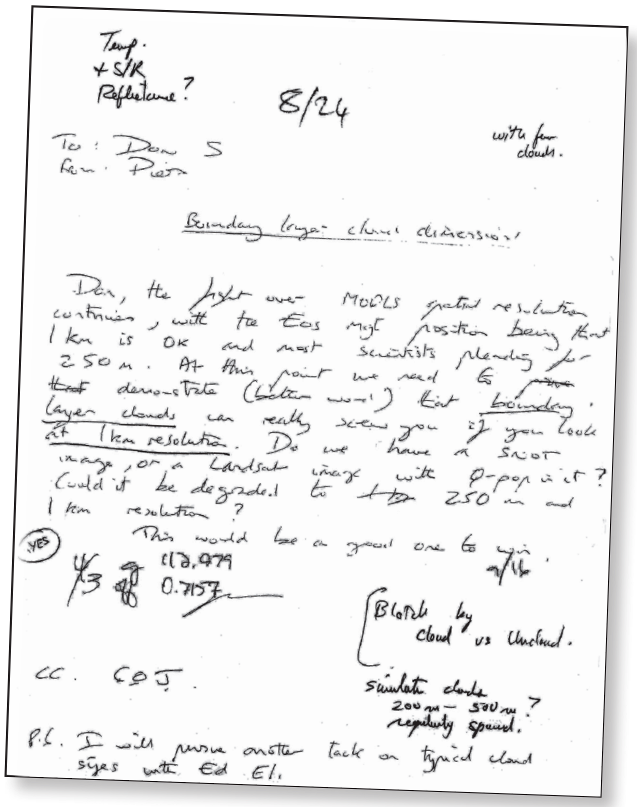
Planning and Implementing FIFE and BOREAS (a.k.a. *Herding Cats*)

Jaime Nickeson [GSFC/Science Systems and Applications, Inc.] recalled some of her experiences at GSFC during FIFE and BOREAS, spending most of her FIFE years in the laboratory processing satellite data and working to radiometrically rectify the satellite datasets. She did much more field work during BOREAS, however, from early information gathering and data processing to field reconnaissance, to identify and locate tower and auxiliary sites. She discussed how Sellers and Hall worked with GSFC staff to compile the Experiment Plan: three volumes dictating what would be done where and when, and appendices A through P, containing things such as flight plans, procedures, satellite overpass schedules, customs, and shipping. Key to the success of the experiments were planning (laid out in the Experiment Plans), excellent leadership (from both Hall and Sellers), and assigning staff to each of the science disciplines with subsequent building of relationships. Years later, Nickeson found a handwritten memo from Sellers. It was titled *Boundary Layer Cloud Dimension*, and it described the battle Sellers had been waging within EOS over the resolution of the MODIS sensor—see *How FIFE Changed MODIS* on the next page.

[22] PLDS was the data system that NASA HQ was working in the years leading up to FIFE. Strebel and his associates quickly came to the conclusion that PLDS, as it existed at the time, would not be flexible enough for use in FIFE, which led them to develop a separate FIS. This, in turn, fed back into the evolution of the PLDS.

How FIFE Changed MODIS

NASA's Earth Observing System (EOS) was being conceived in the mid-to-late 1980s, right around the same time FIFE was being planned and executed, and the concept continued to evolve as BOREAS unfolded in the mid-1990s. While FIFE/BOREAS data and personnel influenced the design of EOS in many ways, one development was particularly noteworthy: A hotly debated issue at the time was the utility of including a couple of 250-m-resolution bands on the two Moderate Resolution Imaging Spectroradiometer (MODIS) instruments that were being designed and would eventually fly on the EOS Terra (1999) and Aqua (2002) flagship missions.



Temp. + S/R Reflectance?

8/24

with few clouds.

To: Don S
From: Piers

Boundary layer cloud dimensions

Don, the fight over MODIS spatial resolution continues, with the EOS mgt position being that 1 km is OK and most scientists pleading for 250 m. At this point we need to demonstrate (better word) that boundary layer clouds can really screw you if you look at 1 km resolution. Do we have a SPOT image, or a Landsat image with pop-corn in it? Could it be degraded to 250 m and 1 km resolution? This would be a good one to win.

