ABSTRACT

Title of Dissertation: IMPROVING PREDICTIVE CAPABILITIES OF ENVIRONMENTAL CHANGE WITH GLOBE DATA

Jessica Hill Robin, Doctor of Philosophy, 2006

Dissertation directed by: Professor Ralph Dubayah
Department of Geography

This dissertation addresses two applications of Normalized Difference Vegetation Index (NDVI) essential for predicting environmental changes. The first study focuses on whether NDVI can improve model simulations of evapotranspiration for temperate Northern (> 35˚) regions. The second study focuses on whether NDVI can detect phenological changes in start of season (SOS) for high Northern (> 60˚) environments. The overall objectives of this research were to (1) develop a methodology for utilizing GLOBE data in NDVI research; and (2) provide a critical analysis of NDVI as a long-term monitoring tool for environmental change. GLOBE is an international partnership network of K-12 students, teachers, and scientists working together to study and understand the global environment. The first study utilized data collected by one GLOBE school in Greenville, Pennsylvania and the second utilized phenology observations made by GLOBE students in Alaska.

Results from the first study showed NDVI could predict transpiration periods for environments like Greenville, Pennsylvania. In phenological terms, these environments have three distinct periods (QI, QII, and QIII). QI reflects onset of the growing season (mid March – mid May) when vegetation is greening up (NDVI < 0.60) and transpiration is less than 2mm/day. QII reflects end of the growing season (mid September - October) when vegetation is greening down and transpiration is decreasing. QIII reflects height of the growing season (mid May – mid September) when transpiration rates average between 2 and 5 mm per day and NDVI is at its maximum (>0.60). Results from the second study showed that a climate threshold of 153 ± 22 growing degree days was a better predictor of SOS for Fairbanks than a NDVI threshold applied to temporal AVHRR and MODIS datasets. Accumulated growing degree days captured the inter-annual variability of SOS better than the NDVI threshold and most closely resembled actual SOS observations made by GLOBE students. Overall, biweekly composites and effects of clouds, snow, and conifers limit the ability of NDVI to monitor phenological changes in Alaska. Both studies did show that GLOBE data provides an important source of input and validation information for NDVI research.

IMPROVING PREDICTIVE CAPABILITIES OF ENVIRONMENTAL CHANGE
WITH GLOBE DATA

By

Jessica Hill Robin

Dissertation submitted to the faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
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PREFACE

Chapter 2 was published as a separate manuscript (Robin J., Levine, E., and Riha, S., 2005. Utilizing satellite imagery and GLOBE student data to model soil dynamics. Ecological Modelling 185, 133-145). I initiated this research, made a substantial contribution for this publication, and was first author of this manuscript.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

Background

While the Earth surface temperature has increased steadily over the 20th century and is projected to continue, the effects on the hydrological cycle (amount and timing of precipitation, evapotranspiration, discharge rates, and extreme events) have differed across the globe (McCarthy et al. 2001). There have been higher precipitation levels and more flooding in mid and high latitudes and annual fresh water discharge to the Arctic Ocean has increased (Karl and Knight 1998; Jacobs et al. 2001; Milly et al. 2002; Peterson et al. 2002). As temperatures continue to rise, further hydrological changes are expected with more variability between regional and local environments (Jackson et al. 2001; Palmer and Raisanen 2002).

Two critical parameters needed for predicting these changes are evapotranspiration (ETP) and soil moisture. Two-thirds of the precipitation that falls over land each year comes from evapotranspiration from soil and vegetation and soil moisture is a major driver of the ETP process (Chahine 1992). In biomes that have distinct winter seasons, start of spring phenological events, specifically timing of budburst and green-up of leaves, coincides with transpiration. Seasons leave annual signatures that reflect the dynamic nature of the hydrologic and carbon cycles and link the different spheres (atmosphere, biosphere, hydrosphere, and pedosphere/lithosphere) of the Earth system. Furthermore, observed shifts in earlier spring phenological events, both plant and animal responses, have been attributed to anthropogenic climate change (Root et al., 2003; Root et al., 2005). Thus signatures, such as global plant waves of green-up and green-down, can monitor natural and anthropogenic fluxes in the environment.

Given these documented temperature, precipitation, and phenological changes, a corresponding increase in evapotranspiration would be expected. However, with the exception of Israel, in the past 50 years pan evaporation rates have decreased in India, former Soviet Union, and the United States (Peterson et al. 1995; Chattopadhyay and Hulme 1997; Cohen et al. 2002). This pan evaporation paradox has been explained by global decreases in solar irradiance and increases in cloud cover and aerosol levels (Ramanathan et al. 2001; Ohmura and Wild 2002; Roderick and Farquhar 2002). Brutsaert and Parlange (1998) contend that pan evaporation is only a good indicator of potential evaporation in environments with ample land-surface moisture supply and that the decreasing pan evaporation rates actually indicate an increase in terrestrial evaporation. Additionally, extrapolating daily or seasonal canopy transpiration rates from single leaf porometer measurements, the most widely used instrument for measuring stomatal conductance, is difficult and requires simulation modeling (Pearcy et al., 1992). Therefore, as the Earth continues to warm, monitoring start of season (SOS) and accurately simulating transpiration becomes increasingly more important for predicting effects of climate change on carbon and hydrologic cycles.

Normalized difference vegetation index (NDVI), with its spatial and temporal extent, has been an instrumental tool for monitoring inter- and intra-annual transpiration and phenological changes on the Earth's surface (Running and Nemani, 1988; Lloyd, 1990; Reed et al., 1994; Myneni et al. 1997; Suzuki et al., 1998; and Tucker et al., 2001; Shabanov et al., 2002; Piao et al., 2006). NDVI, derived initially from Advanced Very

High Resolution Radiometer (AVHRR) data, is the normalized difference between surface reflectance of infrared and red bands and has a near linear relationship with photosynthesis and transpiration (Sellers, 1985). Tucker and Sellers (1986) found NDVI provided information on transpiration capacities of plant canopies in addition to photosynthesis, the more common application. Early applications of NDVI were for classifying land cover and monitoring vegetation dynamics (Tucker et al., 1985; Justice et al., 1986; Townsend and Justice, 1986). Subsequent applications have expanded to include: 1) land cover mapping and change detection (DeFries et al., 1998; Hansen et al., 2000; Loveland et al., 2000; Sturm et al., 2001, Tape et al., 2006); 2) identifying fire disturbances (Kasiscke and French, 1995; Goetz et al., 2006); 3) monitoring transpiration (Running and Nemani, 1988; Suzuki et al.; 1998); and 4) developing phenological metrics to detect changes in growing season length (Lloyd, 1990; Reed et al., 1994; Myneni et al. 1997; Tucker et al., 2001).

Zhou et al. (2001) found a positive correlation between temporal NDVI patterns and surface temperatures in Northern latitudes. Such correlations increase confidence in temperature driven simulations, such as ETP, and in turn NDVI can be used for determining the seasonal onset of transpiration periods. However, correlations between photosynthesis, transpiration, and NDVI are strongest in climates where radiation is the primary control of these two processes (e.g. Seattle) and weakest in water stressed environments (e.g. Tucson) (Running and Nemani, 1988). Furthermore, a high correlation between NDVI and evapotranspiration was found for Siberia but was less apparent over tropical regions of the Indo-China peninsula (Suzuki et al., 1998). Increases in NDVI have also been attributed to longer growing season in Northern latitudes (Myneni et al., 1997; Tucker et al., 2001; Zhou et al., 2001; Shabanov et al., 2002; Piao et al., 2006).

In spite of its wide spread use, NDVI is a surrogate measurement of plant photosynthetic activity and the translation of the actual signal requires careful consideration (Tucker, 1979; Shabanov et al., 2002). Much of the current NDVI research lacks field validation and as a result it is difficult to interpret what observed changes in NDVI mean. NDVI, like all satellite data, characterizes a pixel and rarely is the pixel homogenous, especially when the pixel size is large. Heterogeneity of the landscape, coupled with atmospheric effects from aerosols and clouds, compound the interpretation of the NDVI signal making field validation essential. GLOBE, through its suite of data collection and extensive worldwide network of students, provides a means to validate such research.

Research Objectives

For my dissertation I developed two distinct research projects to determine if, and how, GLOBE measurements could support satellite data and algorithm evaluation. Both projects incorporated GLOBE and satellite data, specifically NDVI. Furthermore, each project provided a critical analysis of a different application of NDVI. In the first study NDVI was used to monitor transpiration and in second to monitor vegetation phenology. NDVI results were validated with GLOBE measurements as well as external data sources n both studies. While the research differed in each project, the overall objectives of my dissertation were to (1) develop a methodology for utilizing GLOBE measurements in NDVI research; and (2) provide a critical analysis of NDVI as a long-term monitoring tool for environmental change.

Research Projects

My first research project investigated this NDVI-transpiration relationship to determine whether NDVI could accurately predict transpiration periods for a Northern temperate climate. This project utilized a suite of measurements (atmosphere, land cover and soils) made by one GLOBE school in Greenville, Pennsylvania during 1998 through 2001. Students' measurements were used to initialize and validate a soil-vegetation-atmosphere transfer (SVAT) model (GAPS). GAPS, General-Atmosphere-Plant-Soil Simulator, a SVAT model developed by Riha et al. (2003), was used to simulate soil water and energy fluxes at this location from 1998 through 2001. Model outputs were compared to corresponding temporal NDVI time series data derived from SPOT 4 Vegetation.

My second research project investigated whether NDVI could accurately detect phenological changes, specifically start of season (SOS), in high Northern latitude (> 60˚) environments. Vegetation phenology, the relationship between climate and terrestrial plant growing seasons, has become increasingly important in climate change research. Furthermore, mid- and high Northern latitude regions have experienced the largest temperature increases during the most recent warming (1976 to present) (Houghton et al., 2001). This research encompassed phenology metrics derived from multi-temporal AVHRR and Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data. These metrics, in addition to climate based metrics, were used to detect start of season for Alaska. Results from both methods were validated with phenology observations from GLOBE students in Alaska for 2001 through 2004.

Dissertation Outline

Each study was written as a publication manuscript for submission to refereed scientific journals. Chapter Two is the first manuscript, which was published in Ecological Modelling (Robin et al., 2005). Chapter Three is the second manuscript. Each paper has its own applicable abstract, literature review, research objectives, methods, results, discussion, and conclusion sections as well as corresponding figures and tables. Specific GLOBE datasets used are also outlined in each paper. Although much of these GLOBE measurements were made prior to the start of this dissertation, each school site was visited and, when needed, collaborations for supplemental measurements were carried out with the schools. Those additional measurements are also outlined in each paper. Chapter Four discusses the GLOBE program and provides recommendations for utilizing GLOBE data in future research projects. Chapter Five provides overall conclusions of the dissertation research. All references cited throughout the dissertation are provided at the end of the dissertation.

This dissertation addresses two applications of NDVI essential for predicting environmental changes. The first study focuses on whether NDVI can improve evapotranspiration simulations for SVAT models. The second study focuses on whether NDVI can detect phenological changes in start of season. The spatial and temporal extent of NDVI makes it a useful tool for monitoring change. This dissertation helps clarify how NDVI can be used to monitor environmental changes. Furthermore, it evaluates the suitability of utilizing GLOBE data for these types of research.

Chapter 2: Utilizing Satellite Imagery and GLOBE Student Data to Model Soil Dynamics

Abstract

General Purpose Simulation Model of the Atmosphere-Plant-Soil System (GAPS), a menu-driven soil-vegetation-atmosphere transfer (SVAT) model, was used to simulate soil water dynamics from 1998 through 2001 for Greenville, PA, USA. GLOBE student data collected by students from Reynolds Junior and Senior High School, coupled with normalized difference vegetation index (NDVI) data derived from SPOT4 Vegetation imagery, were used to parameterize and validate the model. Data from the National Weather Service Cooperative (NWSC) was used to evaluate the GLOBE dataset. Overall, there was a high index of agreement (d>.80) between field measurements and simulated soil water values from both datasets (GLOBE and NWSC). Simulations using the GLOBE climate data outperformed the NWSC data for the 1999, 2000, and 2001 growing seasons. In addition, the GLOBE simulations showed that NDVI could be utilized to predict transpiration periods (QI, QII, and QIII) for Northern latitudes > 35º with a distinct winter period. In phenological terms, QI reflects the onset of the growing season when vegetation is greening up (NDVI < 0.60) and transpiration is beginning (< 2mm/day) and QII reflects the end of the growing seasons when vegetation is greening down and transpiration is decreasing. QIII reflects the height of the growing season when transpiration rates average between 2 and 5 mm per day and NDVI is at its maximum (>0.60). Results of this study demonstrate that GLOBE student data, coupled with remotely sensed data, can provide an important source of input and validation information for capacitance SVAT models such as GAPS.

Introduction

As the Earth's climate changes, scientists are seeing changes in the phenology of global vegetation using satellite imagery (Myneni et al., 1997; Myneni et al., 1998; Tucker et al., 2001; Zhou et al., 2001). In biomes where climate changes seasonally, soil moisture and temperature also show seasonal patterns, which correspond with above ground climate (Levine and Knox, 1994). Thus, the variability in the length of the growing season may be due to the number of days that moisture and heat in the soil are available for plant growth. Soil moisture and temperature are dynamic in that they change rapidly depending on the climate, topography, land cover and soil properties that are present. They play a major role in the type, amount, and timing of vegetative growth as well as in the hydrologic cycle by affecting the rate of evapotranspiration (ET), drainage, and surface run-off. These processes are difficult to measure directly, but are nonetheless important for understanding water and energy fluxes. Furthermore, evapotranspiration and soil moisture are recognized as the central physical process and variable for predicting these fluxes (Milly, 1992; Mintz and Walker, 1993; Felzer and Heard, 1999).

Soil-vegetation-atmosphere transfer (SVAT) models have become an important tool for simulating these processes and furthering our understanding of water and energy dynamics (McIntyre et al., Oliosio, 1996; Koster and Milly, 1997). For accuracy and reliability, detailed measurements obtained over a wide spatial scale at regular temporal intervals are required to drive and validate these models. However, these types of data are often difficult to obtain, or when available, insufficient in the time domain (e.g. daily net radiation measurements may be required but are unavailable for cloudy days). Ideally, simulation models should make use of the minimum number of regularly available field measurements to remain accurate enough to capture ecosystem dynamics effectively.

While many consider Penman-Monteith (1948 and 1964) the most accurate method for estimating ET, it also requires the most detailed measurements (Jensen et al. 1990; Choudhury, 1997). Furthermore, net radiation, the most essential parameter for the Penman-Monteith algorithm, is not available for many parts of the world. For example, FLUXNET, a global network of micrometeorological tower sites, lacks sufficient radiation measurements to spatially capture surface energy fluxes. With this lack of field measurements, remote sensing observations coupled with surface flux models have been used to calculate ET (Gillies et al., 1997; Olioso et al., 1999; French et al. 2000). The problem with these methods is that they often rely on observations at a coarser resolution than the land surface features that influence the surface energy fluxes (French et al., 2003). Given the difficulties in capturing surface energy fluxes across spatial domains, empirical methods for calculating ET, such as Thornthwaite (1948) and Linacre (1977), still retain much appeal (Mintz and Walker, 1993). Both of these methods rely on mean surface air temperature, day length, and elevation to estimate potential evapotranspiration. The Linacre method approximates the Penman equation and has shown closer estimations to actual ET measurements and Penman calculated ET values (Linacre, 1977).

In this study, student environmental data from the GLOBE Program, and remotely sensed NDVI data were used to determine whether these measurements were sufficient to initialize, drive, and provide accurate results for simulating water and energy fluxes with the General Atmosphere-Plant-Soil Simulator (GAPS). GAPS, a SVAT model developed by Riha et al. (2003), is a menu-driven capacitance model, with multiple soil layers, that simulates soil, plant, and atmospheric processes (e.g. evapotranspiration, soil water flow, plant water uptake) using a choice of algorithms and robust graphical display of output. The graphic display output of GAPS, both during and upon completion of a simulation run, provides a dynamic visualization of a particular process. GAPS can display a dynamic view of up to 4, out of a possible 40, aspects of the plant-soil-atmosphere system as it is being simulated. The software can run on any personal computer that uses Windows95 or higher operating systems. GAPS has been utilized in a variety of studies (e.g. Buttler and Riha, 1987; Buttler and Riha, 1992; Melkonian et al., 1998; McDonald and Riha, 1999; Rossiter and Riha, 1999). The input parameters and degree of detail required to run a simulation in GAPS depend on the model algorithms selected by the user. This attribute makes this model a good choice for GLOBE data. General to more complex simulations can be performed based on the available data for a particular site.

Data collected by GLOBE students from Reynolds Junior and Senior High School in Pennsylvania, USA, were used to parameterize and validate the model. The GLOBE Program is an international partnership network of K-12 students, teachers, and scientists working together to study and understand the global environment. It is a cooperative effort, led by University Corporation of Atmospheric Research (UCAR) and Colorado State University, and funded in the United States by a federal interagency program including NASA, NSF, U.S. State Department. Internationally, GLOBE is a partnership between the United States and over 100 countries. GLOBE is designed as both an education and research Earth Science program. Teachers are trained in the GLOBE protocols and use the educational materials to help students improve their science and math skills (Becker et al., 1997; Haskett et al., 1997; Levine et al., 1998; Brooks and Mims, 2001; Aquino and Levine, 2003). By participating in the program, teachers and students also contribute data for scientific research (Fried, 1997; Krammer, 1998; Mims, 1999; Clemmons, 2000; Congalton, 2002). Currently, over 32,000 teachers have been trained in the program, and over 14 million data measurements have been reported by students worldwide. GLOBE students make observations and measurements on the soils, hydrology, land cover, phenology, and atmosphere at or near their schools. Utilizing GPS receivers, students determine the latitude and longitude of their sites and conduct a series of protocols established by scientists in the various disciplines. Students report their data through the Internet to the GLOBE data archive, where scientists can access these data for research purposes.

GLOBE, through its suite of data collection and extensive worldwide network, provides a valuable resource for parameterization and validation of capacitance SVAT models such as GAPS. As is the nature of SVAT models, the results apply to local scale processes. Satellite imagery was also used in this study to determine whether the local results from GAPS could apply over a larger region. NDVI derived from SPOT4 (Systeme Pour l'observation de la Terre) Vegetation was compared with the model scenarios to assess (1) the accuracy of the student data set for parameterizing GAPS; (2) the temperature threshold for the transpiration simulation; and (3) the feasibility of coupling GLOBE and NDVI data to validate GAPS.

Methodology

(1) Field measurements

GLOBE data from Reynolds Junior and Senior High School, located in Greenville, PA, USA, were selected for this project. The Reynolds students had one of the most complete and longest (since 1995) data sets in the GLOBE data archive. Their study site (41.34º N, 80.40º W, 350 m), located adjacent to the school's athletic fields, had a year round, non-irrigated, grass cover. The students characterized the soil at their site by horizon depth and measured the corresponding soil texture and bulk density. Additional soil samples were taken from each horizon and processed by the Cornell University Lab of Soil and Water to determine field capacity and permanent wilting point (PWP). Field capacity was also determined from analyzing daily trends between the students' precipitation and soil moisture data. The students, using gypsum blocks initially and then Watermark sensors (Irrometer Co, Riverside, California), measured daily soil water content at 10, 30, 60, and 90 cm depths. A Delmhorst hand held meter (Delmhorst Instrument Co, Towaco, New Jersey) was used to read the sensors, and students calibrated the meter annually with gravimetric soil water samples. Students also measured daily minimum and maximum air temperature, precipitation, snow equivalent precipitation, and soil temperature at 5 and 10 centimeter depths following GLOBE protocols (GLOBE Teachers Guide Manual 2003). Data from the U.S. National Weather Service Cooperative (NWSC) weather station at Jamestown, Pennsylvania (41.50º N, 80.47º W, 317 m), the nearest national station to the student's site, was also used. This data is distributed by the NOAA Northeast Regional Climate Center at Cornell University in Ithaca, New York.

(2) Satellite imagery

NDVI values were derived from the SPOT4 Vegetation data set (Sant, 2000). The synthesis data was computed from all the passes at each location acquired during a 10-day period from May 1998 through 2001. The periods included the 1st through 10th (period 1), 11th through 20th (period 2), and 21st through the end of the month (period 3). The best top of the atmosphere pixel (NDVI criteria) was chosen for each of those periods. The spatial resolution of the data was one kilometer and the spectral resolutions of the red and near infrared bands were 0.61-0.68 micrometers and 0.79-0.89 micrometers, respectively. NDVI values of the pixel containing the school site were compared to NDVI values of a three by three pixel window for registration errors. The center pixel was the school location. Registration accuracy values of .5 to 1.0 pixels are considered satisfactory with multitemporal data sets (Townsend et al., 1992). There was a close correspondence between the NDVI values of the site pixel and the average NDVI values of the window pixels. The standard deviations of the pixels were computed for each period and the annual average of the standard deviations were less than .038. The low standard deviations alleviated concerns over misregistration and the NDVI values of the single pixel were used in the analysis. The single pixel analysis also mitigated effects from heterogeneity of the land cover.

The land cover of the NDVI pixels was determined from the National Land Cover Data (NLDC). NLDC is a 21-class land cover classification scheme applied over the United States at a 30-meter spatial resolution derived from Landsat TM images in the Albers Conic Equal Area projection, NAD 83 (Vogelman et al. 2001). Land cover values of a three by three pixel window were evaluated to correspond with the NDVI pixel size. The land cover values of a nine by nine pixel window were also evaluated to correspond with the three by three pixel window of the NDVI data set. The center pixel of both of these windows was the school site location. The majority of the pixels in the three by three and nine by nine windows (67% and 62%, respectively) were pasture. The remaining 33% of the pixels in the three by three window were low intensity residential as were 28% percent of the pixels in the nine by nine window. The remaining 10% pixels in the larger window were deciduous and mixed forest. Field measurements verified that the vegetation over the site was orchard grass.

(3) Model simulations

The students' data were used with the Cornell Lab measurements to parameterize the GAPS model. A 90 cm profile depth was simulated for the root zone based on the observations made by the students and their soil moisture data. The model was used to simulate total daily soil water within the root zone, daily drainage out of the root zone, and daily transpiration from 1998 through 2001. The algorithms used to simulate these processes include: (1) Linacre for potential evapotranspiration; (2); Tipping Bucket for soil water flow; and (3) EPIC for plant water uptake. The Linacre (1977) algorithm estimates potential ET from mean daily air temperature, mean daily dew-point temperature, elevation and latitude. Potential evapotranspiration is partitioned into potential transpiration and evaporation according to the fraction of solar radiation intercepted by the canopy, which is determined by LAI. As the vegetation for the site was a year-round grass of uniform height, a constant height, rooting depth, and leaf area index (LAI) were used. The Tipping Bucket algorithm for soil water flow is a capacitance-based method in which water is transferred to the adjacent downward layer once the layer above exceeds its water-holding capacity (Jones and Kiniry, 1986). GAPS has an additional soil evaporation routine to allow for evaporation from near-surface layers, below the topsoil layer, in addition to surface evaporation (Riha et al., 2003). EPIC algorithm uses a negative exponential distribution of roots with depth to partition the transpirational demand between soil layers and simulate plant water uptake (Sharpley and Williams, 1990).

