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Managing and supporting large integrated and interdisciplinary field studies: The BOREAS example

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Abstract. Large integrated and interdisciplinary field studies, such as the Boreal Ecosystem-Atmosphere Study (BOREAS), are conducted to refine our understanding of the interactions between the land surface and the atmosphere. Viewed as a case study, the BOREAS research objectives and final data set exemplify the complex nature and requirements of earth systems science research. The management and data system activities required to execute the study also echo this complexity. Rather than several research teams providing the needed management and data support, BOREAS management used a dedicated project staff to handle these functions. As the study progressed, the project staff transitioned from support of logistics and study management to information system operation and data publication, drawing upon the background knowledge gained from the earlier stages of the project. Data publication involves the creation and distribution of quality-checked and documented data with all ancillary information required to make it useful to someone unfamiliar with the study. We assert that the success of large integrated and interdisciplinary field studies depends upon having a dedicated staff. This staff focuses on the overall goals of the study throughout all phases of the effort: contributing to project planning, logistics, management, and data collection efforts; distributing, quality checking, and integrating the diverse data sets; working with the science teams to develop standardized data set documentation; integrating the diverse data and documentation for archiving; and publishing the data for long-term use by the larger scientific community. In this paper, the different phases of BOREAS are discussed, and the contributions that the dedicated staff made are examined. The value of spending resources on a centralized staff for project support and data publication activities is also examined.

1. Introduction

Earth systems science (ESS) attempts to understand the complex interactions of Earth's climate using data from a wide variety of science disciplines. Field studies are an important element of ESS: They help to develop an understanding of important processes and provide a baseline data set for future climate studies of specific regions. Managing a large field study requires a great deal of planning and organization, and the large amount of collected data must also be handled and archived for ongoing and future analyses.

The Boreal Ecosystem-Atmosphere Study (BOREAS) [Sell-

ers *et al.*, 1995, 1997a] is a useful case study that illustrates the problems and challenges of a large interdisciplinary field study. In order to create a complete data set that characterizes the ecosystem-atmosphere interactions studied in BOREAS and to preserve this data set for future interdisciplinary modeling and analysis work, resources needed to be allocated for the central storage and integration of the data. The BOREAS Information System (BORIS) integrated and documented the BOREAS data, completing its task with the release of 266 fully documented data sets to an on-line archive and a large subset of those data in a 12-volume CD-ROM package.

The successful execution of BOREAS depended on centralized planning of the project managers and scientists. The completion of this study and the creation of a final integrated interdisciplinary data product was the result of the efforts of a dedicated staff of project and data system personnel in cooperation with investigators. We believe that an examination of the management of BOREAS and its associated information system (BORIS) provides useful guidelines and examples that illustrate what will be required to make large Earth Systems Science studies function successfully in the future.

1.1. Requirements of a Field Study

To be successful, a field study must fulfill a series of requirements. These are tasks that need to be performed for the smooth operation of the fieldwork and the completion of data analysis and research publication.

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Beginning with the design phase, a project's focus should be on clearly defining the problem to be addressed by the study and laying out components of a plan for solving that problem. With a study plan in place, preparation of infrastructure can begin. This includes the evaluation and selection of potential study sites; determination of site access, power, and other needs; development of required infrastructure; assessment of transportation needs for investigators and equipment; and arrangement for accommodations and work areas. During the fieldwork phase, data are collected and stored for later analysis, and logs of field activities are kept to aid in later analyses. Good communication between cooperating field teams is essential, and a centralized operation and planning area is useful. After the fieldwork the collected data are processed into a useful form for analysis, the central problem is examined, and the results are published. If the analysis is based on modeling or other interdisciplinary work, data sharing and documentation are essential.

The level of effort required in each of these phases will vary from study to study, depending on the nature and complexity of the project. As the study becomes larger and more complex, so too does the management effort required. For very complex studies it becomes more efficient to have a dedicated staff performing the management and logistical chores in support of the scientific effort, rather than having them done by several separate research groups.

1.2. Nature of Large Integrated and Interdisciplinary Studies

The level of planning and central coordination required for a scientific study are determined by its nature and complexity. The different classes of studies, in ascending order of complexity, are (1) studies collecting nonintegrated data, (2) studies collecting integrated data, and (3) studies collecting integrated and interdisciplinary data.

Because they require minimal management and coordination, field studies that do not integrate data sets are the least complex. This is usually the methodology used in small-scale field work, looking at relatively "simple" phenomena. Individual scientists or teams go into the field and collect the data they decide are needed at locations that best suit their own needs. These scientists can change their instrumentation, location, and the content and format of their data with no outside considerations. There is no concern about the data other teams may be collecting, and there are no immediate plans to cross-compare data or the calibration of similar instruments. Except to facilitate their own analyses, the format and units of their data are not a consideration nor is formal documentation of the effort, since anyone using the data would most likely be working directly with the data collectors. Essentially, a nonintegrated study is composed of an individual science team collecting the data they want, where they want, with only their own scientific objectives in mind.

Integrated field studies are more complex, usually with more scientists looking at larger-scale phenomena. In integrated efforts the field studies need to be carefully planned, with each science team's data being a puzzle piece used to build the overall picture of the phenomenon being studied. All important aspects of the phenomenon must be addressed by at least one science team. The teams then go into the field and collect the data they have specifically proposed to collect; the freedom to divert from that plan is limited because the scientists are all counting on each other to collect the various pieces of the data

puzzle. Data collection sites must be specifically selected to meet the needs of all the science teams and to allow for direct data comparison. Teams cannot arbitrarily change their instrumentation or the content of their data without affecting the overall integration effort. Teams need to be aware of the data other groups may be collecting and to be cognizant of how it will mesh with their own. There are standing plans to cross-compare all similar data, and the calibration of similar instruments can be closely scrutinized. Adopting data format and unit standards are important considerations. Thorough documentation of the effort is essential since others unfamiliar with the study may be doing the data integration. Essentially, an integrated study is composed of a collection of science teams all recording data according to a coordinated plan, at a group of centralized sites, with larger study-wide objectives in mind. An example of this type of study is the Jornada Prototype Validation Exercise (PROVE) [Privette *et al.*, 2000].

Making an integrated study into an interdisciplinary one adds an additional layer of complexity to the organization and planning required. The interdisciplinary nature of the study means that scientists from various disciplines, with different basic science goals, nomenclature, suppositions, instrumentation, and data types, need to integrate their efforts. For this kind of study to succeed, the scientists' work must be understandable by investigators from all disciplines. Also, the need to combine and compare data from these different science disciplines reinforces the need to coordinate investigation sites. Examples of integrated interdisciplinary studies include the Hydrologic Atmospheric Pilot Experiment-Modelisation du Bilan Hydrique (HAPEX-MOBILHY) [Andre *et al.*, 1986], the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) [Sellers *et al.*, 1988, 1992], the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel) [Prince *et al.*, 1995; Goutorbe *et al.*, 1997], and BOREAS [Sellers *et al.*, 1995, 1997a].

A further element of complexity is the creation of a consistent, integrated, and well-documented data archive. Although this requires additional resources, the cost of creating this kind of archive during a project is much less than trying to create the same quality of archive years after the project is over. The long-term usability of this kind of archive and the benefits to future research efforts far exceed the costs incurred. The project managers and a dedicated staff working closely with the scientists are best suited to handling such a data-archiving effort.