YES

113,979
0.7157

Blotch by cloud vs unclouded.

cc. CoJ.

Simulate clouds 200 m – 500 m? regularly spaced.

P.S. I will pursue another tack on typical cloud sizes with Ed El.

A hand-written Memo from **Piers Sellers** to **Don Strebel** and cc'ing **Chris Justice** [University of Maryland, College Park] (circa 1991-92) asking if the FIFE Team could provide some data that would help him in his effort to convince decision makers at NASA HQ that the proposed 250-m MODIS bands were essential to include. **Image credit:** Jaime Nickeson

At the end of her presentation at the meeting, **Jaime Nickeson** produced a handwritten memo that Piers Sellers had sent to Don Strebel *circa* 1991–1992. Sellers was trying to make the case that "boundary layer clouds can really screw you if look at them at 1-km resolution," and wanted imagery to back up his claim—adding, "this would be a good one to win." Strebel shared the memo with Nickeson, who dug into the FIFE satellite archive that contained plenty of imagery with "popcorn" clouds. She resampled some 20-m SPOT* imagery to the 250-m resolution they were proposing for MODIS, and then also resampled to 500 m and 1 km. They found that many of the small boundary layer clouds, clearly visible in photos from FIFE and higher-resolution images, tended to disappear at lower resolutions. This information helped convince **Dixon Butler** and other decision makers at NASA HQ that including the 250-m MODIS bands was essential. Relying on the poorer temporal coverage of higher-resolution sensors (e.g., Landsat, SPOT) simply would not suffice for global biosphere studies.

Today, MODIS is arguably the workhorse of the EOS satellite fleet, as it provides data for many applications and has been cited in many papers in science journals. How different the world of EOS (and thereafter) would have been had Sellers not prevailed in this argument.

* SPOT stands for Satellite Pour l'Observation de la Terre; it is a commercial, high-resolution, optical-imaging, Earth-observation satellite system run by the French company Spot Image, based in Toulouse.

"I Was There!": Some Personal Views of FIFE and BOREAS

On the afternoon of the first day, the focus of the meeting shifted away from science and more to personal anecdotes and memories of the FIFE and/or BOREAS experience from several individuals who were there, walking on or flying over the prairies of Kansas and/or the boreal forests of Canada. The short summaries we use in this article do not do these reports justice, so we highly recommend watching the online videos of these presentations—and perhaps reading the unabridged presentation summaries.

Willie Dykes [WBOC TV, Salisbury, MD] captured the crowd's imagination as he described the exploits of the helicopter remote sensing team at NASA's Wallops Flight Facility (WFF)—"The Troponauts." He explained that helicopters are ideal for testing new experiments since they are able to hover over a target and take continuous measurements. Dykes concluded by noting that "During BOREAS we learned the troposphere is not just a layer of gas—it's Earth's breath."

The Troponauts helicopter remote sensing team during BOREAS. [*Left to right.*] **Igor Gorankov** [visiting Russian scientist], **Charlie Walthall**, **James Ampe** [University of Kansas (KU)—*Graduate Student of Prasad Gogineni*], **Charles "Smitty" Smith** [*Mechanic*], **Willie Dykes**, and another of Gogineni's grad students at KU. **Photo credit:** Rick Huey [WFF]

Charlie Walthall [U.S. Department of Agriculture, ARS—*National Program Leader*] also went to WFF to test the feasibility of using a helicopter [*top photo*] to acquire detailed spectra of terrestrial surfaces. He described his experiences working with "The Troponauts" and experimenting with a number of different remote sensing instruments.

Ian MacPherson [National Research Council of Canada, *retired*] explained that FIFE and BOREAS put the Twin Otter aircraft [*bottom photo*] "on the map," as they were the first experiments to make extensive use of the aircraft in the flux-measuring role. He shared some of his more memorable experiences while flying, including the largest wind gust ever encountered by the Twin Otter as well as a break fire during takeoff—see related poem on page 21.