(4) Model validation

As both field and remotely sensed data were used in validating model outputs, an accuracy assessment was conducted on the students' and NDVI data. The coefficient of determination (r^2) was used to compare temporal patterns between the complete NDVI data set and the corresponding students' air (mean and max) and soil temperature (5 and 10 cm) measurements. Each of the four students' temperature data sets was averaged over the same 10-day intervals as the NDVI composites. In addition, recorded snowfall events measured by the students were compared to the corresponding NDVI values for those dates. The students' snow data were summed over the same 10-day intervals as the NDVI composites. Snow, especially when fresh, has a significantly higher albedo than bare ground and vegetation and results in low NDVI values (Myneni, 1997). Thereby the dates of large snowfall recorded by the students' events should also have had NDVI values at or near zero. For each year, NDVI values during the growing season (March through mid-October) were compared with simulated transpiration values. The daily transpiration amounts were summed over the same 10-day intervals as the NDVI composites.

The simulated soil water outputs from the model were validated with students' soil water field measurements. Wilmott's (1982) d-index (d), root mean square error

(RMSE) and the coefficient of determination (r^2) were used to evaluate the accuracy between the simulated soil water values and the students' field measurements for each growing season. The d-index measures the correspondence between model output and measured data. Data from the National Weather Service Cooperative (NWSC) was used to evaluate the GLOBE dataset. Two sets of modeling simulations were conducted, the first with the students' weather station data (GLOBE) and the second with the Jamestown weather station data (NWSC). Figure 1 diagrams the methodology.

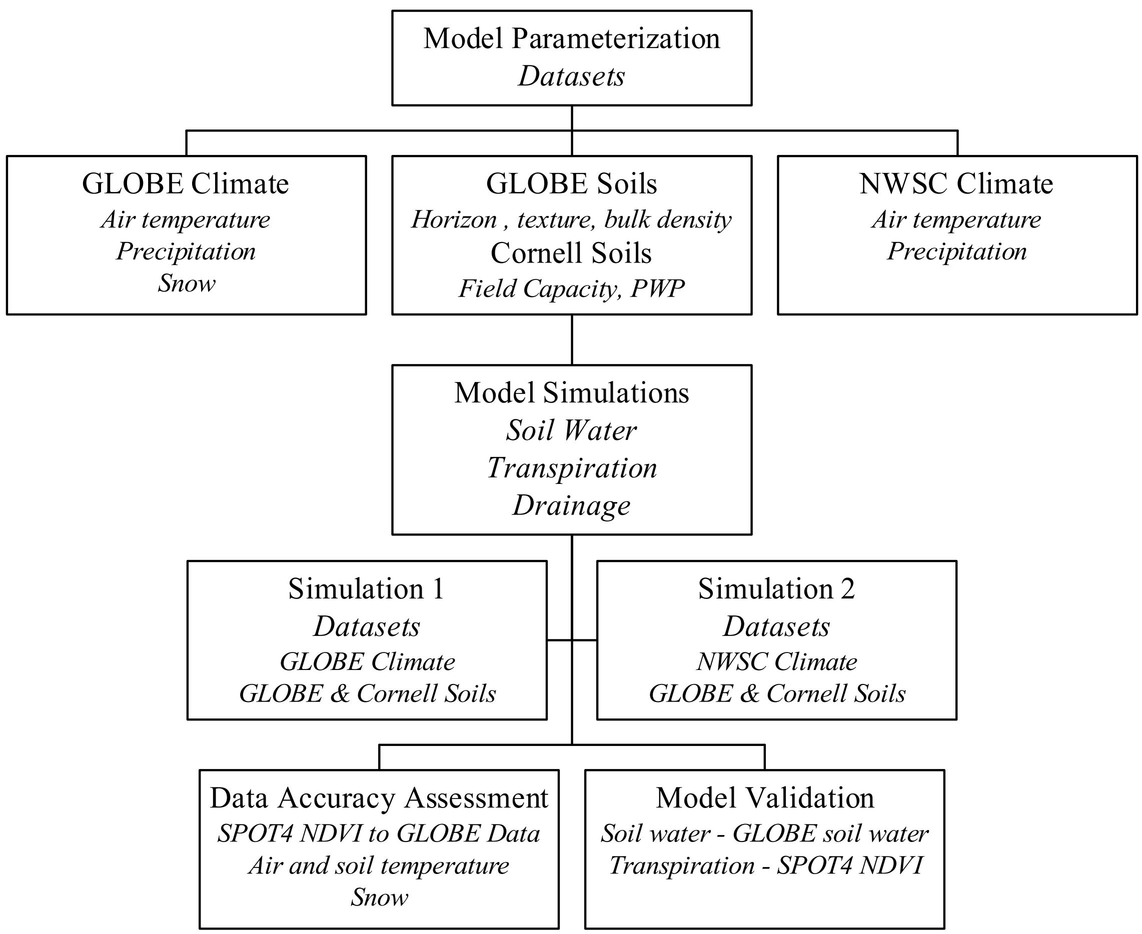

Figure 2-1: **Methodology**

Results

Model predictions of the daily soil water in the root zone were compared with actual soil water measured by Reynolds students. Figure 2 shows the simulated and actual soil water contents for May 1998 through 2001. For all years, the simulated values of both the GLOBE and NWSC datasets showed a reasonable fit to the field measurements. Table 1 shows the statistical analysis between simulations and field data for each growing season. Overall, there was a high index of agreement between field measurements and simulated soil water values from both datasets (GLOBE and NWSC). Simulations using the GLOBE climate data outperformed the NWSC data for the 1999, 2000, and 2001 growing seasons. The GLOBE dataset had higher d-indexes and r^2 values and lower RMSE. Both datasets had d-indexes of .80 or higher for all four growing seasons. A value of one indicates complete agreement between measured and modeled values whereas a value of zero indicates complete disagreement. The r^2 values varied significantly by growing season for both data sets. For GLOBE they were .86, .94, .58, and .62 and for SWSC they were .82, .70, .50, .62 for 1998, 1999, 2000, 2001, respectively. A high r^2 value indicates that the variation in the simulated values corresponded with the variation in the measurement values. The GLOBE dataset had RMSE less than 30 each growing season except 1998 whereas SWSC dataset had RMSE higher than 30 each of the four growing seasons.

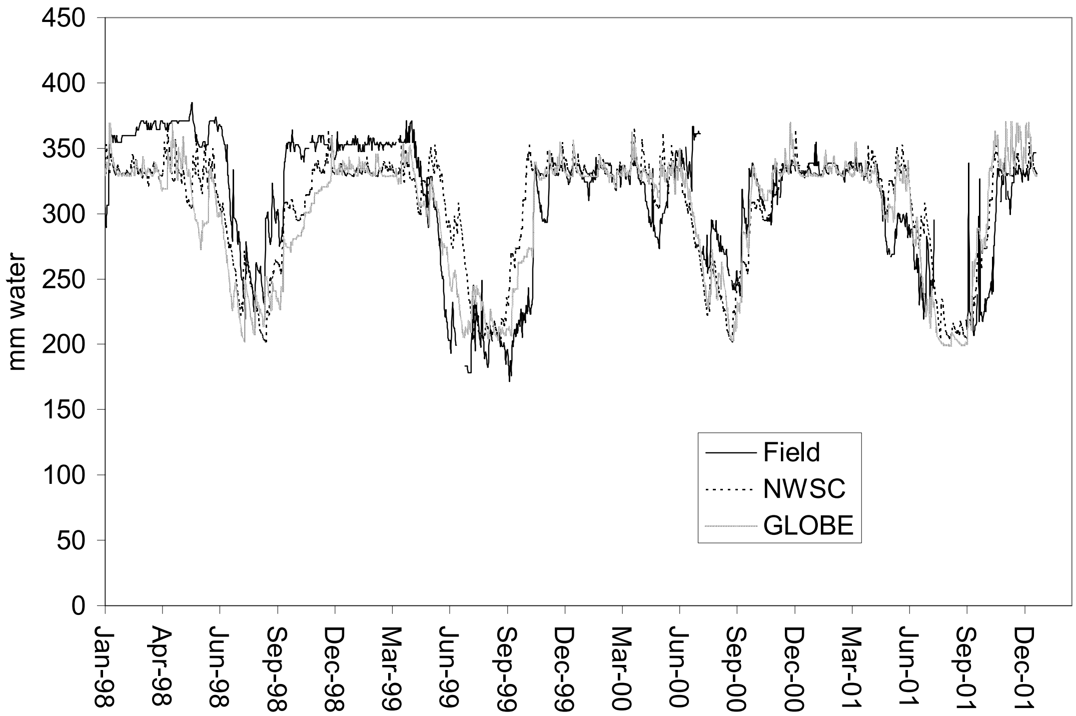

Figure 2-2: Simulated and Measured Soil Water

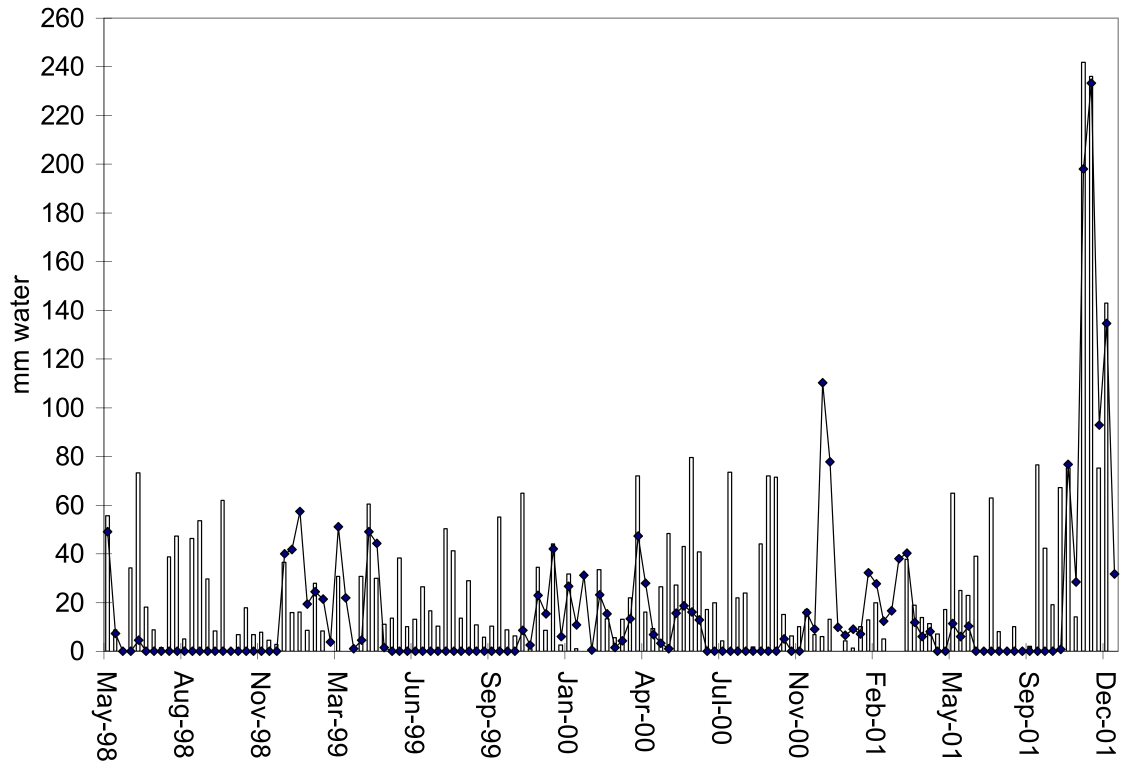

Figure 2-3: Precipitation (□) and Simulated Drainage (♦)

Table 2-1: **Statistical Analysis of Root Zone Soil Water Content**

	1998			1999			2000			2001		
Datasets	d	Rmse	r^2	d	Rmse	r^2	d	Rmse	r^2	d	Rmse	r^2
GLOBE	.80	49	.86	.95	26	.94	.84	29	.58	.87	29	.62
NWSC	.84	40	.82	.88	42	.70	.81	36	.50	.83	33	.62

Figure 4 shows NDVI and the mean air temperature (Avg_AirT), maximum air temperature (Max_AirT), 5 cm soil temperature (5_SoilT), and 10 cm soil temperature (10_SoilT) measured by the students from May 1998 through 2001. In all four years, the NDVI showed the same seasonal pattern; increasing values in the spring, maximum values in the summer, decreasing values in the fall, and minimum values, at or near 0, in the winter. The seasonal NDVI patterns of the school site, with winter values at or near 0, corresponded with data from other latitudes greater than 35º (Myneni et al, 1998, Tucker, et al, 2001). The students' four data sets, Avg_AirT, Max_AirT, 5_SoilT, and 10_SoilT, had r^2 values of .80, .77, .70, and .70, respectively, with NDVI. Zhou et al (2001) also found a positive correlation between NDVI and surface temperatures in northern latitudes.

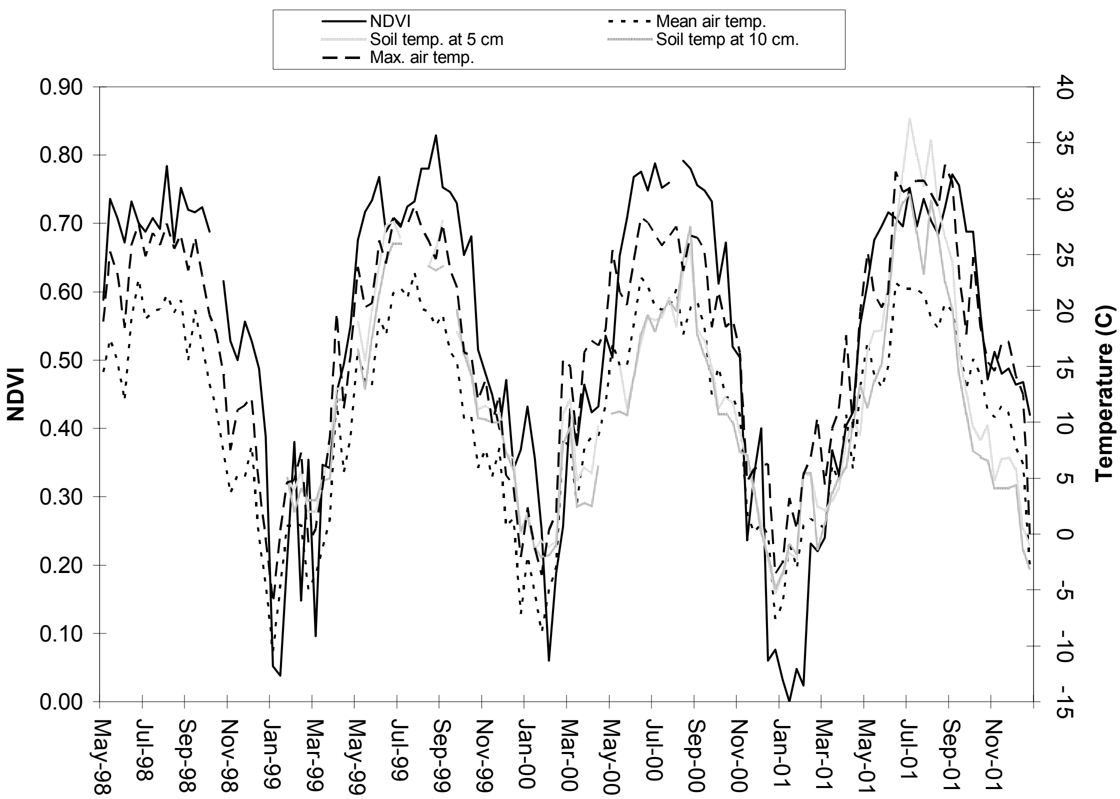

Figure 2-4: Temporal NDVI and Air and Soil Temperatures

Figure 5 shows NDVI and snow equivalent precipitation measured by the students. As expected, large (>30 mm) snow events precipitated sharp declines in NDVI in all four years. The sharp declines occurred in either the same or subsequent time period as the snow event depending on the daily snowfall distribution for the particular time period. Examples include: (1) January 1999 event during which it snowed every day for the first two weeks of that year and resulted in a sharp NDVI decline in period 1 that remained in period 2; and (2) December 2000 event that began in the middle of period 1 and ended in the middle of period 2 and resulted in the sharp NDVI decline occurring in period 2. Overall, Figures 4 and 5 showed that the students' datasets corresponded with the NDVI datasets.

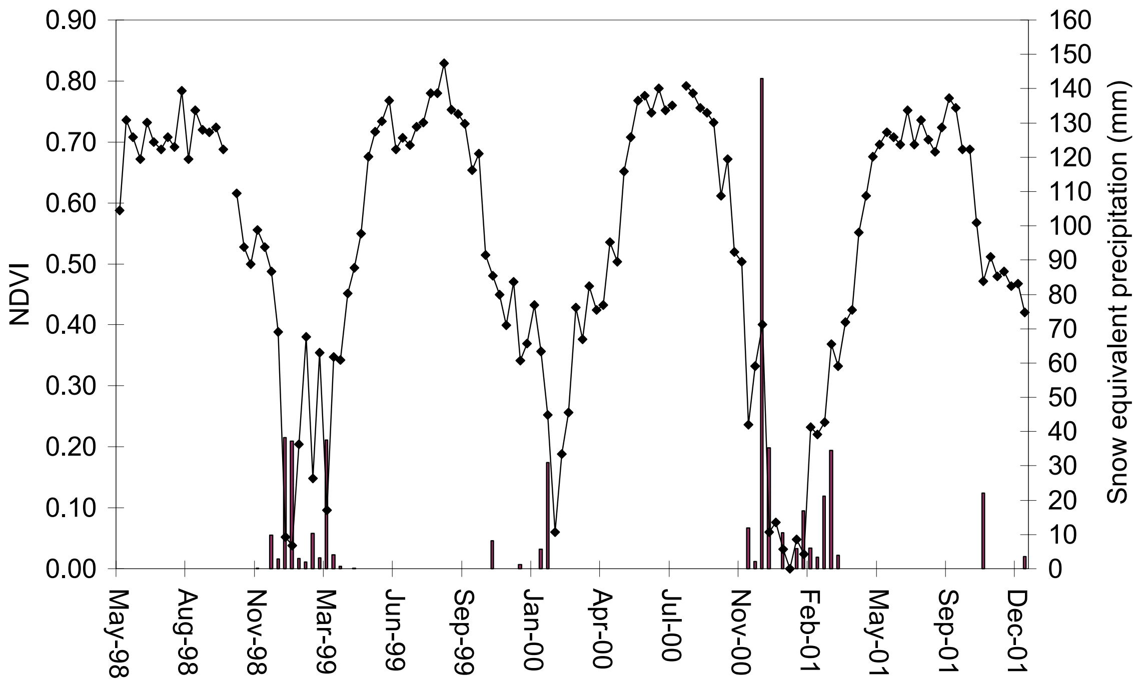

Figure 2-5: NDVI (♦) and Snow Equivalent Precipitation (▌)

Figure 6 shows NDVI and simulated transpiration rates with the GLOBE dataset from May 1998 through 2001. The daily transpiration amounts were summed over the same 10-day intervals as the NDVI composites. As expected, transpiration occurred during the spring through fall with the majority taking place in the summer months.

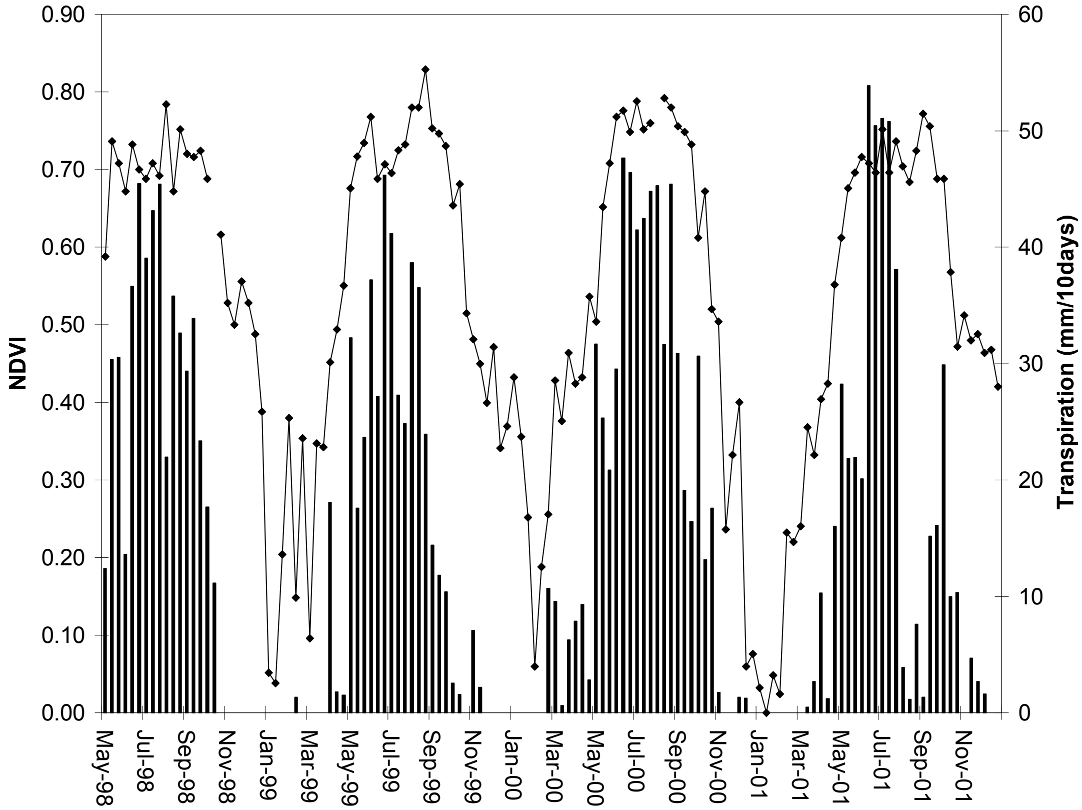

Figure 2-6: NDVI (♦) and Simulated Transpiration (▌)

Figure 7 shows the NDVI values to simulated transpiration for March through the first period in October for 1998 - 2001. The figure is divided into four quadrants (QI-QIV). QI shows the time periods when transpiration rates were averaging less than 2mm/day and NDVI values were below .6 and QII shows the time periods when transpiration rates were averaging less than 2mm/day but NDVI values were above .6. QIII shows the time periods when transpiration rates were averaging more than 2mm/day and NDVI values were greater than .6 and QIV shows the time periods when transpiration rates were averaging greater than 2mm/day but NDVI values were less than .6.