1.3. Introduction to BOREAS

In the early 1980s, scientists recognized that existing models of climate and weather were inadequate to explain the processes controlling the exchanges of heat, water, energy, and carbon between the land surface and the atmosphere. They also realized that remote sensing had the potential to provide information regarding these processes over vast areas. These realizations produced a call for studies to examine the integration of soil, vegetation, and atmospheric models. These studies required new methods for applying small-scale data sets (spatial scales of millimeters to meters) to the large-scale (kilometers) atmospheric models. The development of algorithms that used remote sensing data to quantify important biophysical states for model input were also needed. Integrated and interdisciplinary field studies (such as HAPEX-MOBILHY, FIFE, HAPEX-Sahel, and BOREAS) were conducted to fulfill these scientific requirements. Each provided the scientific commu-

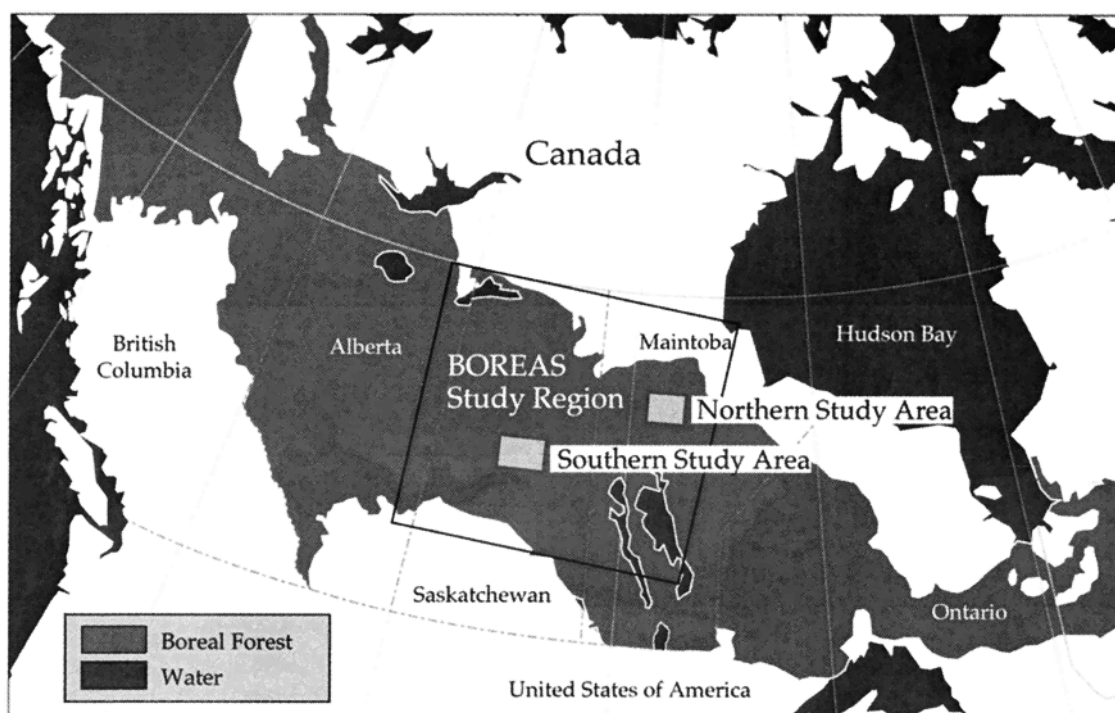


Figure 1. Map showing the BOREAS study region and the northern study area (NSA) and the southern study area (SSA).

nity with a wealth of data regarding the interactions of the landscape and the atmosphere for different vegetation types.

BOREAS was a joint U.S.-Canadian study, overseen by NASA and the Canada Centre for Remote Sensing (CCRS). The goal of BOREAS was to improve the understanding of the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change [Sellers and Hall, 1994]. The three primary scientific issues examined in BOREAS include (1) the sensitivity of the boreal forest biome to changes in the physical climate system, (2) the carbon cycle and biogeochemistry in the boreal forest, and (3) the biophysical feedback on the physical climate system. The goal of BOREAS was to use the data collected to (1) improve the process models that describe the exchanges of energy, water, heat, carbon, and trace constituents between the boreal forest and the atmosphere and (2) develop and test methods for applying the process models over large spatial scales using remote sensing and integrative modeling techniques. From the beginning it was recognized that meeting these goals would require the coordination of data from numerous teams representing a variety of scientific disciplines and skills.

The activities in BOREAS, from planning to the completion of the follow-on effort, occurred from 1988 to 2001, with intensive field campaigns in 1994 and 1996. The BOREAS study region consisted of a 1000-km² area encompassing large portions of the Canadian provinces of Saskatchewan and Manitoba, with two focused study areas ~100 km² in size located in central Saskatchewan near Prince Albert and in northern Manitoba near Thompson (Figure 1).

There were 85 science teams selected for BOREAS that were divided into six discipline groups: (1) 14 airborne flux and meteorology teams collected aircraft-based atmospheric flux data and large-scale meteorological network data; (2) 8 hydrology teams collected hydrology, precipitation, stream flow, and

soil moisture data; (3) 20 remote sensing science teams collected ground, aircraft, and satellite-based remote sensing imagery; (4) 22 terrestrial ecology teams collected data for components of a complete annual carbon budget (photosynthesis and stomatal conductance, productivity, and carbon storage); (5) 11 tower flux teams collected ground- and tower-based energy, CO₂ flux, and meteorology data at central sites in the study regions; and (6) 10 trace gas and biogeochemistry teams collected data on trace gas interactions between soil and atmosphere (primarily CO₂ and CH₄), flux of nonmethane hydrocarbons, and long-term accumulation of carbon in soils. Within each of these groups were teams whose efforts focused on modeling but did not include data collection. These teams were dependent on the data collection of others to achieve their scientific goals. The final data collection amounted to ~500 Gb of data, including satellite imagery, aircraft imagery, and numeric data, encompassed by 266 documented data sets in all.

BOREAS had a dedicated project staff made up of personnel from NASA Goddard Space Flight Center (GSFC), CCRS, Laval University, Environment Canada, and the Canadian Forestry Service, who oversaw components of the project that required significant logistical support and monitoring. The project staff was integral to the functioning of each stage of BOREAS (Figure 2) as follows: (1) study planning and design (1988 to 1993, see section 2), (2) study execution (1994 to 1996, see section 3), (3) individual and interdisciplinary data analyses (1994 and on, see section 4), and (4) data publication (1998 to 2001, see section 5).