The Twin Otter crew during one of the FIFE'87 Intensive Field Campaigns. [*Left to right.*] **Ray Desjardins**, **Peter Schuepp** [McGill University], **John Croll** [*Pilot*], **Chuck Taylor** [*Instrument Technician*], **Ben McLeod** [*Aircraft Maintenance*], and **Ian MacPherson**. **Photo credit:** Ian MacPherson

Christopher Pali [NASA/Dyncorp] showed a *NASA 427* model of NASA's Wallops Flight Facility's C-130 *Hercules*—"The Cutie"—which he piloted for BOREAS during January and July 1996. He shared fond memories from his time in Canada and reflected on the friendship he had with Sellers, who left BOREAS in 1996 to join the NASA astronaut corps.

Steve Ungar [GSFC, *retired*] explained the three roles he had during FIFE: project scientist for FIS; MODIS Airborne Simulator (MAS) instrument scientist during FIFE (which flew on the C-130); and Soil Moisture Measurement principal investigator. He described how his experiences in FIFE, the Kursk 1991 Experiment (KUREX'91) in Streletskaya, Russia (where they studied global climate processes in steppe vegetation), and BOREAS, all helped prepare him for his later role as project scientist for the Earth Observing-1 mission.

Paula Pacholek [Canadian Wildlife Service] discussed Canadian concerns of a NASA invasion that would impact vegetation, wildlife, and/or the experience of the Prince Albert National Park visitor. Such fears were proved unfounded, however, and the BOREAS scientific activities were welcomed and enjoyed, as NASA demonstrated ability to live under local conditions.

Scott Goetz's [Northern Arizona University] initial involvement was in selecting flux tower and other sites for BOREAS. He now leads the Arctic Boreal Vulnerability Experiment (ABoVE), the next generation NASA-led field campaign.

John Norman [University of Wisconsin, Madison, *retired*] described how FIFE led to better models for satellite mapping. The key lesson was that the canopy must be represented as two or more layers—because soil behaves much differently than leaves.

ISLSCP I and II

Forrest Hall described how Piers Sellers was the perfect person to organize large-scale experiments like FIFE and BOREAS, and ISLSCP. He talked about a workshop at GSFC in 1992, convened to assess the current state and direction of biosphere–atmosphere model development, data needs for models, current satellite data algorithms, and other global datasets. This meeting served as an impetus for the ISLSCP-Initiative I data collection, which was a two-year effort (1987 and 1988) and which resulted in a variety of datasets mapped to a common 1º x 1º equal-angle grid, and made available on CD-ROMS. An article describing ISLSCP-I datasets appeared in the *Bulletin of the American Meteorology Society* in 1996.

As noted earlier, Sellers went on to astronaut training in 1996 and Hall took the lead on ISLSCP-Initiative II, which expanded upon ISLSCP I collection—with increased spatial (¼° x ¼°, ½° x ½°, and 1° x 1° grids) and temporal resolution (10 years, from 1986 to 1995, as opposed to 2 years for ISLSCP-I) and added carbon datasets (ISLSCP-I had primarily focused on water). Hall showed a slide that gave an idea of the many organizations involved in ISLSCP-II and also showed an impressive list of publications that site ISLSCP-II. The ISLSCP-II datasets were published in a *Journal of Geophysical Research* article in 2006. The most common uses of the data were for model intercomparisons and for studies of global runoff, global forests, global fire emissions, and global carbon distribution.

Perspectives from NASA HQ

Two presentations were provided by individuals who played prominent programmatic roles in the years leading up to and during FIFE and BOREAS.