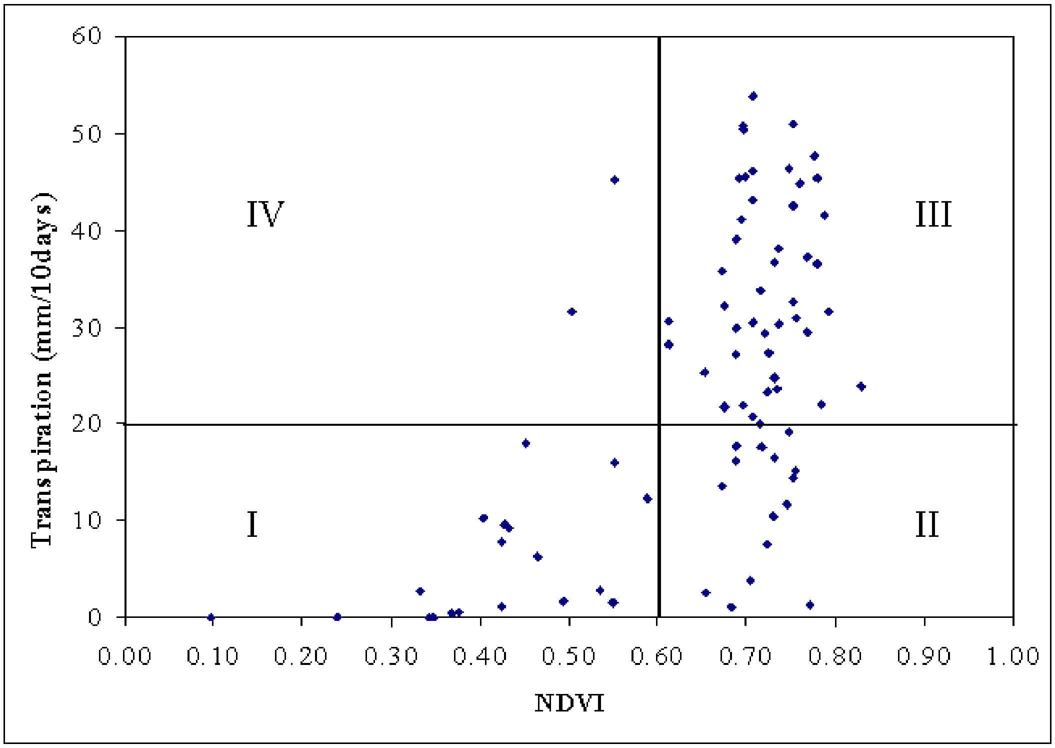

Figure 2-7: NDVI (♦) & Simulated Transpiration (ACT) to Potential Evapotranspiration (PET) (□)

Figure 8 shows NDVI and actual simulated transpiration (ACT) to potential evapotranspiration (PET). When ACT is less than PET, water is limited in the system and vegetation is at risk of stress. During all four summers the ACT/PET ratio decreased to less than one, indicating drought, at some point during the summer. In 1999 and 2001, there was more fluctuation in NDVI values during those drought periods than the 1998 and 2000 drought periods. The ACT/PET values were lowest during the 2001 summer and the ACT/PET values were below one for a longer duration during the 1999 summer.

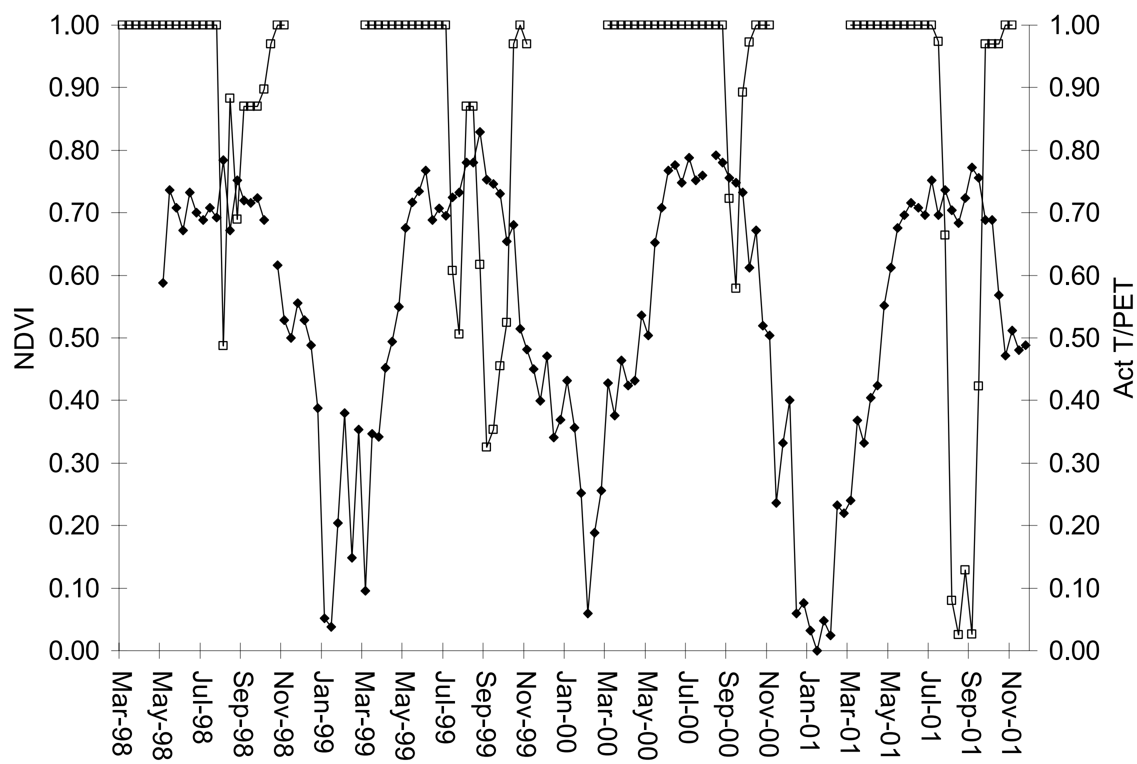

Figure 2-8: NDVI (♦) & Simulated Transpiration (ACT) to Potential Evapotranspiration (PET) (□)

Discussion

A close correspondence between actual and simulated soil water content, as shown in Figure 2, increased confidence in the predicted water fluxes (water uptake and drainage) as these are difficult to measure directly, but are nonetheless important processes for linking soils to atmospheric, hydrologic, and vegetative systems. Two-thirds of the precipitation that falls over land comes from evapotranspiration from soil and vegetation, and the rest from marine evaporation driven by wind (Chahine, 1992). The grass vegetation growing at the Reynolds site usually did not begin transpiring water until end of March or beginning of April. Other types of vegetation might have transpired water earlier in the spring and later into the fall. In this case, the model was structured to allow transpiration to occur only when the daily maximum temperature was above 20^{o}C based on work by Christie and McElroy (1995), showing that the optimum temperature for orchard grass is 20º- 22º C. While transpiration can occur at temperatures below optimum, the purpose of this study was to determine the period when the grass surface was transpiring and how that in turn affected the distribution between uptake and drainage. Transpiration that may occur on a warm winter day would not affect this distribution as it would in the spring and summer when the surface is consistently transpiring. Furthermore, temperature, radiation, and the other variables that affect ET and latent and sensible heat fluxes are not fixed. They fluctuate over the course of the day. Mean temperature would not reflect the temperature range for a given day and would not capture this fluctuation as maximum temperature would. This temperature threshold also gave the best fit to the student soil water data. In the summer months, transpiration by vegetation dried down the soil, making it less likely that large rainfall events would result in movement of water below the root zone and more likely to recharge the surface soil as indicated in Figure 3. This flux would also depend on if and when soil was freezing and thawing during the winter months and the extent and duration of snow cover.

The model simulations of annual ET for this site ranged from a low of 459 mm in 1999 to a high of 632 mm in 2000 with over 80 percent occurring during the months of April through September (Table 2). These rates, as well as the seasonal distribution, correspond with the annual mean estimates for the Northern part of the United States. ET values, derived from precipitation, surface-water inflow, surface-water outflow, and consumptive use, range from 380 to 635 mm with transpiration beginning in April, reaching a maximum in July, and decreasing in October (Hanson, 1991).

Table 2-2: Annual NDVI and Transpiration (T) by Composite Periods

	1998		1999		2000		2001	
Month-Period	NDVI	T(mm)	NDVI	T(mm)	NDVI	T(mm)	NDVI	T(mm)
Mar_Period 1	N/A	0.00	.096	0.00	.428	9.56	.240	0.00
Mar_Period 2	N/A	0.00	.347	0.00	.376	0.61	.368	0.47
Mar_Period 3	N/A	14.66	.342	0.00	.464	6.26	.332	2.70
Apr_Period 1	N/A	7.38	.452	18.07	.424	7.88	.404	10.28
Apr_Period 2	N/A	1.89	.494	1.77	.432	9.29	.424	1.20
Apr_Period 3	N/A	6.31	.550	1.53	.536	2.80	.552	16.01
May_Period 1	.588	12.38	.676	32.22	.504	31.68	.612	28.23
May_Period 2	.736	30.35	.717	17.58	.652	25.33	.676	21.81
May_Period 3	.708	30.52	.734	23.66	.708	20.83	.696	21.92
June_Period 1	.672	13.58	.768	37.19	.768	29.51	.716	20.09
June_Period 2	.732	36.66	.688	27.16	.776	47.64	.708	53.86
June_Period 3	.700	45.48	.707	46.16	.748	46.40	.696	50.42
July_Period 1	.688	39.05	.695	41.16	.788	41.48	.752	51.04
July_Period 2	.708	43.11	.725	27.30	.752	42.48	.696	50.80
July_Period 3	.692	45.40	.732	24.84	.760	44.80	.736	38.08
Aug_Period 1	.784	21.99	.780	36.68	.552	45.27	.704	3.91
Aug_Period 2	.672	35.81	.780	36.51	.792	31.61	.684	1.17
Aug_Period 3	.752	32.60	.829	23.91	.780	45.40	.724	7.62
Sept_Period 1	.720	29.35	.753	14.42	.756	30.89	.772	1.33
Sept_Period 2	.716	33.85	.746	11.80	.748	19.12	.756	15.17
Sept_Period 3	.724	23.35	.730	10.40	.732	16.43	.688	16.12
Oct_Period 1	.688	17.69	.654	2.55	.612	30.64	.688	29.88

In phenological terms, NDVI and simulated transpiration can be divided into three periods (Figure 7). QI reflects the onset of the growing season when vegetation is greening up and transpiration is beginning and QII reflects the end of the growing seasons when vegetation is greening down and transpiration is decreasing. QIII reflects the height of the growing season when transpiration and NDVI are at their maximum. The onset of transpiration and greening up (QI) occurred by the first period in April for all four years. During this period transpiration rates were less than 2 mm per day and NDVI was less than 0.60. The NDVI value rose above the annual average (.512) by the third period in April for 1999, 2000, and 2001. The annual average was calculated from the 1999 through 2001 NDVI values. The 1998 values were not included since NDVI data was not available for the entire year. By the second period in May, NDVI values for all years were at or greater than .60 representing the end of the greening up period and the onset of maximum NDVI and transpiration (QIII). The model predicted similar increases in transpiration rates during this one-month greening up period. Between the third period in April and the first period in May transpiration rose respectively, from 1.53 to 32.22 mm, 2.80 to 31.68 mm, and 16.01 to 28.23mm, in 1999, 2000, and 2001, respectively. For 1998, the model showed that transpiration rates increased from 6.31 to 12.38 mm for these two periods followed by a sharp increase to 30.35 mm for the following period. NDVI increased correspondingly from .588 during the first period in May to .736 during the second period in May.

For all years, with the exception of 2001, QIII began in May and ended in September (Figure 7 and Table 2). During the QIII period NDVI values were greater than 0.60 and transpiration rates averaged between 2 and 5 mm per day. The two exceptions were the second period of May in 1999 and the first period of June in 1998 when NDVI was greater than .6, but transpiration rates averaged less than 2mm/day. In these two cases transpiration returned to rates higher than 2 mm/day in the subsequent time period. As mentioned, the 2001 growing season experienced the most severe drought and this may explain the shortened QIII time period for that year. The simulated transpiration rates were significantly lower during that period in 2001 in comparison with the other years. There were only two QIV events, one in May 2000 and the other in August 2000. In the May case, the NDVI value increased significantly the following period and in the August case, the NDVI value dropped unseasonably low for only one composite period, indicating partial cloud contamination of the composite value (Table 1).

The model simulations showed that the timing and distribution of transpiration coincided with the seasonal NDVI pattern (Figure 6). The onset of transpiration, and its subsequent increased rate, corresponded with the continuous rise in NDVI values. Once NDVI began to decline, signaling the greening down of vegetation, transpiration also began to decline. These results correspond with Suzuki et al. (1998) who found a high correlation between seasonal changes in NDVI and ET in Siberia and Northeast China. They investigated a spatial distribution from 40° to 75° N and 40° to 160° E. Furthermore, they found a phenological regionality of NDVI across Siberia where green-up, maximum NDVI, and senescence occurred earlier in the western part of the region than the eastern (Suzuki et al., 2001; Suzuki et al. 2003).

While Suzuki's work corresponds in part with this study, a direct comparison of land surface models is difficult due to variations in simulated outputs and validation methods. Nonetheless, the methodology and model presented here does provide a simplified alternative with comparable results to other more complex models. In general, land surface models share two commonalities. First, they have detailed above ground parameterization requirements for vegetative and atmospheric processes and minimal below ground requirements for soil processes (Liang and Lettenmaier, 1994; Liang, Wood and Lettenmaier, 1996; Stamm et al., 1994; Sellars et al. 1996; Birky, 2001). The soil system, at best, is defined by three layers (surface, root zone, and recharge zone) and often represented as either a single or two layer column. In both SiB (Simple Biosphere Model) and VIC (Variable Infiltration Capacity), the overlying vegetation determines the underlying soil properties. Furthermore, rooting depth is simplified either having one generalized depth for the entire region or varying depths solely as a function of vegetation (Seaquist et al., 2003; Churkina et al. 1999). In a review of global terrestrial models conducted by Churkina et al., only three models, Carbon Assimilation in the Biosphere Model (CARAIB 2.1), Frankfurt Biosphere Model (FBM 2.2) and Terrestrial Ecosystem Model (TEM 4.0), have rooting depth as a function of vegetation and soil texture. In addition, the above ground parameterization requirements, such as solar radiation and leaf area index, are often difficult to obtain, and when unavailable are simulated or interpolated from coarser data sets.

The second similarity relates to the first in that these models integrate remotely sensed data to augment unavailable field data requirements for parameterization. As mentioned, the problem with utilizing remotely sensed data is that it is often at a coarser resolution than the land surface features that influence the surface energy fluxes (French et al., 2003). In addition, NDVI, often used as a surrogate for leaf area index (LAI) to simulate heat, water, and carbon fluxes, is a problematic one. Under certain environments, such as humid and well vegetative environments, the NDVI-LAI relationship provides favorable results (Szilagyi, 1999). Yet, in Mediterranean environments a fixed LAI, rather than a derived, variable, LAI from NDVI yields comparable or better results under certain conditions (Chiesi et al., 2002). Furthermore, the relationship between NDVI and LAI deteriorates at high biomass levels due to NDVI saturation (Tucker 1979; Sellars 1985; Gao et al. 2000; Thenkabail et al. 2000). Narrow band and soil-adjusted indices have been offered as alternatives for high biomass canopies (Huete et al., 1994; Gao et al. 2000; Mutango and Skidmore, 2004). Nonetheless, there lacks a universal NDVI-LAI relationship.

The approach presented in this study is unique in that it utilizes a simple capacitance model with multiple soil layers with minimal input parameters that are field based, not simulated or interpolated. NDVI is not used to derive LAI, rather to predict transpiration periods. In addition, 10-day, in lieu of the more common monthly, composites are utilized. While monthly composites mitigate cloud and other effects, they are too coarse to capture temporal changes in the very processes being simulated or derived, e.g. transpiration. Finally, a more representative, multi-layer, soil process modeling with rooting depth parameterization linked to soil water uptake is used.

Conclusion

The data collected by GLOBE students from Reynolds Junior and Senior High School were highly correlated with SPOT4 vegetation data for the study site. The GAPS model, parameterized with the student measurements, successfully predicted soil water dynamics for 1998 through 2001. The model's maximum temperature stipulation for transpiration was accurate for the site as shown by: (1) the strong index of agreement and correlation between the simulated and measured soil water values with both the GLOBE and SWSCS datasets; (2) the strong correlation between the students' temperature measurements and the NDVI values; and (3) the correspondence between NDVI values and simulated transpiration rates during the growing season. Furthermore, the students' weather dataset outperformed the National Weather Service Cooperative dataset.

This study illustrates that NDVI could be utilized to predict transpiration periods for Northern latitudes >35^{o} that have distinct winter periods. Furthermore, GLOBE student measurements, coupled with NDVI data, can provide an important source of input and validation information for capacitance SVAT models such as GAPS. GLOBE through its extensive worldwide network provides a valuable resource for data that is currently underutilized for these types of models. In addition, data from GLOBE schools provides the opportunity to compare ecosystem function across a wide variety of biomes.

Chapter 3: Monitoring Start of Season in Alaska with GLOBE, AVHRR and MODIS Data

Abstract

This paper evaluates whether continuity between AVHRR and MODIS normalized difference vegetation index (NDVI) is achievable for monitoring start of season (SOS) and whether a threshold based on NDVI or accumulated growing degree days (GDD) most accurately predicts SOS for Fairbanks. Ratio of maximum greenness at SOS was computed from biweekly AVHRR and MODIS composites for 2001 through 2004 for Anchorage and Fairbanks regions. SOS dates were determined from annual green-up observations made by GLOBE students. Results showed that different processing as well as spectral characteristics of each sensor restrict continuity between the two datasets. MODIS values were consistently higher and had less inter-annual variability during the height of the growing season than corresponding AVHRR values. Furthermore, for Fairbanks, a threshold of 153 ± 22 accumulated growing degree days (GDD) was a better predictor of SOS than a NDVI threshold applied to AVHRR or MODIS datasets. The NDVI threshold was developed from biweekly AVHRR composites from 1982 through 2004 and corresponding annual green-up observations at University of Alaska-Fairbanks (UAF). The GDD threshold was developed from 20+ years of historic daily mean air temperature data and the same green-up observations. SOS dates computed with the GDD threshold most closely resembled actual green-up dates observed by GLOBE students and UAF researchers. Overall, biweekly composites and effects of clouds, snow, and conifers limit the ability of NDVI to monitor phenological changes in Alaska.

Introduction

Since the late 19th century the global annual surface temperature has increased 0.6 ± 0.2° C with the largest temperature increases of the most recent warming (1976 to present) occurring over the mid- and high latitude continents of the Northern Hemisphere (Houghton et al., 2001). Extent of annual snow cover also decreased during this time period over the Northern Hemisphere (Groisman et al. 1994). Alaska has been particularly sensitive to these changes. Since the 1960s mean annual temperatures in Alaska have increased by 3º Celsius, the largest regional warming of any state in the United States (Weller et al., 1999). Furthermore, day-to-day temperature variability has decreased in the Northern Hemisphere (Karl et al., 1995). Globally, daily minimum temperature has increased at a faster rate than daily maximum temperature resulting in a decrease in the diurnal temperature range (DTR) (Karl et al., 1991; Easterling et al., 1997). In the US, decreases in DTR have been strongest during autumn. However, Alaska has had strong decreases in DTR throughout the year (Karl et al., 1993). In addition, a 400-year arctic temperature record reconstructed from proxy data shows that the arctic temperatures of the 20th century are the highest of the past 400 years (Overpeck et al., 1997).

Along with this warming, satellite data, specifically Advanced Very High Resolution Radiometer (AVHRR) NDVI, from the past two decades shows a corresponding increase at these Northern latitudes. These increases in NDVI have been attributed to a longer growing season (Myneni et al., 1997; Tucker et al., 2001; Zhou et al., 2001; Shabanov et al., 2002; Piao et al., 2006). However, these studies did not have field validation making it difficult to interpret these NDVI increases. NDVI, while long used to monitor vegetation, is only a surrogate measurement of plant photosynthetic activity and the translation of the actual signal requires careful consideration (Tucker, 1979; Shabanov et al., 2002).

A review of multi-temporal remote sensing Arctic research from the past decade found the strongest signal of NDVI change corresponded with the expansion of the tundra shrub (Stow et al. 2004). The same increases in AVHRR NDVI, substantiated with corresponding field data and 50 years of repeat aerial photography, showed an increase in both range and size of tundra shrub in Northern Alaska and the Pan-Arctic (Sturm et al., 2001, Tape et al., 2006). In Arctic Alaska, field biomass data also corresponded to these NDVI changes (Jia and Epstein, 2003; Walker et al. 2003). Using AVHRR NDVI time series analysis, Goetz et al. (2005) found the boreal biome had undergone substantial changes during 1981 through 2003. However, these changes varied by vegetation type. Growing season length and photosynthetic activity of the tundra shrub showed temperature-related increases. In contrast, interior forests showed a decrease in photosynthetic activity and no change in growing season length. They attributed these differences to a variety of influencing factors including fire disturbances, drought stress and nutrient limitations on interior forest regions.

Each of these NDVI studies does indicate, however, that Northern latitudes, and especially boreal regions, exhibit strong evidence of change. In addition, various phenological field observations across Europe and North America show a corresponding lengthening of growing season, specifically an earlier start of season, since the 1960s. In Europe, SOS has advanced by six days and eight days for the 1959 to 1996 and 1969 to 1998 periods, respectively (Menzel and Fabian, 1999; Menzel, 2000; Chmielewski and Rozter, 2001). In Britain, SOS advanced by four and a half days during the past decade compared to the previous four decades (Fitter and Fitter, 2002). A combination of lilac observations and modeled phenological data showed that, on average, SOS advanced by five to six days during 1959 though 1993 across North America (Schwartz and Reiter, 2000). In Boston, SOS of herbarium specimens began eight days earlier during 1980 to 2002 compared to 1900 to 1920 (Primack et al. 2004). Additionally, a spring warming of 1˚ Celsius showed a corresponding advance in SOS by four, four and a half, and seven days across Great Britain, Western United States, and Europe, respectively (Cayan et al. 1994; Fitter et al., 1995; Chmielewski and Rozter, 2001).

Establishing whether temporal NDVI can detect these earlier SOS dates is beneficial as the spatial extent of satellite data allows for a larger area of study than field observations. Furthermore, observed shifts in earlier spring phenological events, both plant and animal responses, have been attributed to anthropogenic climate change (Root et al., 2003; Root et al., 2005). Various approaches exist for estimating SOS from satellite data. However, careful interpretation of what exact properties are being estimated by these approaches is required. The objective of deriving phenology metrics from satellite data is to characterize the individual pixel and if the pixel size is large (e.g. hundred meters or greater), the objective is to characterize the phenology of a mosaic of vegetation types rather than specific species or populations (Reed et al., 2003). Reed et al. (2003) classifies these methods into three groups; threshold-based, inflection point, and curve derivative.

Threshold-based approaches utilize either a set NDVI values or a value calculated from minimum and maximum NDVI to determine start, end, and length of growing season (Justice et al., 1986; Lloyd, 1990; Kogan, 1995; Markon et al., 1995; White et al., 1997; Goldman, 2000; Suzuki et al, 2003). Values above the threshold indicate new growth and start of the growing season and values below dormancy and end of the growing season. While simple computationally, choosing the right threshold is essential because the threshold determines all metrics. In addition, choosing one threshold to represent all land cover types is problematic as minimum NDVI values differ by vegetation type (e.g. deciduous versus evergreen forest). Furthermore, in regions like Alaska, which often has snow through spring, the 0.09 threshold used by Justice et al. (1986), Lloyd (1990), and Markon et al. (1995) is too low. For Siberia, Suzuki et al. (2003) utilized a 0.2 threshold to account for the effects of snow. Mid-point value techniques minimize these problems by using actual NDVI data to determine the threshold. White et al. (1997, 2000, 2002) used seasonal mid-point calculated from annual minimum and maximum NDVI values as their threshold. Similarly, Goldman (2000) used annual range to compute maximum greenness required for start and end of seasons in Alaska. Kogan (1995) computed a NDVI ratio of maximum greenness for each composite value based on a multiyear range of minimum and maximum NDVI values.