The project staff personnel consisted of science professionals from the fields of meteorology, ecology, physics, chemistry, computer science, and remote sensing. Many of the BOREAS staff personnel were able to oversee the study execution from inception and planning through to final data archiving. The

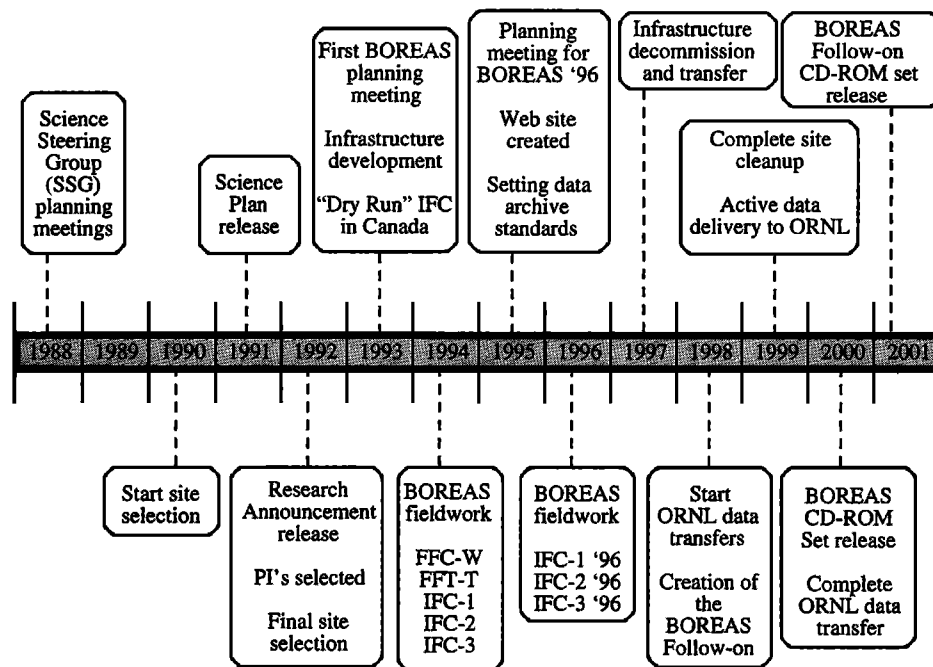


Figure 2. Timeline of key events in BOREAS from initial planning in 1988 to the release of the follow-on CD-ROM set in 2001.

staff were committed to seeing that all data sets were submitted, were quality assured, and were well documented for future use. This was facilitated by staff interaction with the investigators from the start of the project and participation with them in the study design, infrastructure implementation, and field campaigns. In this way the staff became familiar with the study, the data sets being collected, and the investigators as well.

The project planners and many of the NASA staff members for BOREAS worked on a previous interdisciplinary study on the tallgrass prairie of Kansas, called FIFE. This project tested many of the organizational concepts later used in BOREAS and gave the planners and staff considerable experience that could be brought to bear on BOREAS, which was over twice as large and complex as FIFE. Lessons learned from the planning and organization of the FIFE fieldwork, the management of the associated information system [Srebel *et al.*, 1990], and the creation of an integrated and documented data archive on CD-ROM all played a large role in the planning and functioning of BOREAS.

2. BOREAS Study Planning and Design

2.1. Science Team Selection

Because of the interdisciplinary and integrated nature of BOREAS the planning stage required significant coordination and a team effort. The planning process began with the formation of the Science Steering Group (SSG), which held a series of workshops from 1988 to 1991 to formulate ideas for a new interdisciplinary field study (Figure 2). A small staff assisted in preparing information and gathering background data for these early workshops. The efforts in these SSG workshops led to the development of the initial science plan [Sellers *et al.*, 1991], which illustrated the overall science questions and goals, a study design, and implementation schedules for study execution. Early discussions with modeling teams helped define what

types of measurements were needed to address the key interdisciplinary science issues. The core ideas of the science plan were used to form the research announcements, released in Canada and the United States in early 1992. To meet the established goals of BOREAS, researchers in the fields of meteorology, biology, hydrology, remote sensing, and biogeochemistry were sought.

In the selection of research teams the overall study goals were considered to ensure that all significant parameters were being measured or modeled. The selection process also focused on minimizing redundancy in data measurements to minimize cost and encouraging teamwork among groups to achieve the interdisciplinary research goals. The proposal review process resulted in the selection of 85 investigation teams that were grouped into six science themes (noted in section 1.3), each of which contained important modeling components. The varied data needs of the modeling teams required integration of the sciences and helped to define the data that would be collected.

2.2. Site Selection

The centralized data needs of BOREAS resulted in a study design that concentrated the efforts of most teams at specific sites during specific time periods, called intensive field campaigns (IFCs). Spatial and temporal colocation would maximize the opportunities for data comparison and integration. The variety of measurements needed at these centralized sites meant that the site locations and study timing had to be a compromise between the needs of the different ground teams and those of the satellite and aircraft teams. Thus a significant aspect of the BOREAS planning effort from 1988 to 1992 was identifying representative areas within the boreal forest to study.

The project office personnel helped organize and assist in several reconnaissance missions to remote areas of the Cana-

dian boreal forest. After selecting a potential study area using aerial photographs and Landsat imagery, maps and other information were gathered to verify the existence of adequate roads, trails, a nearby town with accommodations, and an airport within a 2-hour flying time that had facilities to support the needed aircraft.

Two study areas were eventually selected: a southern study area (SSA) near Prince Albert, Saskatchewan, and a northern study area (NSA) near Thompson, Manitoba. Although these sites met the bulk of the selection criteria, each had some peculiarities. In the SSA, there was a pulp and paper mill north of the town of Prince Albert with a large smokestack. In the NSA, there was a smelter at the nickel mine in Thompson. Each of these plants release gases that can affect trace gas measurements. However, detailed examination of satellite imagery and historic wind data showed that the emissions would not have an adverse effect on BOREAS measurements.

Once the two study areas were identified, the actual measurement sites had to be determined. The goal was to have a set of intensive study sites (tower sites) and a set of less intensive sites (auxiliary sites) within each study area. The sites were to cover each of the key land cover types (jack pine, black spruce, aspen, and fen) at various ages (young and old) and a few mixed cover and burned sites. The selection process required fine-scale information to locate appropriate areas of homogeneous cover within each of the two study areas. Some of the preliminary work by project staff included merging Landsat thematic mapper (TM) imagery with forest cover and road network information in a geographic information system (GIS) to identify a set of potential sites that were close to roads.

The site selection team, made up of scientists and project office personnel, then traveled to the potential sites to do first-hand surveys. The ground crews, aided by crews in small aircraft, performed detailed reconnaissance of the candidate tower sites. The ground crews traveled to potential sites then raised a helium balloon above the canopy to be detected and photographed by low-flying aircraft. The aircraft crew then redirected the ground crew to another location if the site was not desirable. This process continued until both ground and air crews reached agreement on the site. Finally, the ground crew characterized and “flagged” the site for later detection by site preparation crews.

2.3. Infrastructure Development

The first infrastructure activities involved compiling travel and lodging information (availability and cost of lodging and vehicle rentals) along with specifications and capabilities of available airports within the two study areas. Next came the logistical issues related to the construction of towers, buildings, sanitation facilities, trail and road access, and electrical power at the tower sites. Each site required a tower for instrumentation, one or two heated structures to house computers and other equipment, raised platforms for storage, and boardwalks and access trails. With two study areas 500 km apart and in different provinces of Canada, it was often necessary for the project staff to pursue information and resource availability simultaneously on two fronts.

The project office handled a multitude of issues before moving forward with tower site plans. Among these were meeting provincial engineering and environmental impact study requirements, upgrading the forest fire control priorities within the study areas, and negotiating with the native Nelson House

tribe and commercial and government (provincial) landholders regarding access and land use plans. An unexpected and positive result of the site development effort was the documentation of forest use by the Nelson House tribe. This work was presented at a BOREAS workshop to assure that the science teams remained sensitive to the concerns of the native people. Eventually, project staff were successful in seeing to the construction of 10 tower sites and their supporting infrastructure. In the SSA, there were five tower sites, four double-scaffold (walk-up) towers 3 to 55 m in height and one 12-m Rohn (single-spire truss) tower. In the NSA, five Rohn towers were erected, ranging from 3 to 31 m in height (Figure 3).