Bob Murphy [NASA HQ, *retired*] shared his perspective as one who participated in the birth of FIFE and BOREAS both at GSFC and NASA HQ, noting the early lack of any biospheric science at NASA in 1977 and the activities that led to formation of the Biospheric Branch at GSFC, which subsequently organized FIFE. He ended his reflections by asking: "Did FIFE/BOREAS change the world?", and answered his own question with an enthusiastic, "You bet!" As a result of these campaigns, many scientific findings have been brought into practical use in forecast models and continue to feed our understanding of crucial environmental problems. Of particular note is that a scientific discipline and community of researchers have been formed that did not exist 35 years ago.

Diane Wickland [NASA HQ, *retired*] called the event being reported on here a "lovely trip down memory lane." She particularly liked hearing perspectives on FIFE that were different from what she experienced as a NASA program manager—see *"I Was There!": Some Personal Views of FIFE and BOREAS* on page 20. She commended Murphy's role in actively pursuing the resources to do FIFE, which provided the budgetary foundation for future field campaigns. Wickland also commended Sellers and Hall for "figuring out" the logistics of how to organize and implement a large-scale experiment the likes of which NASA had never done before. She expressed great pride in the accomplishments of the FIFE–BOREAS community.

FIFE, BOREAS, and EOS: Precursor and Consequent

Piers Sellers provided some remarks connecting the FIFE/BOREAS story to the broader story of EOS, describing how he was enjoying life as a young scientist at GSFC in the mid-1980s, working on FIFE with Hall and others when EOS began to take shape. He eventually became deputy to Gerry Soffen [the first EOS Project Scientist (PS)], served on the EOS Review Group (ERG), and then was dismissed as EOS Deputy PS after sharing the conclusions of the ERG, returned happily to FIFE, but then was summoned back to EOS within 18 months to become the first AM-1 PS.[23]

Eyeball-to-eyeball with the tree

flies Aiken John—so low that he

is wont to say when crewmen squeal,

"that's how I like to spin the wheel".

And much desired photo-ops

are when he shaves the black-spruce tops.

The camera in Raymond's hand

spasmodically scans the land

a flash of Otter, blue and white,

a drunken hurtling out of sight,

a hint of sky, a blur of tree,

that's what you might or might not see.

—Peter Schuepp

[23] Sellers recounts more details of this tale in his "Perspectives on EOS" article, previously referenced.

Sellers described three areas where results from FIFE/BOREAS and the people who developed them impacted the design of EOS. These included:

1. Selection of the equator crossing time for AM-1 (which later became Terra)—choosing a morning orbit (1030 local Equator crossing time) as opposed to afternoon (1330);
2. the design of MODIS (see *How FIFE Changed MODIS* on page 19); and
3. FIS, the forerunner of what became the EOS Data and Information System (EOSDIS).

In each case, Sellers shared personal anecdotes of his experiences in the field and his contributions to these discussions. One noteworthy observation was his thinking that the early EOS Data System as being developed at Raytheon would not work. To some extent he was correct, although elements of the original concept were incorporated into the final system.[24]

Fluxnet-Canada built on the success of BOREAS to make high-quality field measurements of biosphere–atmosphere fluxes, which were combined with remote sensing data and used to help develop and test predictive models of northern forests and peatlands.

Long-Term Influence of BOREAS on Carbon Cycle and Ecosystem Research in Canada

Hank Margolis [NASA HQ—*Program Manager of Terrestrial Ecology*[25]] shared his BOREAS journey, and then discussed Fluxnet-Canada, which built on the success of BOREAS to make high-quality field measurements of biosphere–atmosphere fluxes, which were combined with remote sensing data and used to help develop and test predictive models of northern forests and peatlands.

Margolis described the archived dataset, which he called Fluxnet-Canada's "major legacy." They have amassed 185 site-years of flux data from 34 sites through 2011; they also have basic ecological data for nearly all sites. Some 932 users from 51 countries downloaded data between 2012 and 2014 from the Oak Ridge National Laboratory Distributed Active Archive Center (DAAC) and the Ameriflux database, which are used extensively for regional and global analyses.