Inflection point methods detect time of transition (rate of change of the NDVI curve) from the temporal NDVI profile, and metrics are derived with time derivatives or logistic functions (Moulin et al. 1997; Zhang et al. 2003). This method, while useful for biomes with multiple growing seasons, is problematic for regions with evergreen, snow effects, and slow rates of senescence (Reed et al., 2003). Curve derivative methods identify a rapid and sustained increase in the temporal curve with a delayed moving average (Reed et al., 1994). A sudden increase in NDVI signals onset of photosynthetic activity and SOS. However, this method is difficult to implement in high Northern regions such as Alaska since most AVHRR (1-km) composites prior to SOS are not available. Only mid-April through mid-October composites are available for Alaska because of snow and excessive clouds during the winter months (Markon, 2001). Schwartz et al. (2002) compared satellite-derived SOS dates produced by the moving average and seasonal mid-point techniques for deciduous and woodland sites across the conterminous United States. Overall, the seasonal mid-point technique tracked SOS better than the moving average technique but had larger average errors. With both methods, error varied considerably by year.

To date, most of the studies for predicting SOS from NDVI have focused on AVHRR data. Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI is referred to as the continuity index for the longer (20+ years) AVHRR-derived NDVI product (Huete et al. 2002). Initial studies suggest continuity is achievable between these two sensors (Steven et al., 2003; Brown et al., 2006). However, Huete et al. (2002) found that over various North American sites NDVI seasonal profiles from MODIS were more sensitive and reliable than equivalent NDVI profiles from AVHRR. They attributed these differences to: (1) wider spectral NIR band of AVHRR, which is more sensitive to water vapor and dampens NDVI values (Cihlar et al., 2001); (2) increased chlorophyll sensitivity of the MODIS red-band (Gitelson and Kaufman, 1998); (3) MODIS' atmospheric correction for aerosols, which AVHRR does not have; and (4) constrained-view angle compositing (CV-MVC) of MODIS versus the AVHHR maximum value compositing (MVC). MVC tends to select pixels with large view and solar zenith angles and results in spatio-temporal variations in the time series data (Goward et al., 1991).

CV-MVC compares the two highest NDVI values and selects the observation closest to the nadir view to represent the composite value thereby reducing spatial and temporal discontinuities in the time-series data (Huete et al., 2002).

This study relates budburst observations made by GLOBE students in Alaska for 2001 through 2004 to SOS dates derived from AVHRR and MODIS NDVI data. Since 1999, GLOBE students from more than 120 schools around the world have made over 95,000 phenology measurements at their schools (www.globe.gov). Students in Alaska have collected nearly half these measurements. This data set, largely untapped for scientific purposes, provides an exceptional means to validate satellite-derived phenology for Alaska. The objectives of this research were to determine: (1) whether continuity of AVHRR and MODIS NDVI is achievable for monitoring SOS in Alaska; and (2) whether a threshold based on NDVI or accumulated growing degree days (GDD) most accurately predicts SOS for Fairbanks.

Data Products

(1) Field Phenology

GLOBE students located in or near the Anchorage, Fairbanks, and Wasilla regions made observations and measurements from 2001 through 2004 of budburst and green-up on *Betula* (Birch), *Populus* (Poplar), and *Salix* (Willow) at their school locations following established GLOBE plant phenology protocols (***www.globe.gov***). All three trees are native to Alaska (Viereck and Little, 1972). Latitude and longitude of the school sites ranged from 61.16º N to 64.88º N and 147.52º W to 149.85º W, respectively. Green-up and Green-down protocols were developed at the University of Alaska

Fairbanks and the Budburst protocol at Utah State University. All protocols were pilot-tested by teachers during development and aligned to national science standards.

Green-up observations at the University of Alaska-Fairbanks (UAF) campus, made by two separate UAF research groups, were also used. The first group made green-up observations from 1976 through 2004 and the second from 1988 through 1998 (Thoman and Fathauer, 1998). Both groups made observations near the UAF campus on the Chena hillside, a site largely populated by birch (Goldman, 2000). These three phenology datasets will be referred to as GLOBE, UAF_1 and UAF_2, respectively. SOS will refer to both budburst and green-up.

(2) Climate

Climate data were obtained from NOAA weather stations at the Fairbanks International Airport for 1976 through 2004 (NOAA NCDC). Soil temperature data were obtained from Bonanza Creek Long-Term Ecological Research (LTER) program (Miller, 2004). The Bonanza Creek site is located 20 kilometers southwest of Fairbanks and has two weather stations collecting soil temperature (LTER1 and LTER2) since 1989. LTER1 is an upland site, elevation 355 meters, with loess parent material. Its soil classification and series are Alfic Cryochrept and Fairbanks silt loam, respectively. LTER2 is a floodplain site, elevation 130 meters, located 150 meters from the Tanana River, with alluvium parent material. Its soil classification and series are Typic Cryofluvent and Salchaket, respectively.

(3) Satellite

Maximum value, 14-day, 1-km resolution AVHRR NDVI composites for 2001 through 2004 and corresponding cloud mask files from the U.S. Geological Survey's

National Center for Earth Observation and Science were used (USGS/EROS). This dataset includes data from AVHRR sensors onboard NOAA-16 and 17 satellites. Only mid-April through mid-October composites were available for Alaska. Red and infrared bandwidths are 580 to 680 nm and 725 to 1100 nm, respectively. AVHRR data were atmospherically corrected for ozone, water vapor absorption, and Rayleigh scattering. A water vapor correction was applied as of 2001 to all, past and subsequent, time series data (DeFlice et al., 2003). Maximum value compositing (MVC) was applied to 14-day NDVI data (Holben, 1986). In addition, all composites were cloud screened using an adaptation of the CLAVRR (Clouds from AVHRR) algorithm developed by Stowe et al. (1999). It was not possible to use the 7-day 1-km AVHRR NDVI product because of excessive clouds.

Maximum value biweekly 8-km resolution AVHRR NDVI composites for 1982 through May 2004 from the NASA Global Inventory Monitoring and Modeling Systems (GIMMS) group at the Laboratory of Terrestrial Physics were also used (Tucker et al., 2004). This dataset includes data from the AVHRR sensors onboard the NOAA-7 through 17 satellites and provides improved results based on corrections for calibration, view geometry, volcanic aerosols, and other effects not related to actual vegetation change. AVHRR (1-km) and AVHRR (8-km) datasets will be referred to as AVHRR_1km and AVHRR_8km, respectively.

In addition, 16-day, 1-km resolution MODIS NDVI composites (MOD13A2) and 8-day, 250-m resolution MODIS Surface Reflectance (MOD09Q1) composites for 2001 through 2004 from the EOS Terra Satellite were used (LP DAAC). However, it was not possible to use the 8-day MOD09Q1 product at all locations because of excessive clouds.

Cloud-contaminated composites were identified with corresponding QA files from each dataset. Red and infrared bandwidths are 620 to 670 nm, centered at 648 nm, and 841 to 876 nm, centered at 858 nm, respectively. These bands were chosen to minimize the impact of water vapor absorption, a limitation of previous instruments for land remote sensing (Vermote et al., 1997). MODIS products were corrected for molecular scattering, water vapor, ozone absorption, and aerosols (Vermote et al., 2002). A constrained-view angle-maximum value composite (CV-MVC) algorithm to constrain strong angular variations encountered in the maximum value compositing (MVC) process was applied to MODIS data (Huete et al., 2002). MODIS 1 kilometer and 250 meter NDVI datasets will be referred to as MOD_1km and MOD_250m, respectively.

Methodology

A statewide land cover map was used to determine land cover for each GLOBE site. This map was based on 1991 1-km AVHRR data (Fleming, 1997). A mean filter (3 by 3 pixels) of each GLOBE site was applied to the land cover map. Sites with similar locations, land cover classification, and temporal NDVI signatures were grouped together. Table 1 shows location, land classification, land group, and soil group for each GLOBE site. There were six land groups, AN_SHR, AN_URB, WAS_FOR, FB_FOR, FB_URB1, and FB_URB2. AN, WAS, and FB were in Anchorage, Wasilla, and Fairbanks, respectively, and SHR, URB, and FOR represented shrub, urban, and forest land classifications, respectively.

Table 3-1: GLOBE Site Location and Information

Site & Location	Lat, Lon, & Elev	Land cover	Land Group	Soils Group
Central (Anchorage)	61.21˚N, 149.89˚W 80 meters	Urban: 67% Shrub Tundra: 33%	Urban (AN_URB)	-----
Polaris (Anchorage)	61.17˚N, 149.85˚W 41 meters	Shrub Tundra: 67% Spruce Forest: 22% Urban: 11%	Shrub (AN_SHR)	-----
Wasilla (Wasilla)	61.59˚N, 149.41˚W 105 meters	Spruce Forest/Shrub: 67% Mix Forest: 33%	Forest (WAS_FOR)	-----
Barnette (Fairbanks)	64.82˚N, 147.73˚W 150meters	Urban: 89% Mix Forest: 11%	Urban (FB_URB1)	Floodplains (LTER2)
Joy (Fairbanks)	64.86˚N, 147.73˚W 144 meters	Urban: 67% Spruce Forest: 22% Mix Forest: 11%	Urban (FB_URB2)	Floodplains (LTER2)
Monroe (Fairbanks)	64.85˚N, 147.72˚W 143 meters	Urban: 67% Spruce Forest: 33%	Urban (FB_URB2)	Floodplains (LTER2)
Moosewood (Fairbanks)	64.88˚N, 147.79˚W 168 meters	Spruce Forest/Shrub: 44% Mix Forest: 33% Urban: 22%	Forest (FB_FOR)	Upland (LTER1)
North Pole (North Pole)	64.75˚N, 147.34˚W 167 meters	Spruce Forest/Shrub: 89% Mixed Forest: 11%	Forest (FB_FOR)	Upland (LTER1)
Ticasuk (Ticasuk)	64.83˚N, 147.52˚W 150 meters	Spruce Forest/Shrub: 78% Mixed Forest: 22%	Forest (FB_FOR)	Uplands (LTER1)
West Valley (Fairbanks)	64.85˚N, 147.82˚W 122 meters	Urban: 67% Mix Forest: 22% Tall Shrub: 11%	Urban (FB_URB1)	Floodplains (LTER2)

Corresponding AVHRR_1km and MOD_1km NDVI datasets were used to determine if continuity between the two sensors was achievable for Alaska. The same mean filter as above was applied to biweekly composites from each dataset for 2001 through 2004. The four-year mean and corresponding standard deviation for each biweekly composite were computed for each land group. MOD_1km data were stitched and re-projected to Albers Equal Area Conic of Alaska to match the AVHRR product. Composites from mid-April through mid-October were only available for the AVHRR_1km dataset. Corresponding composites from mid-March through mid-November were used for the MOD_1km dataset. Cloud screening was done on both datasets and cloud-contaminated composites were replaced with mean values calculated from composite values preceding and following contaminated ones.

Ratio of maximum greenness (MG), a threshold algorithm based on methods developed by Kogan (1995), White et al. (1997), and Goldman (2000), was used to determine SOS from AVHRR and MODIS NDVI. This algorithm was chosen because of the high amount of snow in Alaska. Most of the GLOBE sites also had spruce land cover. As discussed above, inflection point methods are problematic for regions with evergreen and snow effects (Reed et al., 2003). Furthermore, a delayed moving average method was difficult to implement for this study since AVHRR_1km composites prior to mid-April were not available for Alaska.

Ratio of maximum greenness (MG) was calculated from biweekly AVHRR_1km and corresponding MOD_1km NDVI composites for 2001 through 2004 for each of the six groups from the following equation:

$$MG = (NDVI - NDVI_{Min})/(NDVI_{Max} - NDVI_{Min}) \quad (1)$$

NDVI represented the biweekly composite value, $NDVI_{Min}$ the annual minimum NDVI value, and $NDVI_{Max}$ the annual maximum NDVI value.

Annual MG at SOS was computed from AVHRR_1km and MOD_1km datasets for 2001 through 2004. SOS was determined from the GLOBE students' field observations. SOS was defined when 50 percent of the leaves for all sites of the same genus at one school had budded. A site was defined as one branch and the students made measurements on four leaves per branch. On average, schools located in the Anchorage region had four sites per year and schools located in the Fairbanks region had seven sites per year. However, not all schools were able to make measurements on all tree types each year. Mean MG at SOS (MG_SOS) was computed from 2001 through 2004 annual values. These values were then evaluated to determine whether SOS thresholds were transferable between the two datasets. Figure 1 diagrams the methodology of the AVHRR_1km and MOD_1km NDVI analysis.

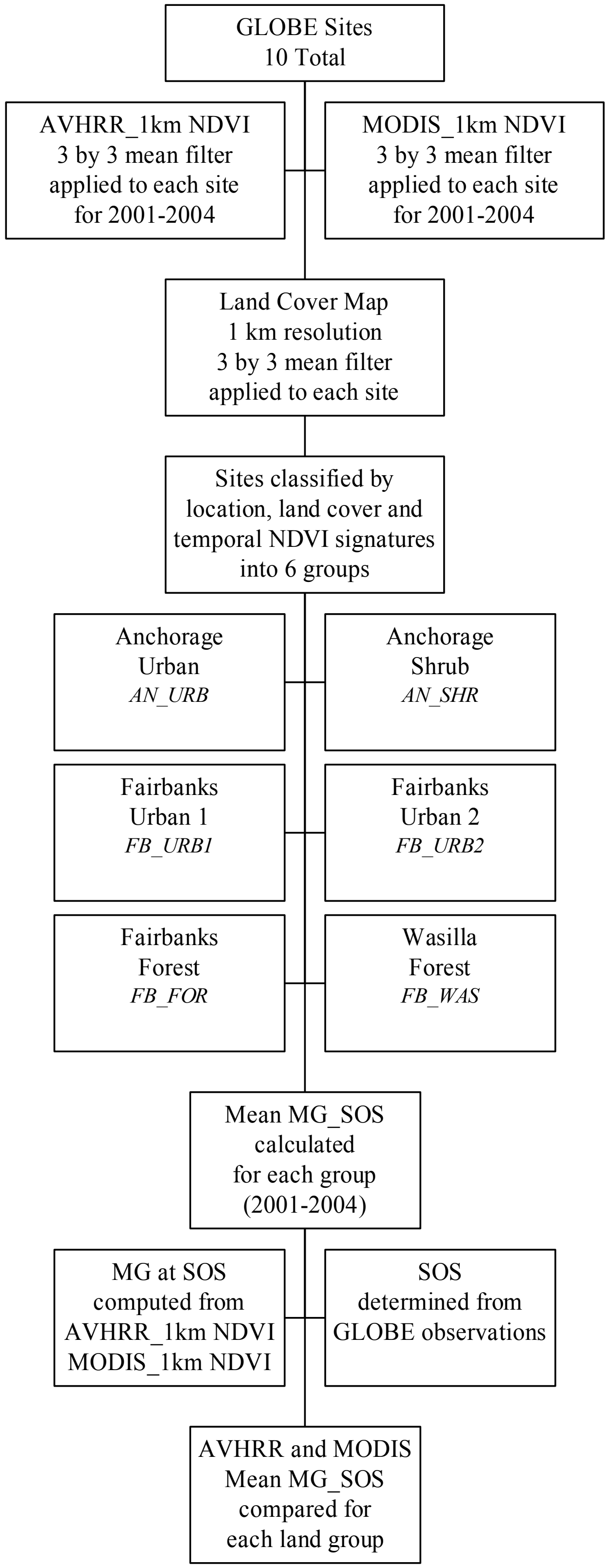

Figure 3-1: Methodology of AVHRR_1km and MODIS_1km NDVI Analysis

AVHRR_8km, AVHRR_1km, MOD_1km, and MOD_250m were used to determine whether NDVI or GDD was a better predictor of SOS for Fairbanks. MOD_250m data were also stitched and re-projected to Albers Equal Area Conic of Alaska to match the AVHRR products. A mean filter (4 by 4 pixels) of each GLOBE site was applied to this dataset for 2001 through 2004 with the same cloud screening process as MOD_1km. NDVI was then calculated from mean values of bands 1 (Red) and bands 2 (NIR).

$$NDVI = (Band\ 2 - Band\ 1)/(Band\ 2 + Band\ 1) \qquad (2)$$

NDVI composite values from 1982 through 2004 were extracted from AVHRR_8km for each GLOBE site. However, some sites were in the same 8-km pixel because of their proximity to one another. Therefore, for the AVHRR_8km dataset GLOBE sites were categorized by location. These groups included Anchorage (AN), Wasilla (WAS), Fairbanks 1 (FB1), and Fairbanks 2 (FB2). Vegetation of Anchorage and Fairbanks 1 groups were a combination of urban, shrub, and forest land covers while Wasilla and Fairbanks 2 groups were a combination of spruce and mixed forest land covers. No filter was applied to this dataset due to its large pixel size.

Annual growing degree days required for SOS were calculated based on prior research by Thoman and Fathauer (1998). They determined for Fairbanks that the best GDD threshold was derived from accumulated maximum temperature greater than 0º Celsius from March 1st through time of observed SOS. They observed hillside green-up in Fairbanks was strongly dependent on elevation and terrain aspect and that GDD calculated from mean temperature did not discriminate between these factors. For this study, GDD were calculated from maximum and mean temperatures because GLOBE Fairbanks' sites were located at a range of elevations. Only mean values were available for soil temperature. To correspond with the appropriate LTER site, Fairbanks GLOBE sites were categorized into upland and floodplain groups based on their elevation and soil classification determined from the county soil survey (Mulligan, 2004) (Table 1).

Annual GDD from March 1st through observed UAF_1 SOS observations were computed for 1976 through 2004 with daily maximum (GGD_Max) and mean (GDD_Mean) air temperatures. Annual GDD were also computed for 1989-2004 with LTER1 (GDD_LTER1) and LTER2 (GDD_LTER2) 10 cm soil temperatures. Results from all four GDD methods were evaluated and validated with UAF_2 and GLOBE SOS observations from 1988 through 1998 and 2001 through 2004, respectively. The best method was chosen as the GDD threshold for SOS (GDD_T).

Annual MG at SOS was computed from AVHRR_8km with Equation 1. SOS was determined from UAF_1 field observations from 1982 through 2004. UAF SOS was defined by "a distinct green coloration in the forest" (Thoman and Fathauer, 1998). A NDVI threshold for SOS (NDVI_T) was computed from the 1982 through 2004 annual values. SOS for 1988 through 1998 and 2001 through 2004 were computed from AVHRR_8km data and were validated with UAF_2 and GLOBE observations. This threshold was then applied to AVHRR and MODIS NDVI datasets and all results were compared to the GDD_T results. Figure 2 diagrams the methodology for computing GDD and NDVI thresholds. Table 2 defines all the acronyms used in this study.

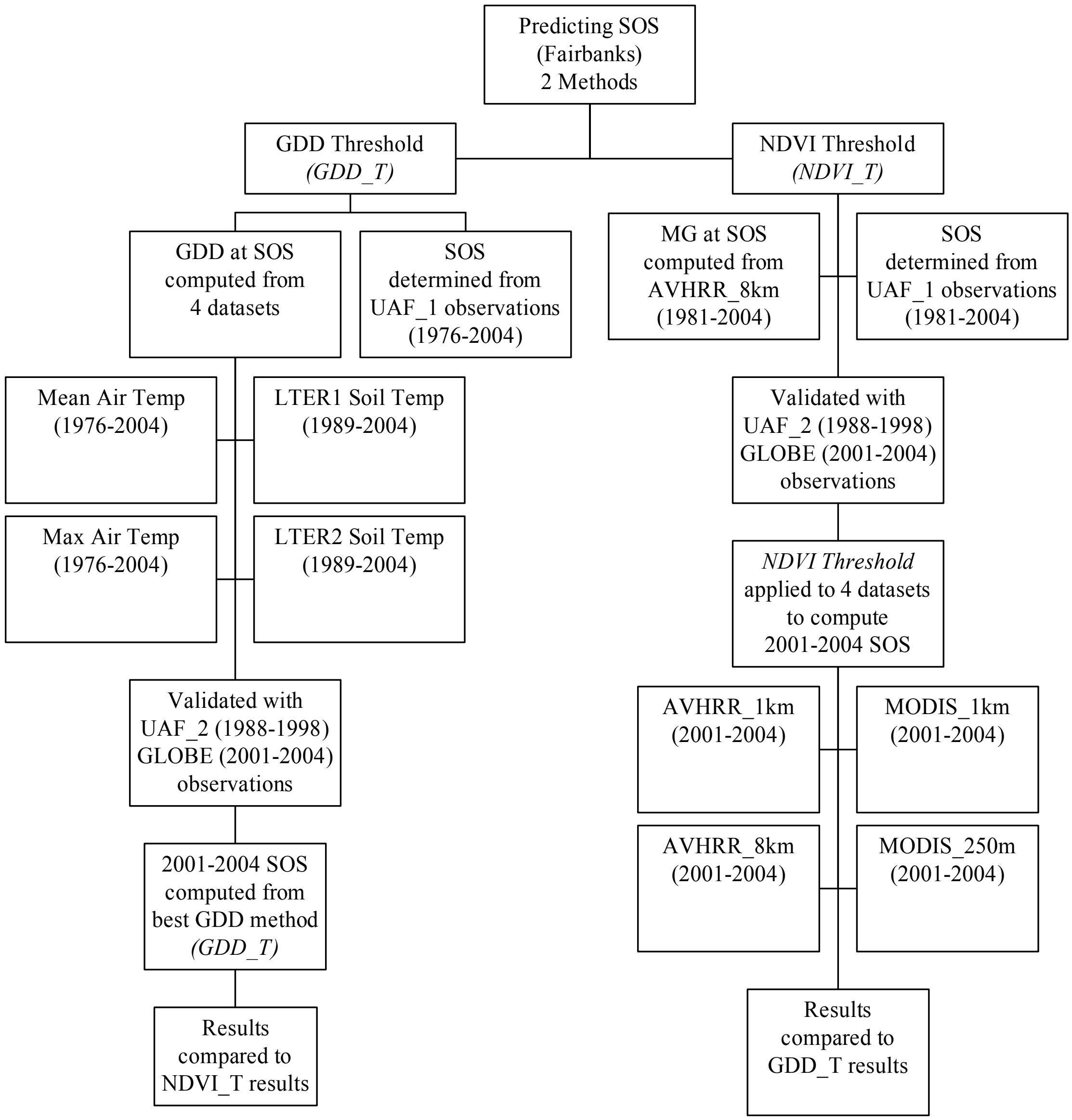

Figure 3-2: Methodology for Computing GDD and NDVI Thresholds

Table 3-2: List of Acronyms

Satellite Acronyms	
AVHRR	Advanced Very High Resolution Radiometer
AVHRR_1km	14 day, 1 kilometer resolution, AVHRR NDVI composites
AVHRR_8km	14 day, 8 kilometer resolution, AVHRR NDVI composites
MODIS	Moderate Resolution Imaging Spectroradiometer
MOD_1km	16 day, 1 kilometer resolution, MODIS NDVI composites
MOD_250m	8 day, 250 meter resolution, MODIS NDVI composites
NDVI	Normalized Difference Vegetation Index
Site Acronyms	
AN	GLOBE phenology sites located in Anchorage
AN_SHR	GLOBE phenology sites located in Anchorage with shrub land cover
AN_URB	GLOBE phenology sites located in Anchorage with urban land cover
FB1	GLOBE phenology sites located in Fairbanks region 1
FB2	GLOBE phenology sites located in Fairbanks region 2
FB_FOR	GLOBE phenology sites located in Fairbanks with forest land cover
FB_URB1	GLOBE phenology sites located in Fairbanks with urban land cover
FB_URB2	GLOBE phenology sites located in Fairbanks with urban land cover less than FB_URB1
GLOBE	All GLOBE phenology sites
LTER1	Long-Term Ecological Research program's weather station; upland site
LTER2	Long-Term Ecological Research program's weather station; floodplain site
UAF_1	University of Alaska Fairbanks phenology dataset 1
UAF_2	University of Alaska Fairbanks phenology dataset 2
WAS	GLOBE phenology sites located in Wasilla
WAS_FOR	GLOBE phenology sites located in Wasilla with forest land cover
Analysis Acronyms	
CV	Coefficient of variation
GDD	Growing degree days
GDD_LTER1	Growing degree days computed with soil temperature from LTER1 weather station
GDD_LTER2	Growing degree days computed with soil temperature from LTER2 weather station
GDD_MAX	Growing degree days computed with maximum air temperature from Fairbanks station
GDD_MEAN	Growing degree days computed with mean air temperature from Fairbanks station
GDD_T	GDD Threshold; Mean growing degree days required for start of season (1976-2004)
MG	Ratio of maximum greenness of temporal NDVI composite
MG_SOS	Mean MG for start of season; computed from AVHRR_1km & MOD_1km (2001-2004)
NDVI_T	NDVI Threshold; MG_SOS computed from AVHRR_8km data (1982-2004)
SD	Standard deviation
1SD	1 Standard deviation (Range)
SOS	Start of season

Results

Overall AVHRR_1km and corresponding MOD_1km NDVI curves showed similar seasonal temporal patterns for all six groups. However, MODIS values were consistently higher (Figs. 3-8). MODIS data also had less inter-annual variability during June through August, the height of the growing season. However, MODIS data did show large inter-annual variability (>0.10) during March-April and October-November at Anchorage and Wasilla sites (Figs. 3-4 and 7). MODIS QA files indicated annual fluctuations in start and end of snow periods at these sites, which would account for this variability. In contrast, there was snow through the third week of April in all four years at Fairbanks sites. This consistency would explain the low mean NDVI values (< 0.1) and low inter-annual variability (<0.05) during early spring at these locations (Figs. 5-6 and 8). However, first fall snow fluctuated in Fairbanks' forest sites (FB_FOR) between mid-October and early November while there was snow in Fairbanks' urban sites (FB_URB1 and FB_URB2) by mid-October in all four years. Correspondingly, during mid-October through mid-November, FB_URB1 and FB_URB2 had low mean NDVI values (<0.1) and inter-annual variability (0.01) while FB_FOR had higher mean NDVI (>0.1) values and inter-annual variability (0.10).