The project office staff established a safety policy for all sites in accordance with Canadian occupational and liability law. This involved outfitting all sites with fire extinguishers, first-aid kits, and tower-climbing equipment. The project office staff also established a tower-climbing policy and arranged training sessions, allowing staff members to become climbing instructors (Figure 3). These staff members then trained dozens of science team members in tower safety and rescue techniques. The project office also prepared for potential emergencies by having landing sites cleared for a medivac helicopter near each tower site.

A major infrastructure concern was how to best supply each tower site with electrical power. In the SSA it was feasible to run power lines from the main roads to the tower sites. In the NSA, however, the cost of such an endeavor was prohibitive because there were no power lines in the study area outside the town of Thompson. Thus tower sites in the NSA were powered by diesel generators, which required additional approval procedures, structures to house the generators, and impermeable berms for fuel storage. The generator huts had to be a safe distance from the towers so that the generator fumes would not contaminate the trace gas measurements. The size of the generators was also an important consideration: Increased wear results if a diesel generator operates at less than 50% capacity, and data collection efforts could be compromised if a generator could not deliver the needed capacity. Loss of power meant the loss of continuously measured data. The diesel generators also required regular maintenance, fuel delivery, and occasional repair during periods of heavy use. The project office staff procured a maintenance contract for the generators and arranged for regular fuel delivery.

Because site access in some cases was difficult or lengthy depending on the season, all-terrain vehicles (ATVs) were purchased for use at each of the study areas. Because of sometimes harsh conditions and heavy use during the IFCs these vehicles required regular maintenance and repair. Project staff procured a maintenance and repair contract with local dealers to keep these machines running.

During this initial phase of the project a problem was identified by the terrestrial ecology groups. No method had been identified in the infrastructure plan to allow investigators direct access to the forest canopy for measurements. Once this concern was brought to the attention of the project office, several options for canopy access were explored, and scaffold towers that could be disassembled and moved were procured. These towers were placed so that investigators could work from platforms to access the foliage at various heights within the canopy.

Laboratory facilities where field samples could be dried, weighed, or otherwise measured by methodology unavailable in the field were required in nearby towns. Project staff iden-

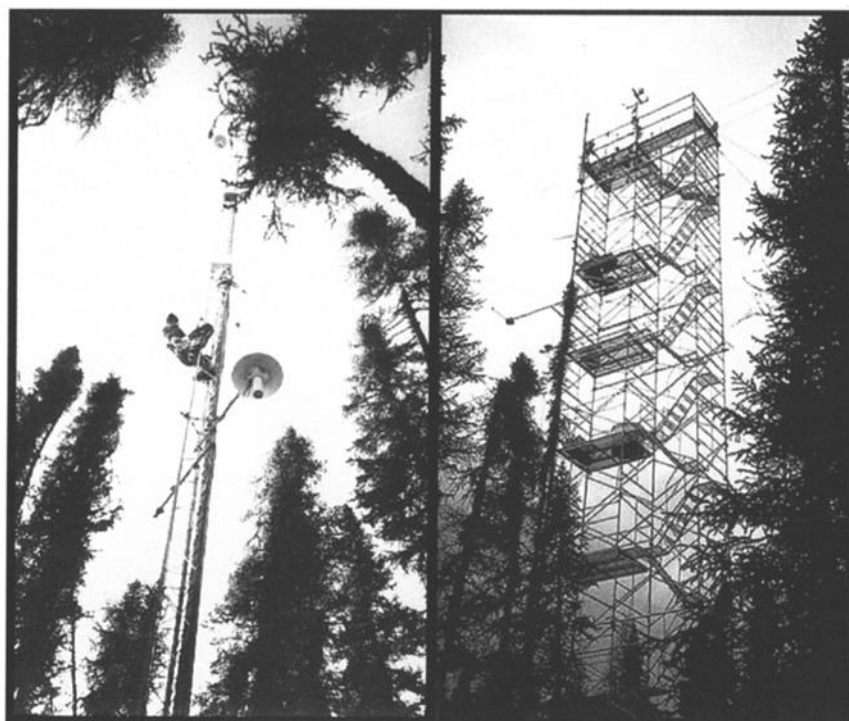


Figure 3. Pictures showing (left) a single-spire Rohn tower (note the climber on the tower) at the NSA-OBS (old black spruce) site and (right) a double-scaffold walk-up tower (note the internal stairway) at the SSA-OBS site.

tified, leased, and modified the laboratory space to meet investigator needs. These modifications included electrical upgrades, bench space, climate control, sample drying ovens, refrigerators, communication services, and tanks of reference gases for calibration of instruments.

During the IFCs, seven research aircraft required housing, fuel, and maintenance. To this end the project office assisted the aircraft teams in securing the support needed at the two airports designated for the study areas.

With all the people involved in BOREAS, many of whom sometimes worked outside the designated IFC periods, it became obvious that a local point of contact needed to be established in each study area to deal with any problems that might arise. To meet this need, site managers were hired for the SSA and NSA that would be available to assist at all times of the year.

2.4. Final Preparations for Field Activities

The initial science team workshop in December 1992 led to a dry run IFC in August 1993 and a second workshop in late 1993 to evaluate results. The wealth of information gained in these early activities enabled the development of a comprehensive BOREAS experiment plan [Sellers and Hall, 1994], a blueprint of the upcoming study. This large volume of information was printed and distributed to the science teams before the first fieldwork in early 1994. The experiment plan covered scientific background and objectives, study design, project organization, project office staff activities, science team activities, and study execution and operations. It included maps of the aircraft flight plans that were helpful during the IFCs in coordinating aircraft activities. It also included project participants and contact information; customs, immigration, import-export, and shipping information; U.S.-Canadian agreements; accom-

modations; directions to sites and site layout maps; the project calendar; and satellite overpass schedules.

Prior to and during the study, certain background data needed to be acquired and processed. These data were of interest to multiple teams and consisted of data sets that required routine processing with consistent quality assurance (continuous surface meteorological data) or specialized processing to allow for wide use (GIS layers and satellite imagery). There were also aircraft videotapes and flight logs, historical and current meteorological data, satellite and aircraft imagery, fire and forest cover maps, and soil maps. These data did not require a principal investigator, yet they were of wide general interest and thus important for the overall success of the project. The BOREAS staff coordinated the collection and handling of all of these types of data. For example, project staff worked with personnel from the Atmospheric and Environment Service in Canada to obtain and process regional meteorological data sets. To supplement the existing meteorological network, the Saskatchewan Research Council was contracted to construct and operate 10 additional automated meteorological stations to enhance the spatial distribution of the network.

Project staff also worked to improve the quality of geographic positional information at the sites. In the SSA, topographic maps provided good coordinate information, as verified by Global Positioning System (GPS) readings. However, the topographic maps from the NSA had errors up to 100 m and thus were not of sufficient accuracy for the registration of digital imagery. The staff arranged for an additional set of 13 GPS ground control points to be collected in the NSA by the Geodetic Survey of Canada. These new ground control points were used to register Landsat TM imagery that served as base maps for the registration of other images.

2.5. Creating the BOREAS Information System (BORIS)

While the BOREAS staff were searching, acquiring, processing, and archiving background data sets for planning and implementation, the BOREAS Information System (BORIS) was being developed. BORIS was established because experience from FIFE showed that a centralized information system, integrated with project management, benefited the science effort by (1) coordinating and distributing current and historical data needed for project planning and design; (2) recording science team data collection activities and locations to improve subsequent data processing, integration, quality assurance, and documentation; (3) centralizing storage of all data sets from the science teams and the location for data access by investigators; (4) standardizing site designations, mapping projections, and measurement units to assist in quality control and ease of use of the data; (5) consistently and thoroughly documenting the data sets; (6) handling publication and final archiving of the integrated data.