Margolis presented some data from the Gravity Recovery and Climate Experiment (GRACE) that shows a gravity anomaly (attributed to groundwater) over White Gull Creek—which just happens to be centered exactly where Sellers and Hall chose to locate BOREAS more than two decades ago (because early models suggested climate change would be significant in this area) and which served as the basis for the longer-term BERMS studies. He showed how *in situ* BOREAS results validate the GRACE results. Work that began in BOREAS and continued with Fluxnet-Canada has laid groundwork for the current ABoVE campaign.

Concluding Remarks by the Organizers

To start a general conversation, **Piers Sellers** asked: *What did we do in FIFE and BOREAS and why does it matter?* As the presentations at the meeting made clear,

[24] Rama Ramaprayin tells the story of the progress, perils, and pitfalls along the way to developing the EOS Data and Information System (EOSDIS) in his two-part article "EOS Data and Information System, Where We Were and Where We Are" in the July–August 2009 and September–October 2009 issues of *The Earth Observer* [**Volume 21**, **Issue 4**, pp. 4-10 and **Volume 21**, **Issue 5**, pp. 8-15].

[25] Margolis replaced Diane Wickland in this role in 2015; prior to that he was at Université Laval, Québec City, Canada.

prior to FIFE non-credible models were used to make predictions of significant societal importance. For example, in 1988, when Jim Hansen, then at NASA's Goddard Institute of Space Studies (GISS), testified before the U.S. Senate on June 23, 1988, stating his opinion that, "the greenhouse effect has been detected, and its changing our climate now," his conclusions were based on the unreliable models created in the 1970s and 1980s.[26] It is noteworthy that at the end of his remarks Hansen said to the Senators, "I would like to stress that there is a need for improving these global climate models, and there is a need for global observations if we're going to obtain a full understanding of these phenomena.

Hansen's words read like a harbinger of FIFE (which was already underway in 1988), BOREAS, and EOS. Indeed FIFE and BOREAS contributed to the improvement of models that Hansen had asked for in his testimony. In essence, data from these field experiments "broke" the old models, but also provided the information needed to "fix" them, which in turn led to the development of much-improved versions of these models. And the models have kept on improving since then.

Improved models are needed now more than ever as we try and tackle the underpinnings and consequences of climate change—and to convince the world of the seriousness of related issues. While there has been significant progress in this area since 1987, there is still much work to be done.

Sellers emphasized that improved models are needed now more than ever as we try and tackle the underpinnings and consequences of climate change—and to convince the world of the seriousness of related issues. While there has been significant progress in this area since 1987, there is still much work to be done. The scientific community created by FIFE/BOREAS continues to play a crucial role in studying such global issues and communicating the results of their findings. What was shared during this meeting shows the many ways in which these experiments changed the world—or at least, our understanding of it. Such contributions are indeed foundational and formative to the present and future of Earth system science.

Forrest Hall also offered some concluding words. He thanked everyone who participated, and particularly those who presented both data and information and their personal views of the activities. He specifically thanked Carla Evans, who works at the NASA Carbon Cycle and Ecosystems Office for Science Systems and Application Inc.—and herself a FIFE/BOREAS veteran—for the logistical work she did to make this meeting possible.

Summary

Overall, FIFE and BOREAS arrived at an opportune time for the emerging field of Earth system science—just in time for the concepts for EOS to emerge and to take shape. The campaigns accelerated collaboration between previously discrete scientific communities, and moved interdisciplinary science from theory to reality. They also accelerated development and validation of GCMs and served as a pathfinder for scientific and organizational work done by EOS. Also, a new generation of now-experienced and motivated students participated in these two experiments, subsequently completing their studies, with many acquiring doctoral degrees using FIFE and BOREAS datasets. They also forged lasting friendships and work relationships, without which ongoing important scientific work could not be done. With FIFE and BOREAS as the basis for early work, there are many scientists that are leaders in the field today, pushing our understanding of Earth system science into new and deeper realms. ■

[26] Hansen's findings were based on a 1988 publication in the *Journal of Geophysical Research* that described his work using the GISS model (developed in the 1970s).