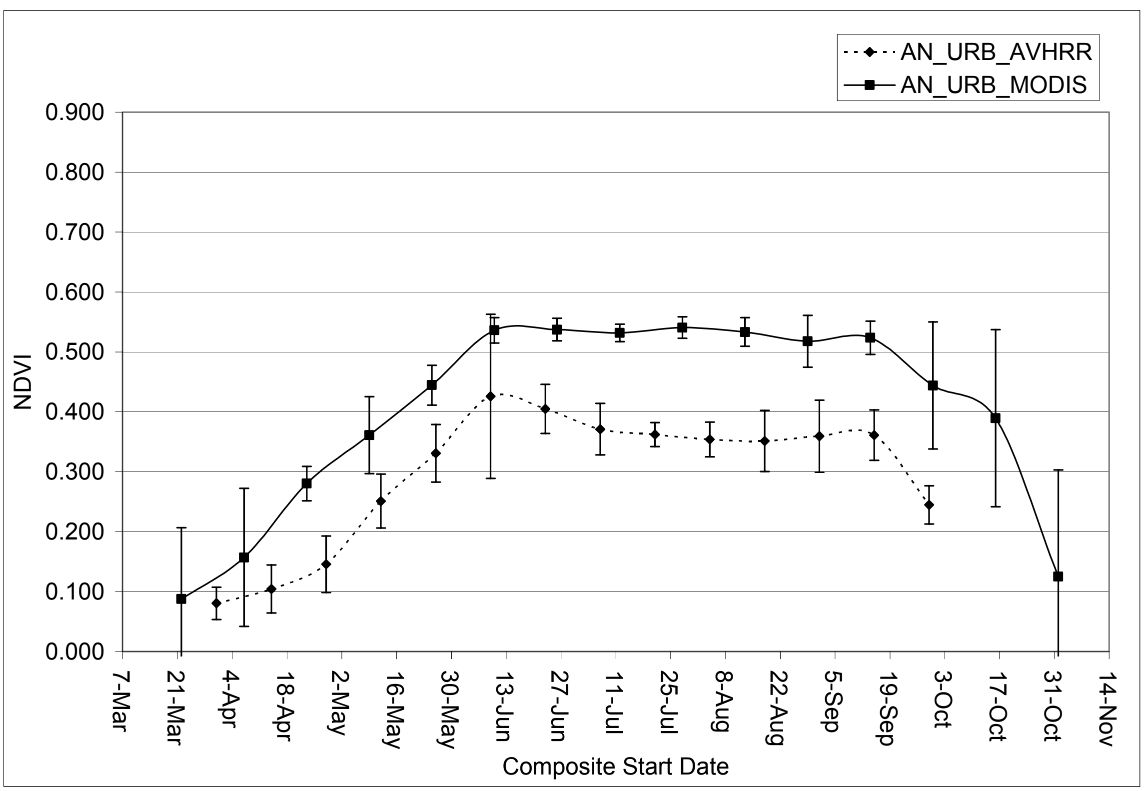

Figure 3-3: 2001-2004 Mean Biweekly AVHRR and MODIS NDVI for Anchorage Urban

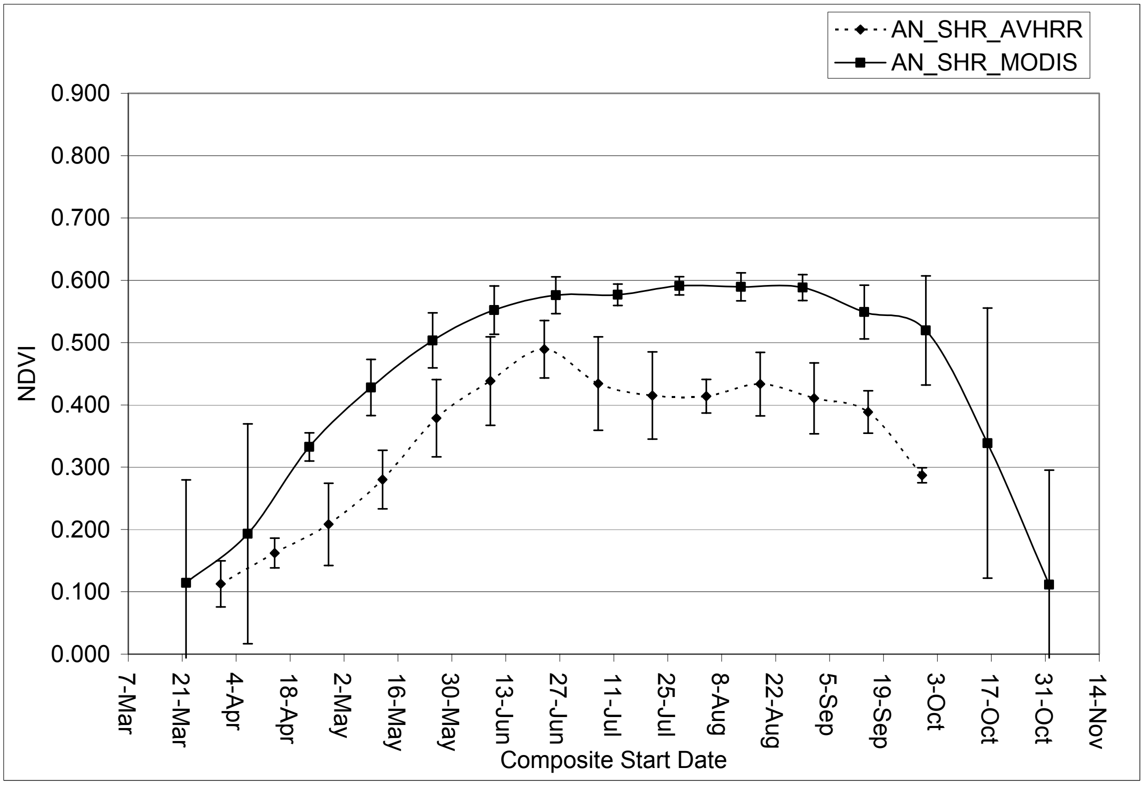

Figure 3-4: 2001-2004 Mean Biweekly AVHRR and MODIS NDVI for Anchorage Shrub

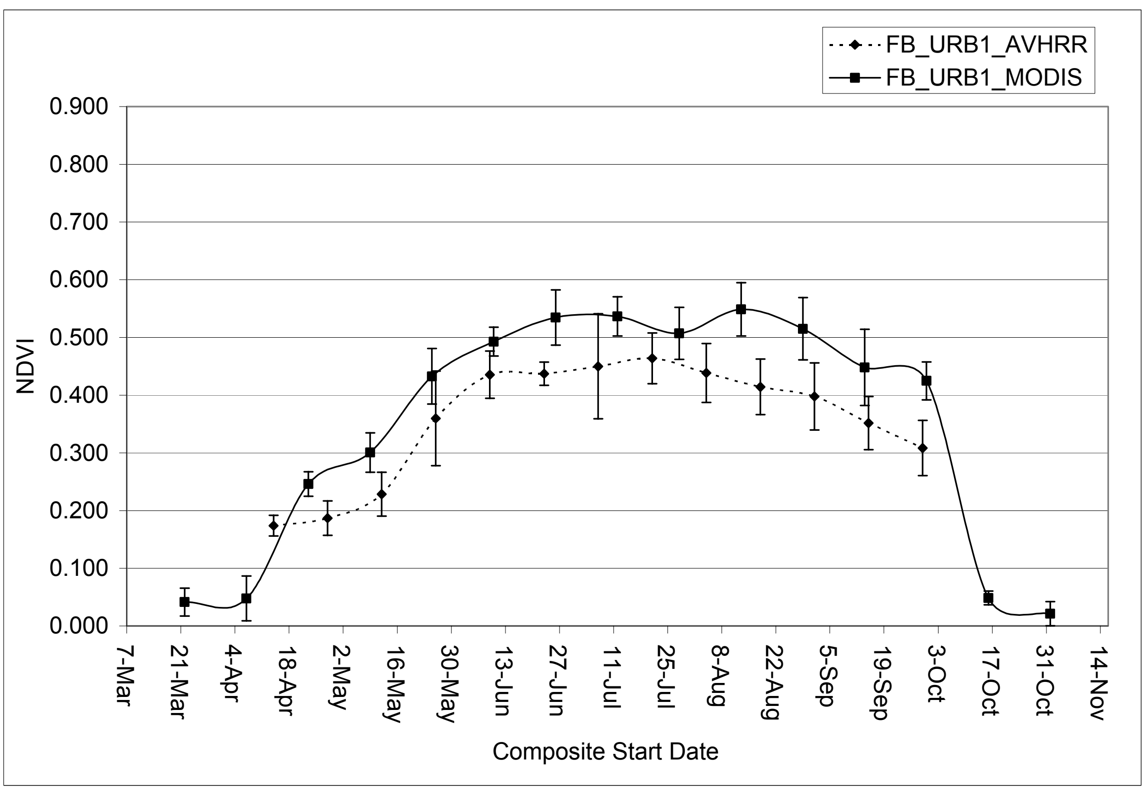

Figure 3-5: 2001-2004 Mean Biweekly AVHRR and MODIS NDVI for Fairbanks Urban 1

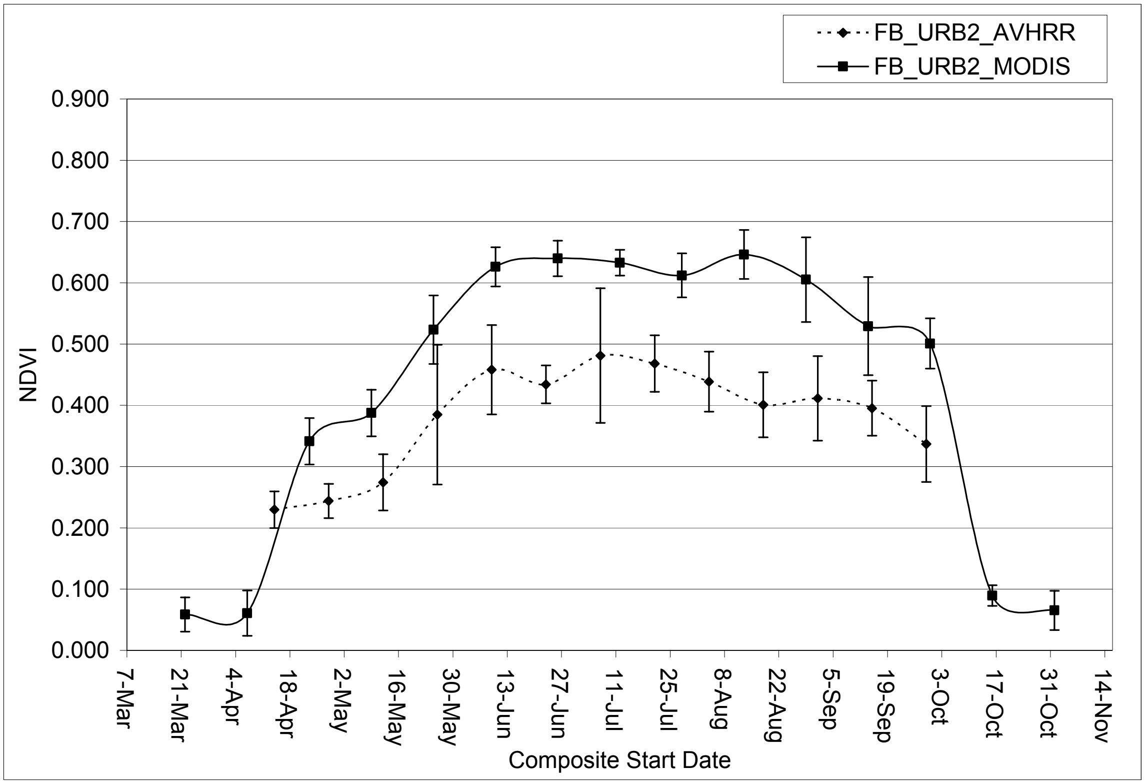

Figure 3-6: 2001-2004 Mean Biweekly AVHRR and MODIS NDVI for Fairbanks Urban 2

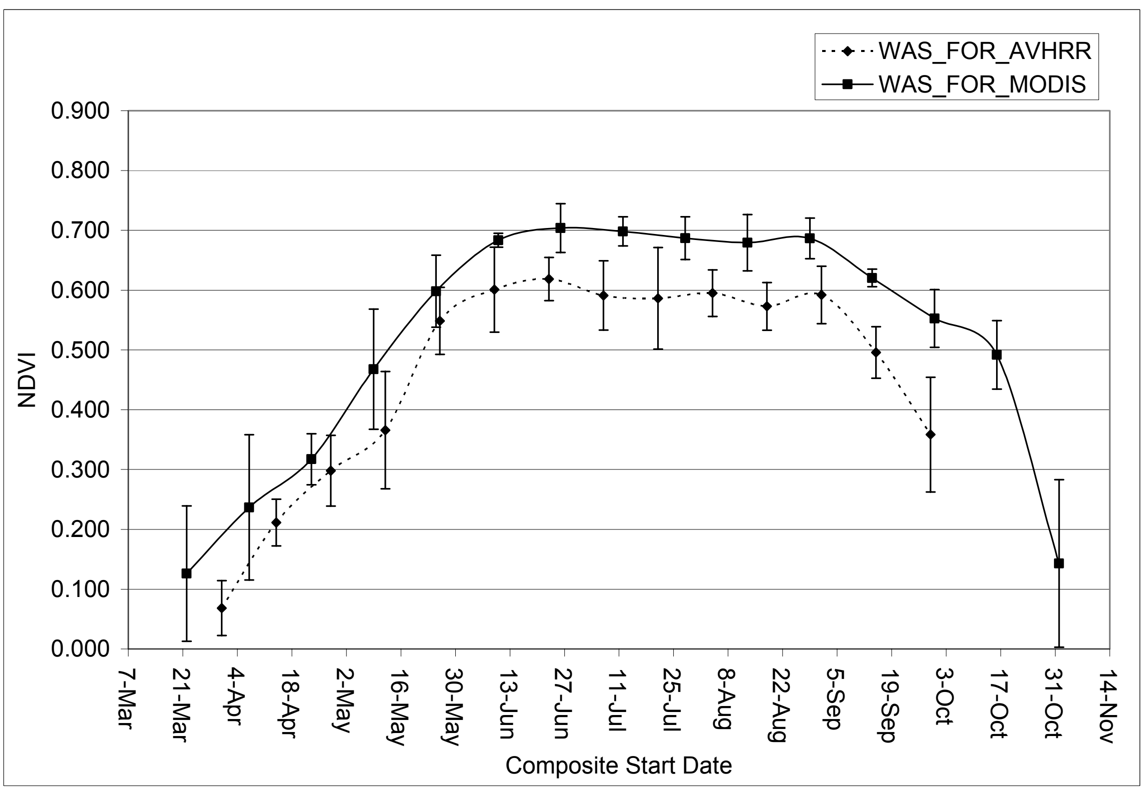

Figure 3-7: 2001-2004 Mean Biweekly AVHRR and MODIS NDVI for Wasilla Forest

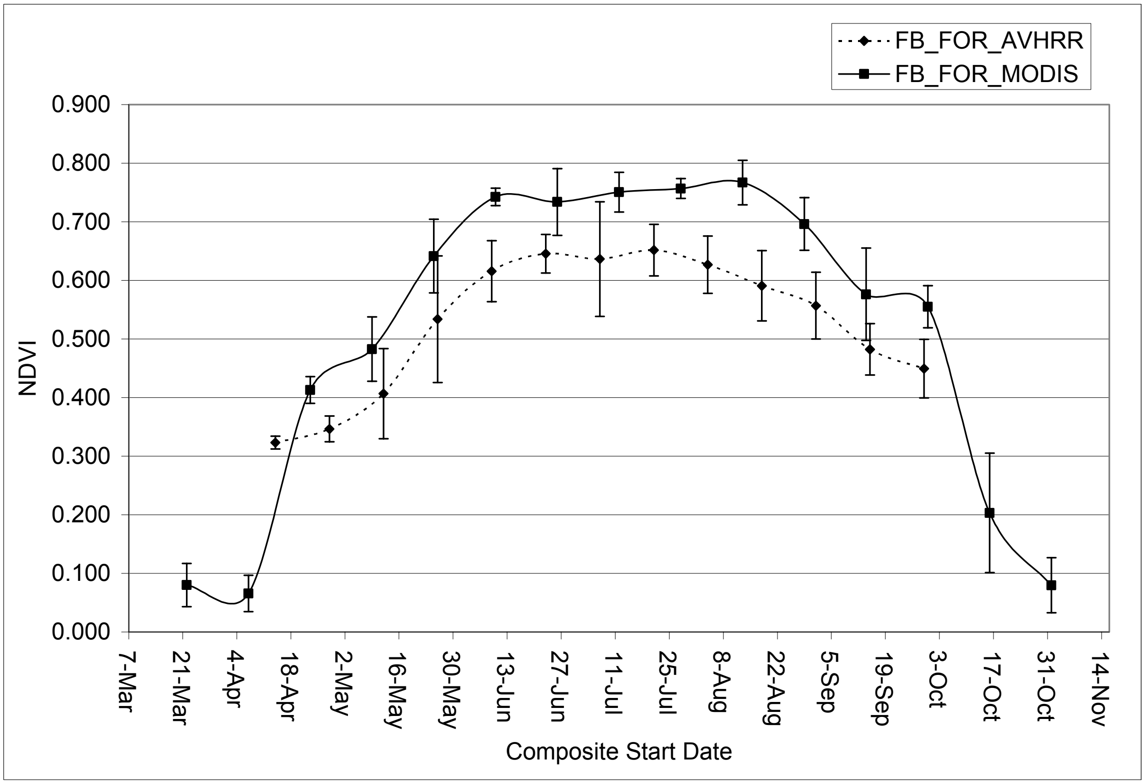

Figure 3-8: 2001-2004 Mean Biweekly AVHRR and MODIS NDVI for Fairbanks Forest

Table 3 shows mean ratio of maximum greenness at SOS (MG_SOS) for each group. Mean, standard deviation (SD), range of one standard deviation (Range), and coefficient of variation (CV) were computed for AVHRR_1km and MOD_1km NDVI datasets. Overall, MOD_1km had a higher MG_SOS with less inter-annual variation than AVHRR_1km. For MOD_1km, MG_SOS ranged from 43 to 56 percent with inter-annual variation from 5 to 9 percent. There was no relationship between MG_SOS and vegetation type or site location. For AVHRR_1km, MG_SOS ranged from 19 to 34 percent with inter-annual variation from 12 to 23 percent. There was also no relationship between MG_SOS and vegetation type, but there was a relationship between MG_SOS and site location. Groups in Fairbanks had lower MG_SOS than groups in Anchorage.

Table 3-3: Ratio of Maximum Greenness at SOS (MG_SOS) for 2001 - 2004

	Anchorage Urban		Fairbanks Urban 1		Fairbanks Urban 2	
MG_SOS	AVHRR	MODIS	AVHRR	MODIS	AVHRR	MODIS
Mean	26%	48%	19%	46%	20%	54%
SD	12%	6%	18%	5%	19%	7%
Range	14-38%	42-54%	1-37%	41-51%	1-39%	47-51%
CV	45.5%	12.4%	95.2%	11.5%	97.7%	12.2%
	Anchorage Shrub		Wasilla Forest		Fairbanks Forest	
MG_SOS	AVHRR	MODIS	AVHRR	MODIS	AVHRR	MODIS
Mean	25%	56%	34%	43%	21%	55%
SD	22%	7%	19%	9%	23%	8%
Range	3-47%	49-63%	15-53%	34-52%	0-44%	47-63%
CV	85.5%	13.3%	56.1%	20.4%	108.3%	14.1%

MOD_1km's higher, and wider range of, NDVI values account for its higher MG_SOS (Equation 1). In contrast, for Fairbanks, AVHRR_1km had lower, and a smaller range of, NDVI values which in turn explain its lower MG_SOS. The smaller range in Fairbanks' AVHRR NDVI values resulted from cloud contamination of the March 31st to April 13th composites. Subsequently these composites could not be used and annual minimum AVHRR NDVI values in Fairbanks were higher than in Anchorage because there was a later annual start in the temporal time series data. MOD_1km composites for Fairbanks did not have this issue, most likely due to improved cloud screening techniques.