To provide these benefits, BORIS staff needed to (1) work with project managers and scientists to provide data and information as needed during the study, (2) perform management and integration of the diverse and voluminous data collected, and (3) oversee the documentation of each data set for inclusion in a long-term archive. BORIS personnel worked with the science teams to agree on standardized parameter names, units, site labels, and spatial coordinates. Although these standards were not always adhered to by the science teams, they were imposed on the data by BORIS staff during the integration of the data sets. The operations of BORIS are described in section 4.2 of this paper.

3. BOREAS Study Execution

One of the most dynamic periods of an interdisciplinary field study is the time spent in the field collecting data, when the results of the planning efforts are tested. Failure of a component of the data collection effort could compromise the ability of the study to meet its goals. During this period, over 300 people participated in BOREAS among the two study areas. The primary role of the project staff during this period was to support and monitor the field efforts.

In BOREAS some of the surface flux and meteorological data were collected continuously throughout the project. However, continuous operation of most of the instrumentation was not feasible. The IFCs were designed to ensure that all of the desired parameters were measured within the same 1-month periods. During the IFCs the project staff maintained operations centers in both the NSA and SSA, with an overall mission manager, a study area manager, and additional support personnel. The mission manager set priorities for and coordinated all field and aircraft operations for both study areas, while the study area manager monitored the daily operations in that study area. The operations centers were equipped with computers, printers, fax machines, and multiple telephone and data lines to act as communications centers. The operations center staff also recorded information on BOREAS participants, their accommodations, contact and emergency telephone numbers, and vehicle identification. Field teams were provided with two-way radios to assist communications in the field, and their daily activities were monitored to assure their safe return each evening. Coordination of aircraft and ground operations was also facilitated by the operations centers. Investigators conducting measurements were notified of aircraft flight patterns,

and the pilots were notified of potential hazards (tethersonde balloons, etc.).

To aid in the coordination of the science team activities, the operations center staff conducted nightly meetings throughout each IFC. These meetings were held simultaneously in both study areas and were linked by speaker phones. At these meetings, daily activities were summarized, weather forecasts were presented, and measurement plans were reviewed for the next day. These meetings proved useful to the investigation teams for coordinating transportation and ATV use, equipment maintenance, and other collaboration. The operations center staff also arranged for weekly science meetings during each IFC, where participants shared brief presentations on their observations and insight into the processes at work. The weekly meetings exposed investigators to other measurements being made, provoked discussions that often planted seeds for future collaboration, and served to maintain focus on larger, project-wide issues. These meetings also helped the project staff gain a better understanding of the sometimes unique perspective of the various science disciplines, an important aspect of data management in multidisciplinary science [Olson *et al.*, 1999; National Research Council, 1995].

Operations center staff documented the activities of the science teams during each IFC and compiled an overview of the measurements being collected. Midway through the 1994 IFCs this documentation was used to provide an overview of the status of the field efforts to date. This overview assured investigators that measurements assigned to others were being collected and provided BORIS with an index of the data and parameters.

Another form of IFC documentation was photography of the study sites and investigators at work in the field. This was a valuable lesson learned from the earlier FIFE project. Many users of the FIFE data never visited the study site in Kansas, and the photographic archive on the FIFE CD-ROMs provided a useful visual aid for understanding the landscape characteristics of the field site.

4. Individual and Interdisciplinary Data Analyses in BOREAS

4.1. Staff and Science Team Interactions

Although preliminary review of some data occurred during the IFCs, the bulk of the data analyses began after the science teams returned to their home institutions and organized their data. BOREAS data analysis proceeded in two phases, beginning with the analysis of individual science team data sets and followed by the use of data in interdisciplinary and modeling studies. In the first phase, investigators focused on evaluating, validating, and publishing results from their own individual data sets. During this 12- to 24-month period, scientists used similar data from other investigations to calibrate or validate their own measurements. It was not until investigators were satisfied with their own data that they moved to the second phase of analysis, which was looking at other data sets for the purpose of interdisciplinary studies. In BOREAS the step to interdisciplinary analyses was delayed by a second year of field campaign activities in 1996.

Project managers and staff further reinforced the goals of modeling and interdisciplinary analyses by organizing teleconferences, science team meetings, and workshop discussions that focused on scaling and interdisciplinary topics. Along with

presentations on the status of collected data these activities provided regular reminders of the interdisciplinary nature of the overall effort. It was through these formal and informal social interactions that investigators were exposed to science outside their realm of expertise. These interactions began to form the basis of the interdisciplinary science collaborations that were the goal of BOREAS. Eventually, interdisciplinary results were presented at workshops, further stimulating discussion. Publication of results in special issues of journals also increased the opportunities for BOREAS research to be seen beyond a single discipline group.

Despite the extensive planning efforts the project managers and staff had to be flexible and take on additional tasks as new information about the dynamics of the boreal forest was obtained. Experience from FIFE showed that as early results were revealed, the necessity for variables not considered in the planning and design phases were exposed. BOREAS managers had to be prepared for this eventuality and provide the resources to fill the gaps as needed. One such gap became the primary justification for the return to the field in 1996 [Sellers and Hall, 1996]. After the 1994 field season, as one tower site in the NSA continued to measure fluxes into what was thought to be the dormant winter period, significant photosynthetic uptake was measured beyond the conclusion of the last IFC, and significant respiration fluxes continued throughout the winter. Most of the 1994 measurements did not begin before the spring thaw nor extend into the freeze-up period, leaving a gap in the measurement plan and thus in our understanding of the processes controlling carbon and energy fluxes for these time periods. In 1996 the flux towers started earlier and ran longer to capture data for the entire growing season.

With the conclusion of the BOREAS field efforts in 1996, staff worked with project managers to determine how to decommission the tower flux sites and associated project infrastructure. The BOREAS project office coordinated the removal of this infrastructure and the required site cleanup. This involved working with Canadian contractors to deconstruct and remove towers, huts, generators, fuel berms, boardwalks, and other structures. Excess equipment was sold or donated to other organizations. Canadian environmental requirements had to be met, and the cleared sites had to pass inspection. Several BOREAS sites were transferred intact to Canadian scientific agencies for ongoing operations, such as the Boreal Ecosystem Research and Monitoring Sites project (see <http://ecsask68.innovationplace.com>). The BOREAS NSA-OBS (old black spruce) and three sites in the SSA are still in use by other projects [Goulden *et al.*, 1997; Justice *et al.*, 1998; Reich *et al.*, 1999].

4.2. BORIS Operations: Collecting and Distributing Preliminary Data

The BORIS staff initially began their data distribution via off-line media, but with the increasing capability of the Internet in 1994 and the desire of the BOREAS scientists for quick and easy access and delivery of the preliminary data, an on-line ftp site was created at NASA GSFC. BORIS supported data analysis activities by facilitating the transfer of information between investigators. The BORIS data manager functioned as the overall data delivery and information contact point for the science teams. Questions about the location and status of data and documentation were handled by the data manager. User requests helped to set BORIS priorities on data processing and

were useful in subsequently encouraging investigators to submit their data for everyone's use.

As BOREAS and the Internet both evolved and the information system needs of the project increased, BORIS added computer hardware and implemented a World Wide Web (or "Web") site in 1995. The BOREAS Web site provided a general overview of the project for the public that included the history and purpose of BOREAS, site information, scanned site photographs, reports on fieldwork, and graphics for papers and presentations. It also provided investigators with password-protected access to preliminary data and project documents.

During the data analysis period, investigators were encouraged to submit preliminary data sets with the understanding that these data would be available only to the other BOREAS science teams until they were checked for quality and documented. The investigators replaced existing data with updated data when necessary. The sooner the data were available, the sooner modeling groups could perform interdisciplinary analyses. The need for timely data had to be balanced with the desire to avoid too many data set updates and changes that would require scientists to redo analyses or derive confusing results due to the use of different versions of the same data set. A "What's New" section was added to the Web site to track changes in data sets.

The initial efforts of BORIS were to make data and information available quickly and to gather information to clearly document the measurements while information was fresh in the minds of the science teams. Each of the six science groups were assigned a dedicated BORIS staff representative as their primary contact. The BORIS group representatives worked with the individual teams to answer data and documentation questions, maintain delivery status information, develop and review documentation, and assist in any way possible in data access and delivery needs. Information system staff were important in fulfilling the immediate needs of the science teams, achieving the goal of interdisciplinary science, and assuring long-term viability of the data and thus its publication and archiving [Michener *et al.*, 1997].

Following the IFCs, the project staff compiled the mission log information to produce an inventory of the data collected. Much of this information was later published in the operations documents following each year of fieldwork [Sellers *et al.*, 1996, 1997b]. Eventually, digital versions of the experiment plan and operations documents were made available on the Web site.

5. BOREAS Data Publication

In the initial phases of BOREAS the objective of the data system was simply to centralize the data transfers between investigation teams. From the outset, there was also a long-term goal of creating a final data archive. Because it was funded for a limited time, BORIS was not designed to "be" the long-term data archive but to "create" that archive. In creating this final data archive, BORIS had to consider how to make the data understandable to people not connected with the project.

5.1. An Overview of Data Publication

The objective of a good data archive is to pass the "20-year test," [Webster, 1991]; that is, "the data should be usable by a scientist unfamiliar with the data after 20 years." To meet this goal, an archive has to contain more than just scientific data. The project background, study sites, data collection procedures, instruments used, and analysis techniques employed all need to be described. The archive effort should be aimed at

producing a self-contained compilation of fully explained data, the digital equivalent of a reference book. This archiving process is referred to as data publication [Meeson and Strebel, 1998; Strebel et al., 1998]. It is analogous to the publication of books or journals, with investigators acting as authors (providing the data and documentation), the data system staff acting as editors and publishers (organizing and quality checking the data and editing the documentation), and an archiving center acting as a bookstore or library (providing advertising and distribution of the archive). This is the model that BORIS used in planning the final archiving procedures to be applied to the BOREAS data. It involved not only integrating the data but capturing as much information about the project as possible so that future investigators could have the best understanding possible without having been there.

5.2. Preparing the BOREAS Data for Publication

BOREAS investigators were encouraged to submit their preliminary data sets to the information system as soon as they were ready. The BORIS staff representative for each science group tracked all the data sets for his or her group and loaded the data into a large database. This is where the initial data integration occurred, where the data system “standards” (created with the help of the investigators) were applied to each data set. Parameter and site names were standardized, sign conventions were checked, and observation times were converted to UT if necessary. The parameter units were verified to make sure they were standard, and the data were converted if necessary.

The data were then quality checked by the discipline-experienced staff representatives. This was very important, as common sources of error in a given technique or instrument could be spotted and fixed, errors that might not be as evident to users from other disciplines. The quality review included examining data for outliers or extended periods where data values did not change and checking the times and locations of measurements against the mission log inventories. Any problems found in the data were quickly relayed to the investigators for resolution. This continued interaction allowed problems in the data to be identified and either eliminated or documented. For example, by conducting independent data checking, BORIS staff sometimes found data discrepancies that resulted from multiple people processing different parts of a data set.

The BORIS staff also attempted to foresee potential user problems with the data and to either resolve or document them. Similar data from different disciplines were checked to eliminate potential sources of confusion for future users. This included making sure that discipline-based differences in sign convention for similar parameters were clearly documented. It also included documenting different parameters given similar names by different disciplines and documenting parameters that were related but called different things by different disciplines. For example, there were at least four different definitions of “humidity” (each with a different parameter name) among the various BOREAS science teams, all of which were explained in data set documentation.

While the data were being processed, standardized documentation was being created by the investigators. Documentation of the data by those who collected them, performed as soon as possible after collection, is optimal for creating the most accurate and useful documentation. BORIS used a standardized 20-part documentation format common in the Earth Sciences community. The documents were created by the in-

vestigator and then reviewed by the BORIS staff representative, who would edit them and add any information needed to help future users understand the data. The documents sometimes went through multiple revisions, with the author and the staff representative exchanging updated copies.

Although BORIS had adopted and followed several standards for integrating the data and documenting the 266 BOREAS data sets, a series of final reviews for data and documentation were required to publish and archive the information. This final set of activities can be likened to the final content and format checks performed by the editor or publisher in scientific literature publication. In preparation for final archiving the data and documentation were reviewed by the original science team and the BORIS staff, and the document was then reviewed by a technical editor and a second science team. The staff then indexed all of the data files and generated keyword and parameter lists. Overview documents were also developed for each science group, providing a short overview of all the data generation and collection efforts of all the teams in each group. The reviewed data set documents were published as a series of NASA technical memoranda (TM) [Hall and Newcomer, 2000] to serve as literature references for the data and data publication effort. The NASA TM can be obtained through the NASA Center for AeroSpace Information World Wide Web site <http://www.sti.nasa.gov/RECONselect.html>.

5.3. Publishing the BOREAS Data

From the beginning of the planning phase, one of the goals of the BOREAS project leaders was to publish the finalized data, making it publicly available to the scientific community for further interdisciplinary work. To facilitate this, two forms of data archiving were planned: an on-line or near-line archive at the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) and a set of CD-ROMs for general distribution.

The ORNL DAAC is one of NASA’s long-term data archives. It stores, maintains, updates, and distributes a large variety of interdisciplinary field data that include FIFE and BOREAS. The DAAC has a complete copy of all the BOREAS data and documentation, including some of the more voluminous image data sets. These can be ordered from the DAAC and downloaded through the Internet at http://daac.ornl.gov/BOREAS/boreas_home_page.html or acquired on other media. ORNL also hosts a copy of the original BOREAS Web site, copied from NASA GSFC in October 1999 before the original site was shut down. This “historic” Web site has all of the content of the original site, including the site pictures, maps, and study guides.

Web sites and on-line archives have a tendency to be ephemeral; they may be regularly altered and even disappear without warning. They also require continuous hardware and software support, which requires continuing costs which might not be sustainable over long periods. This means that data stored only in this manner may also change over time or vanish. Scientific research requires a data source that is stable over time and can be referenced so that others can repeat the work [Poumay, 1998]. The interdisciplinary nature and short time period of many field studies makes it advantageous to store the data from different disciplines in an integrated and cohesive form. CD-ROMs provide these qualities in a stable, inexpensive medium for data publication. Thus it was decided that a reference source of BOREAS data on CD-ROM would be produced in

addition to the on-line archive. This product allows investigators to receive a large number of BOREAS data sets in a single data delivery. Also, the distribution of hundreds or thousands of copies of a CD-ROM practically guarantees the survival of the data regardless of the uncertainties of future funding.