MOD_1km SOS values at maximum greenness corresponded with White et al. (1997) values with AVHRR NDVI. They found for the continental United States the most rapid change in greenness of AVHRR NDVI occurred at 50 percent, which they used as their SOS threshold. However, Goldman (2000) obtained best results across Alaska with an AVHRR SOS threshold of 30 to 40 percent of maximum greenness.

Results from field observations showed GLOBE SOS dates between Anchorage and Fairbanks regions were within five days or less of one another in all years but 2001 (Table 4). Annual mean budburst was computed from all schools' observations within each region. Wasilla sites were combined with Anchorage sites because of their proximity. In 2001, there was a 15-day difference in budburst dates between the two regions but that year only one school in the Anchorage region made observations. Within each region, *Betula, Populus,* and *Salix* budburst occurred within a three-day period. Linkosalo (1999) also found a similar uniformity of phenological events between different species in Finnish forests. However, in 2003 *Betula* budburst occurred nine days earlier than *Populus* and *Salix* in the Anchorage sites and seven days later than the other two tree types in the Fairbanks sites.

Table 3-4: Observed SOS at GLOBE Sites

Year	GLOBE Fairbanks				GLOBE Anchorage			
	Betu	*Popu*	*Salix*	Mean	*Betu*	*Popu*	*Salix*	Mean
2001	5/15	5/17	5/18	5/17	5/4	4/30	---	5/2
2002	5/14	5/15	5/16	5/15	5/15	5/16	5/17	5/16
2003	5/5	4/28	4/28	4/30	4/30	5/8	5/9	5/5
2004	5/1	5/4	5/4	5/3	5/2	5/4	5/4	5/3

Overall, GLOBE_Fairbanks and UAF_2 SOS observations corresponded with UAF_1 SOS observations (Fig. 9). UAF_2 dates were later than UAF_1 dates by four days or less in 9 of the 11 years and in the other two years SOS dates were the same. GLOBE_Fairbanks SOS observations were earlier by three days or less than UAF_1 SOS observations in 2001, 2002, and 2004. In 2003, GLOBE_Fairbanks observations were six days earlier than the UAF_1 observation. The majority of GLOBE_Fairbanks sites were located in the valley and this most likely accounted for their earlier SOS dates.

Thoman and Fauther (1998) found for Fairbanks green-up began on lower elevations of south facing hillsides, spreading quickly down valley floors, and moving more slowly up higher elevation hillsides. The UAF_1 and UAF_2 sites were located on the Chena Hillside near the UAF campus. Nonetheless, both GLOBE_Fairbanks and UAF_1 datasets showed SOS occurred significantly earlier (>= 12 days) in 2003 and 2004 than 2001 and 2002.

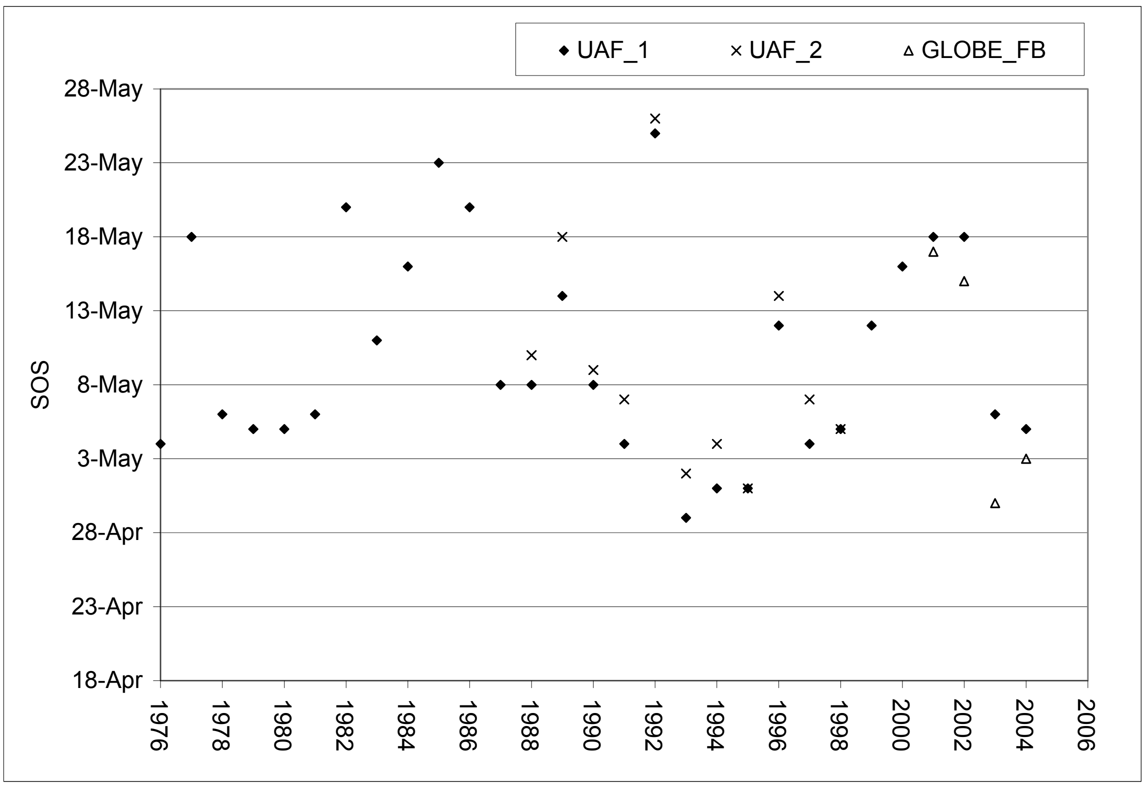

Figure 3-9: Observed Greenup and Budburst Dates for Fairbanks (1976 – 2004)

Accumulated growing degree days through UAF_1 SOS observations were computed with maximum (GDD_Max) and mean (GDD_Mean) air temperature and 10 cm soil temperature (GDD_LTER1 and GDD_LTER2). Table 5 shows mean GDD, standard deviation, range (1SD), and coefficient of variation for each dataset. GDD_Max and GDD_Mean resulted in the lowest coefficient of variations. Table 6 shows actual and computed SOS for Fairbanks from GDD_Max and GDD_Mean range thresholds. GDD_LTER1 and GDD_LTER2 were not used to predict SOS because of their high standard deviations and coefficients of variations.

Table 3-5: Growing Degree Days (GDD) from March 1st to UAF_1 SOS

	Growing Degree Day (>0˚C)			
	Air Temperature (1976-2004)		Soil Temperature (10cm) (1989-2004)	
March 1st to SOS	GDD_Max	GDD_Mean	GDD_LTER1	GDD_LTER2
Mean	391	153	28.3	24.1
SD	45	22	23.6	21.2
Range	354 - 444	131 - 175	4.7 – 51.9	2.9 – 45.3
CV	11.5%	14.4%	83.4%	88.0%

Table 3-6: Actual and Predicted SOS from GDD for Fairbanks

	Actual SOS		Predicted SOS from GDD	
Year	UAF_2	GLOBE	Max Air Temp	Mean Air Temp
1988	5/10		5/4 – 5/10	5/2 – 5/7
1989	5/18		5/6 – 5/15	5/3 – 5/11
1990	5/9		4/28 – 5/6	5/3 – 5/8
1991	5/7		5/4 – 5/10	5/5 – 5/9
1992	5/26		5/21 – 5/25	5/24 – 5/27
1993	5/2		4/24 – 4/30	4/27 – 5/2
1994	5/4		4/30 – 5/6	4/30 – 5/6
1995	5/1		4/28 – 5/2	4/29 – 5/3
1996	5/14		5/5 – 5/10	5/9 – 5/13
1997	5/7		5/3 – 5/9	5/2 – 5/8
1998	5/5		4/23 – 5/4	5/4 – 5/10
2001		5/17	5/16 – 5/21	5/16 – 5/20
2002		5/15	5/19 – 5/23	5/18 – 5/20
2003		4/30	5/7 – 5/14	5/4 – 5/10
2004		5/3	5/4 – 5/12	5/3 – 5/10

Contrary to Thoman and Fauther's (1998) results, daily mean temperature was a better overall predictor of SOS for Fairbanks (Fig. 10). For UAF_2, GDD_Mean predicted SOS within one standard deviation in 7 out of 11 years. Predictions were earlier by three days or less (1<SD<2) in three of the other years with one year (1989) the prediction was seven days earlier (> 2SD). GDD_Max predicted SOS within one standard deviation in 5 out of the 11 years. Predictions were earlier by four days or less (~ 2SD) in the other six years. The GDD_Mean predictions also corresponded more accurately with the GLOBE_Fairbanks observations. As a result, GDD_Mean was selected as the growing degree day threshold for SOS (GDD_T).

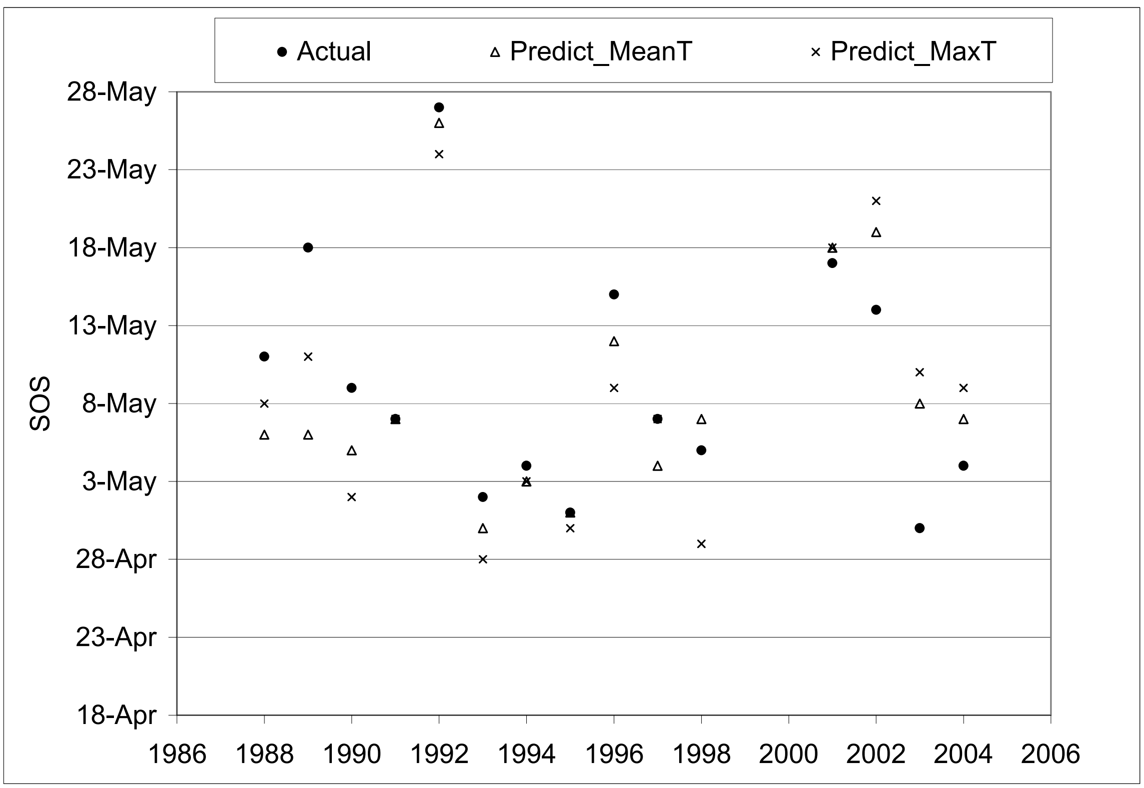

Figure 3-10: Predicted SOS for Fairbanks from GDD for 1988 – 1998 and 2001 – 2004

The NDVI threshold (NDVI_T) was computed from AVHRR_8km and UAF_1 SOS observations. Two thresholds were computed, one for Fairbanks's urban sites (FB1) and one for Fairbanks' forest sites (FB2). Only UAF_1 observations from 1982 through

2004 were used as AVHRR_8km data were not available prior to 1982. Computed SOS dates were validated with UAF_2 SOS and GLOBE observations for 1988 through 1998 and 2001 through 2004, respectively. Computed MG_SOS were similar for both groups at 46 and 47 percent for FB1 and FB2, respectively. This threshold, NDVI_T, was then applied to the MODIS_1km and MODIS_250m to predict SOS for 1988-1998 and 2001-2004 with these two datasets. AVHRR_1km was not used because of its poor performance in the first part of the study (Table 3).

Of the three NDVI datasets, AVHRR_8km most accurately predicted SOS with NDVI_T (Table 7). It predicted SOS in 2003 and 2004. In 2001, actual SOS was one day prior to the predicted SOS period. MOD_1km accurately predicted SOS in 2003 and 2004. In 2001 and 2002 it predicted SOS one week early. MOD_250m predicted SOS one to two weeks early in all four years. However, using the range threshold (1SD of NDVI_T), rather than NDVI_T, MOD_250m accurately predicted SOS in 2002, 2003, and 2004. In 2001, actual SOS was one day prior to the predicted SOS period. The range threshold lengthened the MOD_250m prediction period to 16 days, similar to the length of the other two datasets. These results suggest that the number of days in the composite period rather than the actual NDVI threshold determined prediction accuracy. The longer the composite period the more likely the NDVI threshold method accurately predicted SOS.

Table 3-7: Actual and Predicted SOS from NDVI for Fairbanks

Year	Actual SOS	MODIS_250m Predicted SOS		MODIS_1km Predicted SOS		AVHRR_8km Predicted SOS	
		NDVI_T	Range (1SD)	NDVI_T	Range (1SD)	NDVI_T	Range (1SD)
2001	5/17	4/23-4/30	4/15-5/16	4/23-5/8	4/23-5/24	5/16-5/31	5/1-5/31
2002	5/15	5/1-5/8	5/1-5/16	4/23-5/8	4/23-5/8	4/16-4/30	4/16-5/15
2003	4/30	4/15-4/22	4/15-5/8	4/23-5/8	4/23-5/8	5/1-5/15	4/16-5/15
2004	5/3	4/15-4/22	4/15-5/8	4/23-5/8	4/23-5/8	5/1-5/15	5/1-5/15

Figure 11 shows actual and predicted SOS for Fairbanks from both GDD and NDVI thresholds for 1988 through 1998 and 2001 through 2004. Mean temperatures were used to compute the GDD threshold and AVHRR_8km data were used to compute the NDVI threshold. Computed SOS dates were compared with UAF_2 and GLOBE observations for 1988 to 1998 and 2001 to 2004, respectively. In order to compare methodologies, the middle date of the predicted composite period was chosen to represent SOS for the NDVI method. Overall, GDD was a better predictor of SOS than NDVI for Fairbanks. GDD captured the inter-annual variability of SOS and most closely resembled the actual SOS observations.

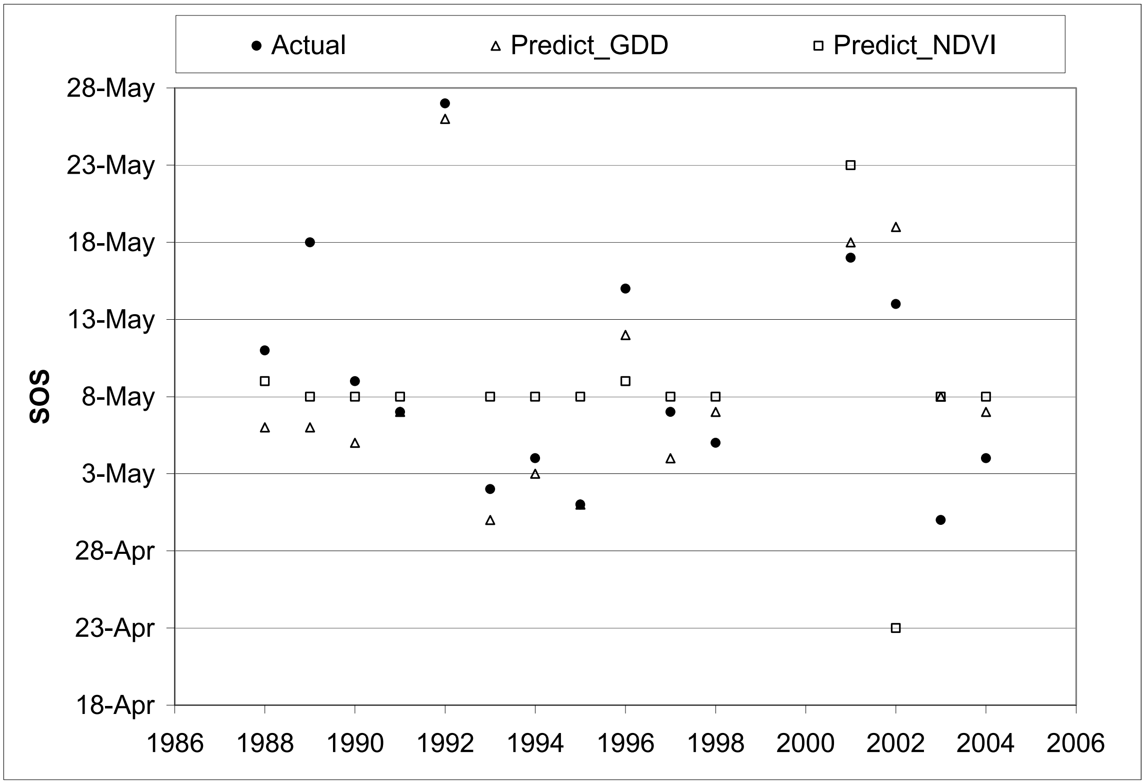

Figure 3-11: Actual and Predicted SOS for Fairbanks for 1988 - 1998 and 2001 - 2004

Discussion

Huete et al. (2002) and Brown et al. (2006) showed similar findings to this work when comparing AVHRR and MODIS NDVI time series data. Brown et al. attributed MODIS' higher NDVI values to the sensors' different processing and spectral characteristics. In addition to the greater sensitivity of MODIS' red and NIR bands, these differences also restricted impacts from clouds, aerosols, and water vapor. Huete et al. (2002) attributed sensor differences to these same factors in addition to MODIS' improved compositing method (CV-MVC). They compared 1-km MODIS NDVI biweekly composites with corresponding AVHRR NDVI biweekly composites across various North American sites for the 2000 – 2001 season. Brown et al. (2006) compared

500-m MODIS NDVI biweekly composites with 8-km AVHRR GIMMS NDVI biweekly composites for 2000 through 2004 across various sites throughout the world.

The AVHRR water vapor effects did not apply for this study because a validated water vapor correction was applied to all, past and subsequent, 1-km AVHRR time series data as of 2001 (DeFlice et al., 2003). Nonetheless, aerosol and compositing factors did apply for this study. AVHRR NDVI data were composited with 14-day maximum values whereas MODIS data were composited with 16-day constrained view angle maximum values. CV-MVC reduces spatial and temporal discontinuities that result from maximum value compositing (Goward et al., 1991; Huete et al., 2002). Furthermore, aerosols significantly impact NDVI values and their effects remain in data even after one-month compositing periods (Vermote et al. 2002). There was a two-fold increase in annual biomass burning, a significant source of aerosols, during 1960 through 1990 in the North American boreal region (Stocks et al., 2000; Andreae and Merlet, 2001; Lavoue et al., 2000). Moreover, boreal fire emissions in the high Northern Hemisphere were higher during 2000 and 2003 than the early to mid-1990s (Kasischke et al., 2005). Kasischke et al.'s (2005) findings are especially relevant given that 1-km AVHRR data from 2001 through 2004 were used in this study.

In addition to higher values, MOD_1km NDVI provided a more stable SOS threshold than AVHRR_1km NDVI. Field observations made by GLOBE students indicated similar SOS dates between both regions for 2001 through 2004 (Table 4). Correspondingly, MOD_1km showed similar MG_SOS thresholds between Anchorage and Fairbanks regions and there were little inter-annual variability within the threshold values (Table 3). In comparison, MG_SOS computed from AVHRR_1km were lower for

Fairbanks than Anchorage and there were more inter-annual variability in AVHRR threshold values. As discussed above, Fairbanks' lower MG_SOS resulted from the smaller annual range in AVHRR_1km NDVI values. More importantly, variations were so high with the AVHRR data it was not possible to establish a stable maximum greenness threshold for SOS.

While MODIS provided a more stable threshold, it was not a good predictor of SOS (Table 7). In all four years, MOD_1km showed SOS occurred in the same composite period (4/23-5/8). Yet, field observations showed annual variations of two weeks or more that should have been detected by the 16-day composite period. While the 8-day composite period did show annual variations, MOD_250m was such a poor predictor of SOS it was difficult to ascertain what exactly was being detected.

These results indicate there are definite limitations to using AVHRR and MODIS NDVI to monitor SOS in Alaska. First, developing a threshold for detecting SOS that is transferable between AVHRR and MODIS is difficult. Ideally, the threshold should be developed with AVHRR NDVI then applied on MODIS NDVI. AVHRR NDVI has a significantly longer time series, which strengthens the threshold validation process. MODIS NDVI has enhanced processing and spectral characteristics, which make it more suitable for detecting small changes in SOS. However, the first part of the study showed that AVHRR_1km NDVI could not produce a stable SOS threshold for Alaska, most likely because cloud free composites were only available mid-April through mid-October. The second part of the study showed that AVHRR_8km NDVI could produce a stable threshold for identifying SOS, but it was not transferable to MODIS products.

Second, detecting SOS from NDVI is further limited by late spring snow and evergreen vegetation. MODIS QA files indicated there was snow through the third week of April in all four years at Fairbanks sites. Correspondingly, the most rapid increase in MOD_1km NDVI occurred during the April 23 – May 8 composite period (Figs 5-6, 8). AVHRR_1km did not show this increase as composites were not available prior to mid-April. MOD_1km predicted SOS occurred during April 23 – May 8 composite period in all four years (Table 7). Yet, GLOBE and UAF_1 field observations showed SOS differed by more than two weeks during the four-year period. In 2001 and 2002, SOS occurred in mid-May and in 2003 and 2004 occurred in early May (Fig. 9). Therefore, in at least two of the years, and perhaps all four, the sharp increase in NDVI during end of April and beginning of May resulted from a change in snow conditions rather than the annual SOS signal. Delbart et al. (2005, 2006) also found that snow restricted the efficacy of monitoring SOS with NDVI in Siberia. They showed that the normalized difference water index (NDWI), similar to NDVI but calculated from the short-wave infrared band instead of the red band, differentiated between snowmelt and green up and was more efficient at estimating SOS. However, this method had limitations in forests dominated by evergreens, which these sites had (Table 1).