5.4. BOREAS CD-ROM Set

The BOREAS CD-ROM set was released in May 2000 (Figure 2) and consists of 12 discs containing the finalized point data and a subset of satellite and aircraft images (6 to 7 Gb of data in total). The CD-ROMs use an HTML interface to introduce users to BOREAS, giving a picture- and map-based view of the study sites in Canada, preliminary conclusions, and multiple indexes for access to the data. The HTML interface operates using a Web browser in “local mode” with no Web server needed. Using HTML for the interface allowed the existing BOREAS Web site to serve as the basis of the CD-ROM interface. HTML also allowed the creation of a multiplatform interface, allowing MacOS, Windows95+, and UNIX users to all use the same product. HTML is a stable language, and chances are good that the HTML interface will still operate in 20 years (remember the “20-year test”). We expect that Web-browsing software will be updated regularly by commercial vendors, insuring that the interface will continue to work as operating systems evolve.

For the BOREAS CD-ROM set all of the tabular data are stored in ASCII files with HTML headers that link related data files. All of the documentation files are included in both HTML and ASCII form. The ASCII document versions are stored with the data so that all of the information is readable and available together, just in case the HTML interface fails in the future. The aircraft and satellite imagery are compressed using GZip, the new open standard in cross-platform file compression. With the data divided among 12 discs, JavaScript is used to prompt users to swap discs when necessary, guiding them to the data they want.

5.5. BOREAS Follow-On

In 1998 a BOREAS Guest Investigator Program (also called the “follow-on”) was funded to continue analysis of the BOREAS data sets and to specifically assist in interdisciplinary modeling efforts. There were 26 investigators selected, organized roughly into remote sensing, carbon modeling, hydrometeorology, and flux groups. These follow-on studies are where much of the integration work of BORIS began to pay off, where true interdisciplinary science was performed. Follow-on investigators used BOREAS data to create new and refined data sets: continuous data with gaps filled by interpolated data, recomputed and synthesized data, and large collections of derived satellite and aircraft image products. One of the main activities was the intercomparison of nine ecosystem process models with seven hydrometeorology process models using a common driver data set for 3 years, from tower site scale to study region scale.

This new data archive contains many data sets specifically designed to initialize climate models for future studies. These data are being assembled and processed for release to the ORNL DAAC by mid-2001 and for a 6-CD-ROM BOREAS follow-on set at the same time. This new CD-ROM archive will use the same data formats, documentation style, and HTML interface design as the original BOREAS CD-ROM set.

6. Discussion

6.1. Case for a Centralized Project Staff

Many of the tasks listed in this paper are required for the success of an integrated and interdisciplinary study. Planning is essential. Data checking and integration are also key. These functions need not be done by a centralized staff; they could be broken up and spread out among investigators and graduate students. However, a centralized staff that focuses on and coordinates these various tasks is more efficient. This approach also leads to a more cohesive and thus a better final product. Work that is parceled out in the “distributed” model will not always be completed if there is not a central lead, or it may have to be done later by someone further removed from the project at increased cost. There are many reasons, both managerial and economic, to devote resources to a professional full-time staff acting to support the project office. A dedicated staff can (1) support and oversee proposal evaluation and the initial planning of the project; (2) oversee the site selection process and infrastructure creation; (3) help develop the science plan and the experiment guide (the “field guide” for the study); (4) provide in-field support to help coordinate and assist the science teams during data collection; (5) oversee site decommissioning and cleanup; (6) operate a centralized data system that works with the investigators to collect, integrate, quality check, document, and publish a final data archive; and (7) assist in organizing science workshops and meetings for the science team members. Project managers and staff personnel working closely together can act as the representatives of interdisciplinary science, helping to make sure that everything comes together as required and allowing the science teams to focus on their own piece of the study, confident that the “big picture” is being looked after. A dedicated staff can support both the field efforts and the information system. In fact, supporting these two efforts can be complementary. During the early phases of a study most staff effort goes into project support; during the later phases the project support requirements decrease and the need for information system support increases. This allows staff to use the experience gained in field support to better understand and handle the incoming data. Spending time in the field, visiting the study sites, and interacting with the investigators can greatly enhance the ability of the information system staff to integrate and document the data.

6.2. Measuring the Value of Integrated Interdisciplinary Data Sets

It is important to examine the question of what the science community gains by spending its limited resources on the creation of high-quality, integrated interdisciplinary data sets. The data sets produced have been cross-compared, quality checked, and well documented. They are readily available for new users to acquire them and make sense of them quickly. New research can be explored using these data, with little effort spent acquiring the background information needed to understand the study itself. New papers will continue to be produced years after the original data collection and research effort has been performed.

The value to science of the results of any field study is difficult to quantify. One measure of “value” is the number of scientific papers produced from data gathered in a study. This is one way in which the value and longevity of a data publication effort comes to light. It is still too early to measure the long-term harvest of the BOREAS archive, but we can exam-

ine the productivity of the earlier FIFE study over the decade since the completion of the original data collection. The FIFE data collection period was from 1986 to 1989, and in 1994 a set of five CD-ROMs containing the integrated interdisciplinary FIFE data were made available to the public. In that same year the FIFE data archive was moved to the ORNL DAAC and the data were made available over the Internet at http://daac.ornl.gov/FIFE/FIFE_Home.html. The ORNL DAAC had recorded 258 FIFE paper citations as of March 1994. The DAAC added 121 citations from a search of several bibliographic databases for a total of 379 publications by early 1996. A search of the Institute for Scientific Information science citation index for FIFE-related papers between 1996 and 1999 yielded an additional 184 papers. Thus several years after the initial data collection and first round of publications this well-designed interdisciplinary field study and its organized data archive continue to stimulate a significant number of scientific papers, many of them from new researchers. Today, the FIFE data archive is the second most active data archive downloaded from the ORNL DAAC (http://www-easdis.ornl.gov/DAAC/cd_roms.html), after the BOREAS data (R. Cook, ORNL DAAC, personal communication, 2000).

According to BOREAS project records the project and data system staff costs were roughly 15% of the total budget of the study. Considering the benefits accrued during the planning and execution of the study and the quality of the final data archive, the costs will dwindle when compared with the long-term benefit provided. The final BOREAS archives (both on-line and the two CD-ROM sets) will continue to be valuable for many years to come, showing the foresight of the project managers' investment in the staff activities and the detailed job of creating these final data archives.

7. Conclusion

BOREAS can be viewed as a "case study" for future Earth Systems Science studies: It is a medium-scale project that illuminates issues applicable to the management and funding of future global studies. How that money will be spent and what end products will be produced will determine the future of this important field.

Centralized planning by the BOREAS project managers and the dedicated staff helped to keep this complex study focused and shows the value of having staff to assist in all project and data management activities. Project staff understood the multifaceted project operations and the multidisciplinary research being conducted in BOREAS. The staff were involved in all aspects of the field and infrastructure efforts, from site selection, progressing through infrastructure creation and site usage during the study, and finally to site decommissioning. As the infrastructure and support efforts were winding down, the data system efforts were ramping up, and staff efforts were transitioned to the new tasks. BORIS staff oversaw all aspects of the data archiving process, from helping to plan the data-gathering efforts, through integrating the data and helping document the data, and finally to publishing the final data archive. Project managers and staff were instrumental in helping to keep the focus on the study goals and to encourage further interdisciplinary science.

Successful scientific studies have long-term value, producing data sets that are expected to be useful to the scientific community for many years. To make the data truly useful, they need to be standardized, quality checked, and integrated into a coherent data archive. Long-term use of the data is an impor-

tant measure of the value of the data and of the science. One of the keys to successful long-term use is complete documentation of both the data and the project. This combination of integrated data and complete project and data documentation can then be published on-line, on CD-ROM, or both. Data publication allows the data, so carefully collected by the investigators, to be useful to future scientists. For example, FIFE was one of the first integrated and published data archives, and it is still the second most actively downloaded data set at the ORNL DAAC, over 10 years after the study's conclusion. Data integration and publication improve ease of use of a data archive in the long term and are tasks well worth the resources spent. The BOREAS Information System facilitated the creation of an integrated, well-documented data set that will continue to be useful.

Considering the costs involved in the planning and execution of large-scale field studies, it is advantageous to expend a bit more to create a finalized data archive that can be the legacy of the project for years to come. For a minimal additional cost (over the long term), centralized staff can help create a better run project, and an information system can publish a data product that will be useful in Earth Systems Science for decades. Too many projects neglect the data publication phase and in the end have no coherent data archive, limiting their usefulness to ESS research. The value of these final data archives to future scientists cannot be overestimated but is often underestimated or, worse, not even considered by project planners and funders. In the end, a scientific field study is not just about publishing scientific papers by the investigators but is about creating a data archive that can be of use to scientists for decades, spawning new work and new publications far into the future.

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data the ORNL DAAC User Services staff may be reached at: ORNL DAAC User Services Office, Oak Ridge National Laboratory, P.O. Box 2008, MS 6407, Oak Ridge, Tennessee 37831-6407; Telephone, +1 (865) 241-3952; Fax, +1 (865) 574-4665; or E-mail, ornl-daac@ornl.gov. The BOREAS data set documents are available in print as NASA Technical Memorandum NASA/TM-2000-20981, volumes 1–248. These can be obtained by contacting NASA Center for Aerospace Information, 7121 Standard Dr., Hanover, MD 21076, or National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161.

References

- Andre, J. C., J. P. Goutorbe, and A. Perrier, HAPEX-MOBILHY—A hydrologic atmospheric experiment for the study of water-budget and evaporation flux at the climatic scale, *Bull. Am. Meteorol. Soc.*, 67, 138–144, 1986.
- Goulden, M. L., B. C. Daube, S. M. Fan, D. J. Sutton, A. Bazzaz, J. W. Munger, and S. C. Wofsy, Physiological responses of a black spruce forest to weather, *J. Geophys. Res.*, 102(D24), 28,987–28,996, 1997.
- Goutorbe, J. P., et al., An overview of HAPEX-Sahel: A study in climate and desertification, *J. Hydrol.*, 189, 4–17, 1997.
- Hall, F. G., and J. Newcomer (Eds.), Technical report series on the Boreal Ecosystem-Atmosphere Study, *NASA Tech. Memo.*, TM-2000-209891, vols. 1–248, 2000.
- Justice, C. O., et al., The Moderate Resolution Imaging Spectroradiometer (MODIS): Land remote sensing for global change research, *IEEE Trans. Geosci. Remote Sens.*, 36(4), 1228–1249, 1998.
- Meeson, B. W., and D. E. Strebel, The publication analogy: A conceptual framework for scientific information systems, *Remote Sens. Rev.*, 16(4), 255–292, 1998.
- Michener, W. K., J. W. Brunt, J. J. Helly, T. B. Kirchner, and S. G. Stafford, Nongeospatial metadata for the ecological sciences, *Ecol. Appl.*, 7(1), 330–342, 1997.
- National Research Council, *Finding the Forest in the Trees: The Challenge of Combining Diverse Environmental Data*, Natl. Acad. Press, Washington, D. C., 1995.
- Olson, R. J., J. M. Briggs, J. H. Porter, G. R. Mah, and S. G. Stafford, Managing data from multiple disciplines, scales, and sites to support synthesis and modeling, *Remote Sens. Environ.*, 70, 99–107, 1999.
- Poumay, Y., Science and the Web, *Science*, 280, 1173–1174, 1998.
- Prince, S. D., et al., Geographical, biological, and remote-sensing aspects of the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel), *Remote Sens. Environ.*, 51, 215–234, 1995.
- Privette, J. L., G. P. Asner, J. Conel, K. F. Huemmrich, R. Olson, A. Rango, A. F. Rahman, K. Thome, and E. A. Walter-Shea, The Prototype Validation Exercise (PROVE) at Jornada: Overview and lessons learned, *Remote Sens. Environ.*, 74, 1–12, 2000.
- Reich, P. B., D. P. Turner, and P. Bolstad, An approach to spatially distributed modeling of net primary production (NPP) at the landscape scale and its application in validation of EOS NPP products, *Remote Sens. Environ.*, 70, 69–81, 1999.
- Sellers, P., and F. Hall, Boreal Ecosystem-Atmosphere Study: Experiment Plan, Version 1994-3.0, NASA BOREAS report, Goddard Space Flight Cent., Greenbelt, Md., 1994.
- Sellers, P., and F. Hall, Boreal Ecosystem-Atmosphere Study: Experiment Plan, Version 1996-2.0, NASA BOREAS report, Goddard Space Flight Cent., Greenbelt, Md., 1996.
- Sellers, P. J., F. G. Hall, G. Asrar, D. E. Strebel, and R. E. Murphy, The First ISLSCP Field Experiment, *Bull. Am. Meteorol. Soc.*, 69, 22–27, 1988.
- Sellers, P. J., et al., BOREAS: Global change and biosphere-atmosphere interactions in the boreas forest biome, report, NASA Goddard Space Flight Cent., Greenbelt, Md., 1991.
- Sellers, P. J., F. G. Hall, G. Asrar, D. E. Strebel, and R. E. Murphy, An overview of the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE), *J. Geophys. Res.*, 97(D17), 18,345–18,371, 1992.
- Sellers, P., F. Hall, and K. F. Huemmrich, Boreal Ecosystem-Atmosphere Study: 1994 operations, NASA BOREAS report, Goddard Space Flight Cent., Greenbelt, Md., 1996.
- Sellers, P. J., et al., BOREAS in 1997: Experiment overview, scientific results, and future directions, *J. Geophys. Res.*, 102(D24), 28,731–28,770, 1997a.
- Sellers, P., F. Hall, and K. F. Huemmrich, *Boreal Ecosystem-Atmosphere Study: 1996 Operations*, NASA BOREAS report, Goddard Space Flight Cent., Greenbelt, Md., 1997b.
- Strebel, D. E., J. A. Newcomer, J. P. Ormsby, F. G. Hall, and P. J. Sellers, The FIFE Information System, *IEEE Trans. Geosci. Remote Sens.*, 28, 703–710, 1990.
- Strebel, D. E., D. R. Landis, K. F. Huemmrich, J. A. Newcomer, and B. W. Meeson, The FIFE data publication experiment, *J. Atmos. Sci.*, 55(7), 1277–1283, 1998.
- Webster, F., Solving the global change puzzle: A U.S. strategy for managing data and information, in *Report by the Committee on Geophysical Data of the National Research Council Commission on Geosciences, Environment and Resources*, Natl. Acad. Press, Washington, D. C., 1991.
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