Third, effects of clouds, and subsequently composite length, also limit NDVI as a monitoring tool for SOS in Alaska. Compositing, while necessary for mitigating cloud effects, restricts the sensitivity of NDVI to detect phenological changes. Furthermore, Kasischke and French (1999) found that clouds and atmospheric haze had significant effects on the AVHRR NDVI signature for boreal forests in Alaska even after compositing procedures were applied to the NDVI data. The advancement of SOS that has been repeatedly observed and documented across Europe and United States has averaged two days per decade (Menzel and Fabian, 1999; Menzel, 2000; Schwartz and Reiter, 2000; Chmielewski and Rozter, 2001). Therefore, short (< 7 days) composite periods are required to detect such changes. However, weekly AVHRRR and MODIS composites could not be used because of high cloud levels.

These factors indicate that biweekly NDVI composites are too long to monitor phenological changes. Results from this study showed that for Fairbanks a threshold of 131 to 175 GDD, computed from daily mean temperature above 0º Celsius and accumulated annually from March 1st, was a more sensitive and better predictor of SOS than a NDVI threshold (Fig 11). Accumulated growing degree days captured the inter-annual variability of SOS better than the NDVI threshold and most closely resembled actual SOS observations.

Conclusions

The results from this study, coupled with the well documented advancement of SOS in the literature, indicate a more sensitive predictor than NDVI is needed to monitor changes in start of growing season. NDVI, while useful for its spatial coverage, has limitations in boreal regions due to clouds, snow, and the large extent of conifers. Furthermore, cloudy conditions found in these regions prohibit use of a composite period shorter than 14 days and a biweekly composite period has limited capabilities for detecting gradual changes in SOS. In addition, differing processing and spectral characteristics restrict continuity between AVHRR and MODIS NDVI datasets. This study showed a NDVI threshold for detecting SOS was not transferable between sensors. In conclusion, a GDD threshold developed from 20+ years of historic daily mean air temperature and annual field phenology observations was a better predictor of SOS than a NDVI threshold developed from AVHRR time series data from the same time period.

Chapter 4: The GLOBE Program

Background

GLOBE is an international partnership network of K-12 students, teachers, and scientists working together to study and understand the global environment. The program, which began in 1994, is a cooperative effort, led by University Corporation of Atmospheric Research (UCAR) and Colorado State University, and funded in the United States by a federal interagency program including the National Aeronautics and Space Administration (NASA) and National Science Foundation (NSF). The objectives of the program are to 1) improve science education and understanding of Earth as a system; (2) increase environmental awareness; and (3) provide scientific contributions in Earth system research through collaborations between educational and scientific communities (NGG, 2005).

In the U.S., the GLOBE program enters into partnership agreements with local and state organizations and these individual partners are responsible for the recruiting, training, and mentoring of the schools in their regions. Internationally, the program is implemented through bilateral agreements between the U.S. government and governments of partner nations. Over 32,000 GLOBE-trained teachers from 17,000 schools have contributed 14 million measurements to GLOBE. This has been made possible through the efforts of 109 participating countries and 123 U.S. Partners.

Over the first 10 years of the GLOBE program, 15 principal investigators (PIs) received funding through NSF for a variety of activities. During this period, these scientists developed a series of GLOBE protocols for K-12 students. These protocols included measurements and observations in atmosphere, hydrology, land cover, phenology, and soils. Once trained, teachers used these GLOBE protocols and corresponding learning activities to help students improve their science and math skills (Becker et al., 1997; Haskett et al., 1997; Levine, 1998; Brooks and Mims, 2001; Aquino and Levine, 2003).

Students in turn made scientifically valid measurements at or near their schools and reported their data through the Internet to the GLOBE data archive for (www.globe.gov) scientists to use in their research. In addition, students were encouraged to develop their own research projects and collaborate with scientists and other GLOBE students. Many of GLOBE data collection efforts to date have been in support of satellite data and algorithm evaluation as connections between GLOBE and NASA satellite missions have been an integral part of the program's scientific activities (NGG, 2005). Nevertheless, the GLOBE data archive has remained largely untapped for scientific purposes. During the first ten years of the program there have been only two publications in refereed scientific journals utilizing GLOBE data (White et al., 2000; Verbyla, 2001).

Program Growth

Each year GLOBE undergoes an external evaluation of its program from SRI International, a nonprofit scientific research institute. These annual evaluations track the overall growth and progress of the program. Statistics are provided on the number of teachers trained, trends in GLOBE data reporting, and number of schools on the GLOBE Honor Roll. The honor roll is bimonthly and recognizes schools with exceptional data reporting skills on the GLOBE web site (www.globe.gov).

Domestically, 1000 to 3000 new teachers have been trained each year since the program's inception and internationally, 500 to 1000 new teachers (Penuel et al., 2005). Domestic training peaked in 1999-2000 and has decreased annually since then although the past two years it has remained stable at approximately 2000 teachers per year. This overall decline has been attributed to lack of previously available funding for training as well as partners providing support to already trained teachers rather than training new ones (Penuel et al., 2004). Internationally, 2003-2004 was the lowest year, which had 609 newly trained teachers, since 1997-1998, which had 499.

The overall trend in data reporting shows a rise in August and September that coincides with the start of the school year in the Northern Hemisphere and remains fairly constant throughout the school year. Data reporting declines sharply in May as schools close with little if any data reporting during the summer months. In recent years, reporting has decreased earlier in the spring. This change is most likely a result of increased time spent by U.S. schools on year-end standardized test preparations (Penuel et al., 2005). Furthermore, there has been a decline in the number of schools reporting data from 1848, 1893, and 1623 in 2001-2002, 2002-2003, and 2003-2004, respectively. Additionally, there is a higher attrition rate among first-year reporting schools, but there is a more steady commitment from schools that report for multiple years (Penuel et al., 2005).

GLOBE students are encouraged to participate fully in the program through incentives such as the GLOBE "Honor Role". To make the honor roll, schools must fulfill specific requirements for scientists to make use of the students' data in their research. For example, atmosphere honor role requires maximum and minimum air temperatures reporting for more than 70% of the days in a four-month period along with precipitation (liquid or solid) reporting for more than 95% of the days during the same time period. There are no limitations to the number of schools that can make the honor roll or the number of times an individual school can be on the honor roll. Schools can make honor roll for specific protocols (e.g. cloud observations), several protocols within an investigation area (e.g. atmosphere, hydrology), or several protocols from various investigation areas (e.g. climate, Earth system science). To make the climate honor roll schools must report a certain number of measurements from at least three of the five investigation areas (atmosphere, hydrology, land cover, phenology, and soils) over a one-year period. Conversely, the Earth System honor roll requires a specific combination of measurements (e.g. budburst, air temperature, and precipitation) of a given quantity over a four-month period.

Since the program began, atmosphere, followed by the hydrology, have been the investigation areas with the highest levels of reporting. Air temperature, cloud observations, rainfall, and snowfall are the most common protocols reported in the atmosphere investigation. Water temperature, water pH, and transparency are the most common protocols reported in the hydrology investigation. For the past three years, the cloud observations (200-225 schools/year), atmosphere (125-130 schools/year), hydrology (100-125 schools/year), and climate (70-95 schools/year) honor roles have had the most schools (Penuel et al., 2005). Soils and land cover honor rolls had less than 10 schools per year and Earth system science honor roll had 15 to 18 schools per year during the past three years.

Lessons Learned from Utilizing GLOBE Data

(1) Research Project 1

One of the objectives of my dissertation research was to determine if GLOBE measurements could support satellite data, specifically NDVI. My first research project utilized a suite of GLOBE measurements from three investigation areas: atmosphere, land cover, and soils, to determine whether NDVI could accurately predict transpiration periods for a Northern temperate climate. Students' measurements were used to initialize and validate the GAPS model, and model outputs were compared to corresponding temporal NDVI time series data derived from SPOT 4 Vegetation. The original intent behind this research was to duplicate this methodology at different GLOBE sites. In the end, only Reynolds Junior and Senior High School, in Greenville, Pennsylvania, had the required datasets and sufficient quantity of data to run multiple years of simulations.

Initially, I surveyed the GLOBE data archive and contacted those schools that had some of the required datasets to see if they would be interested in making the additional measurements needed to run the model. Several new GLOBE schools also expressed an interest and were invited to participate in this research as well. There were 20 schools total from various states in the U.S., including Puerto Rico, as well as Australia, Germany, Ghana, Greece, Mexico, and Thailand. Most were K-12 schools although there was one after school program, one junior college, and four universities.

Various logistical and biophysical factors prevented the duplication of the Reynolds study to these other GLOBE sites. Several sites when contacted were no longer active in GLOBE, often because the main GLOBE teacher had left the school. Those schools, along with several of the newer schools, were initially interested, but could not make all the necessary measurements or did not have the financial resources to purchase the needed equipment to make them. In comparison to my second research project, this study required multiple measurements from different investigation areas.

Furthermore, daily measurements were required throughout the year including the summer months.

Financially, the soil moisture sensors and corresponding meter reader were the most expensive pieces of equipment required for this study. Those measurements were especially important as those validated the GAPS simulation outputs. This equipment, along with soil temperature sensors and a data logger, were given to eight schools. I assisted with the installation of the sensors and the meter calibration at three GLOBE sites, two in Thailand and one in North Carolina. I also assisted these schools with their sites' soil characterization and took additional soil measurements, both required for parameterization of GAPS. Of the five remaining schools, three installed their sensors on their own and two did not. Two of those that did were universities, one in Montana and one in Puerto Rico, and one was a junior college in Montana.

Soil moisture measurements were made at all six locations although schools had difficulty completely the calibration of the soil moisture sensors. In Thailand, students were actively involved in making the measurements, calibrating the meters, and inputting the data on the GLOBE site. However, the teachers managed the Montana, North Carolina, and Puerto Rico sites and little of that data was ever reported. Overall, the amount of time required to maintain this instrumentation, coupled with the other measurements required for the model (daily air temperature and precipitation, soil characterization), was excessive. Ultimately the time factor restricted schools from fully participating in this research.

Another factor that prevented the use of GLOBE student data for my research was that several of the site locations were not appropriate for the study. The initial objective of the study was to determine whether NDVI could predict transpiration periods in different biomes using GLOBE data and the GAPS model. With GAPS, the input parameters and degree of detail required to run a simulation in GAPS depend on the model algorithms selected by the user. General to more complex simulations can be performed based on the available data for a particular site. Given the GLOBE datasets, an empirical algorithm, Linacre, was chosen to simulate evapotranspiration as its input parameters coincided with measurements collected by GLOBE students. The Linacre algorithm (1977) estimates potential ET from mean daily air temperature, mean daily dew-point temperature, elevation and latitude. The model was structured to allow transpiration to occur when daily maximum temperature was above a certain temperature threshold. While transpiration can occur at temperatures below optimum, the purpose of this study was to determine the period when the vegetative surface was transpiring and how that in turn affected the distribution between uptake and drainage. The temperature threshold was effective for Greenville, Pennsylvania. However, this methodology did not transfer to locations such as Puerto Rico, and Thailand that did not have large temperature ranges between winter and spring seasons that Pennsylvania has. In these tropical environments, winter and summer are differentiated by precipitation rather than temperature.

(2) Research Project 2

In contrast to my first research project, my second research project required one set of GLOBE measurements, phenology, from multiple schools within the same geographical area. I utilized phenology observations made by GLOBE students to determine if NDVI could accurately detect phenological changes, specifically start of season , in high Northern latitude (>60˚) environments. For satellite validation, landscape heterogeneity, which is especially prevalent with larger pixel sizes, makes multiple field validation sites essential. Phenology metrics derived from multi-temporal AVHRR and MODIS NDVI data were used to detect start of season and results were validated with field observations from GLOBE students.

The GLOBE phenology data archive was surveyed and schools that had completed budburst and/or green-up measurements for at least one season were selected. Since 1999, GLOBE students from more than 120 schools around the world have made over 95,000 phenology measurements at or near their schools (www.globe.gov). Students in Alaska have collected nearly half these measurements and as a result my research focused on this dataset. While Finland, Germany, Norway, and Sweden, all had schools at high Northern latitudes making phenology measurements, the schools were geographically dispersed making spatial analysis difficult.

In spite of its extensive coverage, there were several difficulties with the GLOBE Alaskan data. Only a fraction of the phenology measurements made by GLOBE school in Alaska were viable for this study. Many of the datasets were incomplete, missing critical budburst observations. This problem was prevalent only in the green-up data. The budburst protocol required students to make daily observations two weeks prior to budburst and the only data students recorded was budburst date. The green-up protocol required students to make observations of dormancy, swelling, budburst, and leaf-growth on four branches of a tree at least twice a week. Several schools would record dormancy, swelling, and leaf-growth, but not the budburst date. In cases with frequent observations (every 2-4 days) the date of budburst could be interpolated. However, often there was a significant lag (1-2 weeks) between observations and budburst could not be inferred. As a result, a lot of data could not be used.

Another difficulty was that schools made observations on a wide range of tree types making comparisons between locations difficult. In order to standardize the observations, only data from *Betula* (Birch), *Populus* (Cottonwood/Aspen/Poplar), and *Salix* (Willow) were used. All three trees are native to Alaska (Viereck and Little, 1972). Furthermore, these were the most commonly selected tree types by students. Nonetheless, this selection restricted the dataset even further to ten schools, three in the Anchorage region and seven in the Fairbanks regions. In addition, not all schools made measurements each year on all three species. Some years had more data than other years. Furthermore, the majority of the data that was viable was from urban sites, Anchorage and Fairbanks, making it difficult to extrapolate information beyond those two cities, as Alaska is a predominately rural state.

Despite these difficulties, the organizational structure of the second research project was more successful for using GLOBE data than the first project. The time commitment required by the schools was reasonable, measurements coincided with the school year and were seasonal, and no equipment was needed to make the observations. Students made visual observations of vegetation at or near their schools. In contrast, the first project required multiple, daily, and year-round measurements and an extra time commitment from the schools that was unrealistic, especially during summer months. Furthermore, the soil moisture and temperature sensors were expensive and difficult to maintain. As a result of these factors, the second research project was more accessible to students of all ages.

Next Generation GLOBE (NGG) and Future Recommendations

In 2004-2005, an extensive ten-year evaluation of the GLOBE program was undertaken. This report was titled the Next Generation GLOBE (NGG) and outlined the next steps in the evolution of the GLOBE program (NGG, 2005). This report found that during the first ten years of the program science drove the training, materials, and activities, specifically data reporting and data use. Yet, as the program matured it became apparent that teachers needed additional support to integrate training materials and protocols into their curriculum. As a result, the NGG report recommended that education rather than science guide the implementation of the program. Materials needed to be more "education-friendly" and, in the U.S., aligned with national educational standards.

The report also recommended that GLOBE focus its resources on a few projects rather than spread its limited resources across many projects as it had done in the past. During the first ten years, with only a small program staff, GLOBE supported over 100 U.S. partners, facilitated implementation of the program in over 100 countries, and worked with 15 different PIs. Over 50 protocols were developed, 32,000 teachers trained in the protocols, and over 14 million measurements were reported to the GLOBE archive (NGG, 2005). The report recommended that GLOBE focus on the quality of the program, specifically the quality of materials, activities, and support services, rather than quantitative statistics such as number of countries, teachers, and students involved in the program. Additionally, the report advised that GLOBE develop an evaluation plan, become more international and less U.S. centric, and promote local and regional projects and field campaigns.

To achieve these objectives the report recommended three new approaches for the overall implementation of GLOBE: (1) Regional Consortia; (2) Project-Based management; and (3) GLOBE Schools Network (NGG, 2005). The first approach involves the formation of a regional network of countries that would collaborate on regional GLOBE implementation. Each consortium would take on some of the program support responsibilities in their regions that in the past had been assumed by the main GLOBE office. The second approach would reorganize educational and scientific activities with interdisciplinary teams. These teams would include GLOBE staff, scientists, local partners, and teachers, as appropriate to the particular project. These teams would then design, implement, and evaluate their specific projects. Currently, the GLOBE program is organized programmatically into by five permanent divisions, management, education, science, partners/outreach, and systems. The third approach would establish criteria for schools to be designated a GLOBE school within a particular project. The schools would commit to certain level of activities and in turn the project would provide specific benefits to the school for its participation. In the past, schools were designated a GLOBE school if at least one teacher had been trained in GLOBE protocols. If the GLOBE trained teacher left the school, the school was no longer considered part of GLOBE.

In my opinion, these three approaches will improve research collaborations between scientists and GLOBE schools. Regional groupings of GLOBE partners, coupled with project-based management, will facilitate collaborative research programs between the scientific and educational communities. Additionally, the GLOBE school networks will decentralize participation by ensuring that a school's connection to

GLOBE is project based rather than teacher based as it has been in the past. Furthermore, schools will have specific criteria they need to follow in order to participate in research projects. These criteria will establish clear objectives that schools can meet and direct data reporting to actual research projects. In the past, schools were encouraged to make measurements without clear guidance on how their data would be used. A clear example was with the honor role schools. Even though these schools showed a clear commitment to data reporting and were commended for their efforts, this data was not specifically connected to research projects and as a result the scientists never used much of this data in their research.

In addition to the NGG's proposals, I would make several recommendations for using GLOBE data in scientific research. First, measurements required by the students should be time sensitive to the school day and calendar. As the SRI evaluation showed, data reporting coincides with the school year and drops considerably during the summer months (Penuel et al., 2005). Expecting schools to make measurements year round even when schools are not in session is unrealistic and prohibits many interested schools from participating in research projects. Second, if more intensive sampling is required then directed field campaigns should be done. These campaigns should be for a discreet period of time such as a weekend or one to two week periods. Third, if protocols need to be modified, schools should receive clear instructions prior to the field campaign with explanations of why the changes are needed. For example, phenology protocols should specifically indicate which trees should be observed, during which periods of time, and how many trees per study site. Fourth, if multiple sites are required within a geographical region, researchers should work directly with schools in the site selection process. The GLOBE protocols do provide site selection instruction for each of the measurements. However, they are general and often do not fit the requirements of specific research projects.

In conclusion, scientists should work closely with the educational community to make their research accessible to the students. Students should understand what the research is, why their data is important, and how their data will be used in the particular research project. Also the research should be integrated into the classroom curriculum. When possible, scientists should visit schools or provide communications through web chats and video conferencing. These recommendations will ensure a more fruitful collaboration between scientists and students, which in turn will further the objectives of the GLOBE program.

Chapter 5: Conclusion

NDVI, with its spatial and temporal extent, has been an instrumental tool for monitoring inter- and intra-annual changes on the Earth's surface. Nonetheless, NDVI is a surrogate measurement of plant photosynthetic activity and the translation of the actual signal requires careful consideration (Tucker, 1977; Shabanov et al., 2002). Each study in this dissertation utilized GLOBE field measurements to evaluate a different application of NDVI. The first study evaluated whether NDVI could accurately predict transpiration periods for a Northern temperate (> 35˚) climate. The second study investigated whether NDVI could accurately detect phenological changes, specifically start of season (SOS), for high Northern latitude (> 60˚) environments. The objective of my dissertation was to provide a critical analysis of NDVI as a long-term monitoring tool for climate change research. In conjunction, I wanted to develop a methodology for utilizing GLOBE measurements to validate these kinds of NDVI studies.

In the first study, GLOBE and NDVI data were used to initialize and validate simulated water and energy fluxes with the GAPS model. For Greenville, Pennsylvania, model simulations showed that the timing and distribution of transpiration coincided with seasonal NDVI patterns. Onset of transpiration, and its subsequent increased rate, corresponded with the continuous rise in NDVI values. Once NDVI began to decline, signaling the greening down of vegetation, transpiration also began to decline. These results corresponded with Suzuki et al. (1998) who found a high correlation between seasonal changes in NDVI and evapotranspiration in Siberia and Northeast China.

Results showed that in phenological terms temperate environments, like Greenville, Pennsylvania, have three distinct periods (QI, QII, and QIII). QI reflects the onset of the growing season (mid March – mid May) when vegetation is greening up (NDVI < 0.60) and transpiration is beginning (< 2mm/day). QII reflects the end of the growing season (mid September - October) when vegetation is greening down and transpiration is decreasing. QIII reflects the height of the growing season (mid May – mid September) when transpiration rates average between 2 and 5 mm per day and NDVI is at its maximum (>0.60).

The approach presented in this study provides a simplified and unique alternative for determining transpiration periods than more complex land surface models. Input parameters for the GAPS model were field based, not simulated or interpolated with remotely sensed data as is often done with land surface models. The result of using remotely sensed data is that input parameters are at a coarser resolution than the land surface features that influence the surface energy fluxes (French et al., 2003). In addition, NDVI was used for validation rather than as a surrogate input parameter for LAI – another common feature of land surface models. Also, a 10-day, in lieu of the more common monthly, NDVI composite was utilized. Monthly composites, advantageous for cloudy environments, are too coarse to capture temporal changes in the very processes being simulated or derived, e.g. transpiration. Finally, this approach utilized a more representative, multi-layer, process model with rooting depth parameterization linked to soil water uptake.

In the second study, phenology observations made by GLOBE students in Alaska were used to validate NDVI and climate based thresholds for detecting start of season. Results showed that a climate threshold of 153 ± 22 growing degree days (GDD) was a better predictor of SOS in Fairbanks than a NDVI threshold applied to temporal AVHRR and MODIS datasets. Accumulated growing degree days captured the inter-annual variability of SOS better than the NDVI threshold and most closely resembled actual SOS observations made by GLOBE students and UAF researchers.

Continuity between AVHRR and MODIS datasets was also evaluated. Results showed that different processing as well as spectral characteristics of each sensor restrict continuity between the two datasets. MODIS values were consistently higher and had less inter-annual variability during June through August than corresponding AVHRR values. Huete et al. (2002) and Brown et al., (2006) showed similar findings and attributed differences to MODIS' greater sensitivity of its red and NIR bands, which restrict atmospheric impacts from clouds, aerosols, and water vapor. Additionally, MODIS' improved compositing method (CV-MVC) reduces spatial and temporal discontinuities that results from maximum value compositing (Goward, 1991; Huete et al., 2002).

Unlike prior research, a water vapor correction was applied to the AVHRR NDVI data used in this study. Therefore, water vapor effects did not account for the large differences between AVHRR and MODIS NDVI values. Most likely, MODIS' higher values and lower inter-annual variability were attributed to its aerosol correction, which AVHRR does not have, and its improved compositing method. Boreal fire emissions, a significant source of aerosols, were notably higher in the high Northern Hemisphere during the time period of this study (Kasischke et al., 2005).

In conclusion, these two studies show that careful consideration is required for each application of NDVI. NDVI can accurately predict transpiration periods in temperate Northern regions such as Pennsylvania. Furthermore, GLOBE and NDVI data provide an important source of input and validation information for SVAT models such as GAPS. However, measurements required by GLOBE students should be time sensitive to the school day and calendar. Expecting students to make measurements year round, as the first research project did, is unrealistic and this requirement prohibits many interested schools from participating in such research projects.

Moreover, NDVI does have limitations as a phenology monitoring tool for boreal regions. Effects of snow and clouds, which confine compositing to biweekly periods, coupled with the large extent of conifers, restrict accurate detection of SOS with NDVI. These results, in addition to the well documented advancement of SOS in the literature, indicate a more sensitive predictor than NDVI is needed to monitor changes in start of growing season. Climate data, specifically mean air temperature, and annual phenology observations provide the most accurate technique to monitor such changes and GLOBE students' green-up observations provides an exceptional dataset for such research.

While climate data exists in most parts of the world, better geographic coverage of land cover, phenology, and soils field measurements are needed for NDVI research. Both these papers illustrate how GLOBE data provides an important source of input and validation information for such research. Thus, continued collaborations between the scientific and GLOBE communities would allow researchers to compare ecosystem function across a wide variety of biomes and further our understanding of NDVI dynamics.

References

Andreae, M. and Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15, 955-966.

Aquino, T.L. and Levine, E.R., 2003. Science and math in the library media center using GLOBE. Knowledge Quest 31, 40-41.

Becker, M., Congalton R., Budd R., and Fried A., 1997. A GLOBE collaboration to develop land cover data collection and analysis protocols. Journal of Science Education and Technology 7, 85-96.

Birky, A., 2001. NDVI and a simple model of deciduous forest seasonal dynamics. Ecological Modelling 143, 43-58.

Brooks, D. and Mims F., 2001. Development of an inexpensive handheld LED-based sun photometer for the GLOBE Program. Journal of Geophysical Research 106, 4733-4740.

Brown, M., Pinzon, J., Didan, K., Morisette, J., and Tucker, C., 2006. IEEE Transactions Geoscience and Remote Sensing 44.

Brutsaert, W. and Parlange, M., 1998. Hydrologic cycle explains the evaporation paradox Nature 396, 30.

Buttler, I. and Riha, S., 1987. General-purpose simulation model of water flow in the soil-plant-atmosphere continuum. Applied Agricultural Research 2, 230-234.

Buttler, I. and Riha, S., 1992. Water fluxes in Oxisols: A comparison of approaches. Water Resources Research 28, 221-229.

Cayan, D., Kammerdiener, S., Dettinger, M., Caprio, J. and Peterson, D., 2000. Changes in the onset of spring in the Western United States. Bulletin of the American Meteorological Society 82, 399-415.

Chattopadhyay, N. and Hulme, M., 1997. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. Agricultural and Forest Meteorology 87, 55-73.

Chahine, M.T., 1992. The hydrological cycle and its influence on climate. Nature 359, 373-380.

Chiesi, M., Maselli, F., Bindi, M., Fibbi, L., Bonora, L., Raschi, A., et al., 2002. Calibration and application of FOREST-BGC in a Mediterranean area by the use of conventional and remote sensing data. Ecological Modelling 154, 251-262.

Chilar, J., Tcherednichchenko, I., Latifovic, R., Li, Z., and Chen, J., 2001. Impact of variable atmospheric water vapor content on AVHRR data corrections over land. IEEE Transactions on Geoscience and Remote Sensing 39, 173-180.

Chmielewski, F. and Rotzer, T., 2001. Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology 108, 101-112.

Choudhury, B., 1997. Global Pattern of potential evaporation calculated from the Penman-Monteith equation using satellite and assimilated data. Remote Sensing of Environment 61, 64-81.

Christie, B. and McElroy, A., 1995. Orchardgrass. In: Barnes, R., Miller, D. and Nelson, C. (Eds.), Forages Volume I: An Introduction to Grassland Agriculture. Iowa State University Press, Iowa, pp. 325-334.

Churkina, G., Running, S., Schloss, A., and the Participants of the Postdam NPP Model Intercomparison, 1999. Comparing global models of terrestrial net primary productivity (NPP): the importance of water availability. Global Change Biology 5, 46-55.

Clemmons, J., 2000. A comparison of water quality methods and data: Globe Program vs. United States Geological Survey. MS Thesis, University of Arizona, Tucson, AZ.

Cohen, S., Iametz, A., and Stanhill, G., 2002. Evaporative climate changes at Bet Dagan, Israel, 1964-1998. Agricultural and Forest Meteorology 111, 83-91.

Congalton, R., 2002. The GLOBE Program: A potential source of land cover reference data. Proceedings of the 5th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Science. Melbourne, Australia, pp. 102-109.

DeFelice, T., Lloyd D., Meyer, D., Baltzer, T., and Piraino, P., 2003. Water vapour correction of the daily 1 km AVHRR global land dataset: Part I – Validation and use of the water vapour input field. International Journal Remote Sensing 24, 2365-2375.

DeFries, R., Hansen, M., Townshend, J., and Sohlberg, R., 1998. Global land cover classification at 8km spatial resolution: The use of training data derived from Landsat imagery in decision tree classifiers. International Journal of Remote Sensing 19, 3141-3168.

Delbart, N., Kergoat, L., Le Toan, T., Lhermitte, J., and Picard, G., 2005. Determination of phenological dates in boreal regions using normalized difference water index. Remote Sensing of Environment 97, 26-38.

Delbart, N., Le Toan, T., Kergoat, L., Fedotova, V., 2006. Remote sensing of spring phenology in boreal regions: A free of snow-effect methods using NOAA_AVHRR and SPOT_VGT data (1982-2004). Remote Sensing of Environment 101, 52-62.

Easterling, D., Horton, B., Jones, P., Peterson, T., Karl, T., Parker, D., et al., 1997. Maximum and minimum temperature trends for the globe. Science 277, 364-367.

Felzer, B. and Heard, P., 1999. Precipitation differences among GCMs used for the US National Assessment. Journal of the American Water Resources Association 35, 1327-1340.

Fitter, A., Fitter, R. Harris, I., and Williamson, M., 1995. Relationships between first flowering date and temperature in the flora of a locality in Central England. Functional Ecology 9, 55-60.

Fitter, A. and Fitter R., 2002. Rapid changes in flowering time in British plants. Science 296, 1689-1691.

Fleming, M., 1997. A statewide vegetation map of Alaska using a phenological classification of AVHRR data. In Walker and Lillie (Eds.), Proceedings of the Second Circumpolar Arctic Vegetation Mapping Workshop and the CAVM-North American Workshop. 62 pp.

French, A., Schmugge, T., and Kupas, W., 2000. Estimating surface fluxes over the SGP site with remotely sensed data. Physical Chemical Earth (B) 25, 167-172.

French, A., Schmugge, T., Kustas, W., Brubaker, K., and Prueger, J., 2003. Surface energy fluxes over El Reno, Oklahoma, using high-resolution remotely sensed data. Water Resources Research 39, 1164.

Fried, A., 1997. New frontiers in land cover classification: A comparison of the accuracies of professional and K-12 student field data collection methods. MS Thesis, University of New Hampshire, Durham, NH.

Gao, X., Huete, A., Ni, W., and Miura, T., 2000. Optical-biophysical relationships of vegetation spectra without background contamination. Remote Sensing of Environment 74, 609-620.

Gillies, R., Carlson, T., Chui, J., Kustas, W., and Humes, K., 1997. A verification of the 'triangle' method for obtaining surface soil water content and energy fluxes from remote measurements of the normalized difference vegetation index (NDVI) and surface radiant temperature. International Journal of Remote Sensing 18, 3145-3166.

Gitelson, A. and Kaufman, Y., 1998. MODIS NDVI optimization to fit the AVHRR data series – spectral considerations. Remote Sensing of Environment 66, 343-350.

GLOBE Program Teacher's Guide. 2003. http://www.globe.gov/

Goetz, S., Bunn, A., Fiske, G., and Houghton, R., 2005. Proceedings of the National Academy of Science (PNAS) 102, 13521-13525.

Goetze, S., Fiske, G., and Bunn, A., 2006. Using satellite time-series data sets to analyze fire disturbances and forest recovery across Canada. Remote Sensing of Environment 101, 352-365.

Goldman, H., 2000. Estimation of growing season length in Northern Alaska with AVHRR NDVI bi-weekly satellite data. MS Thesis, University of Alaska-Fairbanks, Fairbanks, AK.

Goward, S., Markham, B., Dye, D., Dulaney, W., and Yang, J., 1991. Normalized difference vegetation index measurements from the Advanced Very High Resolution Radiometer. Remote Sensing of Environment 35, 257-277.

Groisman, P., Thomas, K., Knight, R., 1994. Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. Science 263, 198-200.

Hanson, M., DeFries, R., Townshend, J., and Sohlberg, R., 2000. Global land cover classification at 1km spatial resolution using a classification tree approach. International Journal of Remote Sensing 21, 1331-1364.

Hanson, R., 1991. Evapotranspiration and droughts, in Paulson, R., Chase, E., Roberts, R., and Moody, D., Compilers, National Water Summary 1988-89 Hydrological Events and Floods and Droughts: U.S. Geological Survey Water-Supply Paper 2375, 99-104.

Haskett, J., Levine E., Carey P., and Niepold F., 2000. Biomass measurement: A science activity for middle school. Science Activities 37, 33-38.

Holben, B., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. International Journal of Remote Sensing 7, 1417-1434.

Houghton, J., Ding Y., Griggs D., Noguer M., van der Linden P., et al., (eds.), 2001. Climate change 2001: The scientific basis. Cambridge University Press, Cambridge, 881pp.

Huete, A., Justice, C., and Liu, H. 1994. Development of vegetation and soil indices for MODIS-EOS. Remote Sensing of Environment 49, 224-234.

Huete, A., Didan K., Miura, T., Rodriguez, E., Gao, X., and Ferreira, L., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83, 195-213.

Jackson, R., Carpenter, S., Dahm, C., McKnight, D., Naiman, R., Postel S., and Running, S., 2001. Water in a changing world. Ecological applications 11, 1027-1045.

Jacobs, K., Adams, D. and Gleick, P., 2001. Water: The potential consequences of climate variability and change for the water resources of the United States. In: National Assessment Synthesis Team, US Global Change Research Program (eds.), Climate change on the United States: The potential consequences of climate variability and Change.

Jensen, M., Burman, R., and Allen, R. 1990. Evaporation and irrigation water requirements, ASCE Manual No. 70, American Society of Civil Engineers, New York, 332 pp.

Jia, G. and Epstein, H., 2003. Greening of arctic Alaska, 1981-2001. Geophysical Research Letters 30, 2067, doi:10.1029/2003GL018268.

Jones, C., and Kiniry, J. (Eds.), 1986. CERES-Maize: A simulation model of maize growth and development. College Station, TX: Texas A & M University Press, 194 pp.

Justice, C., Holben, B., and Gwynne, M., 1986. Monitoring East African vegetation using AVHRR data. International Journal of Remote Sensing 11, 1453-1474.

Karl, T., Kukla, G., Razuvayev, V., Chanery, M., Quayle, R., Heim Jr., R., et al., 1991. Global Warming: Evidence for asymmetric diurnal temperature change. Geophysical Research Letters 18, 2253-2256.

Karl, T., Jones, P., Knight, R., Kukla, G., Plummer, N., Razuvayev, V., et al., 1993. Asymmetric trends of daily maximum and minimum temperature. Bulletin of the American Meteorological Society 74, 1007-1023.

Karl, T., Knight, R., and Plummer, N., 1995. Trends in high-frequency climate variability in the twentieth century. Nature 377, 217-2001.

Karl, T. and Knight, K., 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bulletin of the American Meteorological Society 79, 231-241.

Kasischke, E., and French, N., 1997. Constraints on using AVHRR composite index imagery to study patterns of vegetation cover in boreal forests. International Journal of Remote Sensing 18, 2403-2426.

Kasischke, E., Hyer, E., Novelli, P., Burhwiller, L., French, N., Sukhinin, A., et al., 2005. Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon. Global Biogeochemical Cycles 19, GB1012, doi:10.1029/2004GB002300.

Kogan, F., 1995. Droughts of the late 1980s in the United States as derived from NOAA Polar-Orbiting Satellite Data. Bulletin of the American Meteorological Society 76, 665-668.

Koster, R. and Milly, P., 1997. The interplay between transpiration and runoff formulations in land surface schemes used with atmospheric models. Journal of Climate 10, 1578-1591.

Kramer, A., 1998. GLOBE water quality data in context: A comparative study of volunteer and governmental agency databases. Master's thesis, University of Arizona, Tucson, AZ.

Lavoue, D., Liousse, C., Cachier, H., Stocks, B., and Goldammer, J. 2000. Modeling of carbonaceous particles emitted by boreal and temperate wildfires at Northern latitudes. Journal of Geophysical Research 105, 26,871-26,890.

Levine, E. and Knox, R., 1994. A comprehensive framework for modeling soil genesis. In: Quantitative Modeling of Soil Forming Processes, SSSA Special Publication 39.

Levine, E. 1998. Teaching soil science in primary and secondary classrooms. Science Teacher, October issue.

Liang, X. and Lettenmaier, D.P., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research, 99, 14415-14428.

Liang, X., Wood, E.F., Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. Global and Planetary Change 12, 195-206.

Linacre, E., 1977. A simple formula for estimating evaporation rates in various climates, using temperature data alone. Journal of Agricultural Meteorology 18, 409-424.

Linkosalo, T., 1999. Regularities and patterns in the spring phenology of some boreal trees. Silva Fennica 33, 237-245.

Lloyd, D., 1990. A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. International Journal of Remote Sensing 11, 2269-2279.

LP DAAC, USGS/EROS, Sioux Falls, SD, Weekly and Biweekly MODIS Surface Reflectance and NDVI composites, 2001-2004.

Loveland, T., Reed, B., Brown, J., Ohlen, D., Zhu, Z., Yang, L., and Merchant, J., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. International Journal of Remote Sensing 21, 1303-1330.

Markon, C., Fleming, M., and Binnian, E., 1995. Characteristics of vegetation phenology over the Alaskan landscape using AVHRR time-series data. Polar Record 31, 179-190.

Markon, C., 2001. Seven-year phenological record of Alaskan ecoregions derived from Advanced Very High Resolution Radiometer normalized difference vegetation index data. U.S. Geological Survey Open-File Report 01-11, 58pp.

McCarthy, J., Canziani, O., Leary N., Dokken D. and White, K., 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Geneva, Switzerland.

McDonald, A. and Riha, S., 1999. Model of crop-weed competition applied to maize-*Abutilon theophrasti* interactions. II: Assessing the impact of climate: implications for economic thresholds. Weed Research 39, 371-381.

McIntyre, B., Riha, S. and Ong C., 1996. Light interception as a predictor of evapotranspiration in agroforestry systems. Ag. and Forest Meteor. 81, 41-40.

Melkonian, J., Riha, S., and Wilks, D., 1998. Comparison of physiologically-based formulations for simulating of crop CO_2 fertilization. Agricultural Systems 58, 87-106.

Menzel, A. and Fabian, P. 1999. Growing season extended in Europe. Nature 397, 659.

Menzel, A., 2000. Trends in phenological phases in Europe between 1951 and 1996. International Journal of Biometeorology 44, 76-81.

Miller, S., 2004. Soil Temperature at LTER weather stations: Daily and hourly data. Fairbanks, AK: Bonanza Creek LTER Database: BNZD00098:90. http://www.lter.uaf.edu/data_catalog_detail.cfm?dataset_id=90

Milly, P., 1992. Potential evaporation and soil moisture in general circulation models. Journal of Climate 5, 209-226.

Milly, P., Wetherald, R., Dunne, K. and Delworth, T., 2002. Increasing risk of great floods in a changing climate. Nature 415, 514-517.

Mims, F., 1999. An international haze-monitoring network for students. Bulletin of the American Meteorological Society 80, 1421-1431.

Mintz, Y. and Walker G., 1993. Global fields of soil moisture and land surface evapotranspiration derived from observed precipitation and surface air temperature. Journal of Applied Meteorology 32, 1305-1334.

Monteith, J., 1964. Evaporation and environment. The State and Movement of Living Organisms, 19th Symposium of Society for Exploratory Biology, 204-234.

Moulin, S., Kergoat, L., Viovy, N., and Dedieu, G., 1997. Global-scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements. Journal of Climate 10, 1154-1170.

Mulligan, D., 2004. Soil Survey of Greater Fairbanks Area, Alaska. USDA, NRCS.

Mutango, O. and Skidmore, A., 2004. Hyperspectral band depth analysis for a better estimation of grass (*Cenchrus ciliaris*) measured under controlled laboratory conditions. International Journal of Applied Earth Observation and Geoinformation 5, 87-96.

Myneni, R., Keeling, C., Tucker, C., Asrar G., and Nemani, R. 1997. Increased plant growth in the northern high latitudes from 1981-1991. Nature 386, 698-702.

Myneni, R., Tucker, C., Asrar, G., Keeling, C., 1998. Interannual variations in satellite-sensed vegetation index data from 1981 to 1991. Journal of Geophysical Research 103, 6145-6160.

NGG, 2005. The 'Next Generation GLOBE' (NGG): Developing strategic partnerships to improve science education, enhance environmental awareness, and increase understanding of the Earth as a system. Boulder, CO: GLOBE Program.

NOAA NCDC, http://www.ncdc.noaa.gov/oa/climate/research/ushcn/daily.html.

Ohmura, A. and Wild, M., 2002. Is the hydrological cycle accelerating? Science 298, 1345-1346.

Olioso, A., Carlson, T., and Brisson, N., 1996. Simulation of diurnal transpiration and photosynthesis of a water stressed soybean crop. Agricultural and Forest Meteorology, 81, 41-59.

Olioso, A., Chauki H., Courault D., and Wigneron J., 1999. Estimation of evapotranspiration and photosynthesis of assimilation of remote sensing data into SVAT models. Remote Sensing Environment 68, 341-356.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Chase, R., Douglas, M., et al., 1997. Arctic environmental change of the last four centuries. Science 278, 1251-1256.

Palmer, T. and Raisanen, J., 2002. Quantifying the risk of extreme seasonal precipitation events in a changing climate. Nature 415, 512-514.

Pearcy, R., Detlef-Schulze, A., and Zimmermann, Z., 1992. Measurement of transpiration and leaf conductance. IN: Plant Physiological Ecology, Pearcy, R., Ehleringer, J., Mooney, H., and Rundel, P. (eds), London: Chapman & Hall, 457 pp.

Penman, H.L., 1948. Natural evaporation from open water, bare soil, and grass. Proc. Royal Society London Proceedings A, 193, 120-146.

Penuel, W., Korbak, C., Yarnall, L., Lewis, A., Toyama, Y., and Zander, M., 2004. GLOBE Year 8 Evaluation: Understanding diverse implementation contexts. Menlo Park, CA: SRI International.

Penuel, W., Bienkowski, M., Korbak, C., Molina, A., Russo, D., Shear, L. et al., 2005. GLOBE Year 9 Evaluation: Implementation supports and student outcomes. Menlo Park, CA: SRI International.

Peterson, B., Holmes, R., McClelland, J., Vorosmarty, C., Lammers, R., Shiklomanov, A., and Rahmstorf, S., 2002. Increasing river discharge to the Artic Ocean. Science 298, 2171-2173.

Peterson, T., Golubev, V., and Groisman, P., 1995. Evaporation losing its strength. Nature 377, 687-688.

Piao, S., Fang, J., Zhou, L., Ciais, P., and Zhu, B. 2006. Variations in satellite-derived phenology in China's temperate vegetation. Global Change Biology 12, 1-14.

Primack, D., Imbres, C., Primack, R., Miller-Rushing A., and Del Tredici, P., 2004. Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. American Journal of Botany 91, 1260-1264.

Ramanthan V., Crutzen, P., Kiehl, J., and Rosenfeld, D., 2001. Aerosols, climate, and the hydrological cycle. Science 294, 2119:2124.

Reed, B., Brown, J., VanderZee, D., Loveland, T., Merchant, J., and Ohlen, D., 1994. Measuring phenological variability from satellite imagery. Journal of Vegetation Science 5, 703-714.

Reed, B., White, M., and Brown, J., 2003. Remote sensing phenology. In Schwartz (Ed.), Phenology: An Integrative Environmental Science. Netherlands, Kluwer Academic Publishers.

Riha, S., Rossiter, D.G., Simoends, P., 2003. GAPS: General-Purpose Atmosphere-Plant-Soil Simulator, Cornell University, Ithaca, NY.

Robin, J., Levine, E., and Riha, S., 2005. Utilizing satellite imagery and GLOBE student data to model soil dynamics. Ecological Modelling 185, 133-145.

Roderick, M. and Farquhar, G., 2002. The cause of decreased pan evaporation over the past 50 years. Science 298, 1410-1411.

Root, T., MacMynowski, D., Mastrandrea, M., and Schneider, S., 2005. Human-modified temperatures induce species changes: Joint attribution. Proceedings of the National Academy of Science (PNAS) 102, 7465-7469.

Root, T., Price, J., Hall, K., Schneiders, S., Rosenzweig, C., and Pounds, J., 2003. Fingerprints of global warming on wild animals and plants. Nature 421, 57-60.

Rossiter, D.G. and S.J. Riha., 1999. Modeling plant competition with the GAPS object-oriented dynamic simulation model. Agronomy Journal 91, 773-783.

Running, S. and Nenami, R., 1988. Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. Remote Sensing of Environment 24, 347-367.

Sant, G., 2000. Vegetation 2000 Proceedings, Joint Research Center, Varese-Italy.

Schwartz, M. and Reiter, B., 2000. Changes in North American Spring. International Journal of Climatology 20, 929-932.

Schwartz, M., Reed, B., and White, M., 2002. Assessing satellite-derived start-of-season measures in the conterminous USA. International Journal of Climatology 22, 1793-1805.

Seaquist, J., Olssom, L., and Ardo, J., 2003. A remote sensing-based primary production model for grassland biomes. Ecological Modelling 169, 131-155.

Sellers, P., 1985. Canopy reflectance, photosynthesis and transpiration. International Journal of Remote Sensing 6, 1335-1372.

Sellers, P., Randall, D., Collatz, J., Berry, J., Field, C., Dazlich, D., et al., 1996. A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model Formulations. Journal of Climate 9, 676:705.

Shabanov, N., Zhou, L., Knyazikhin, Y., Myneni, R., and C. Tucker, 2002. Analysis of Interannual changes in northern vegetation activity observed in AVHRR data from 1981 to 1994. IEEE transactions on Geoscience and Remote Sensing 40, 115-130.

Sharpley, A. and Williams, J. R. 1990. Epic, erosion, productivity impact calculator: 1. model documentation. Technical Bulletin 1768, U.S. Dept. of Agriculture.

Stamm, J.F., Wood, E.F., and Lettenmaier, D.P., 1994. Sensitivity of a GCM simulation of global climate to the representation of land-surface hydrology. Journal of Climate 7, 1218-1239.

Steven, M., Malthus, T., Baret, F., Xu, H., and Chopping, M., 2003. Intercalibration of vegetation indices from different sensor systems. Remote Sensing of Environment 88, 412-422.

Stocks, B., Fosberg, M., Wotton, M., Lynhham, T., and Ryan, K., 2000. Climate change and forest activity in North American boreal forest. In Kasischke and Stocks (Eds.), Fire, climate change and carbon cycling in the Boreal forest, NY:Springer-Verlag.

Stow, D., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmric, F., et al., 2004. Remote sensing of vegetation and land-cover change in Artic Tundra ecosystems. Remote Sensing of Environment 89, 281-308.

Stowe, L., Davis, P. and McClain, E., 1998. Scientific Basis and Initial Evaluation of the CLAVR-1 Global Clear/Cloud Classification Algorithm for the Advanced Very High Resolution Radiometer. Journal of Atmospheric and Oceanic Technology 16, 656-681.

Sturm, M., Racine, C., and Tape, K., 2001. Increasing shrub abundance in the Arctic. Nature 411, 546-547.

Suzuki, R., Yatagai, A., and Yasunari, T., 1998. Satellite-derived vegetation index and evapotranspiration estimated by using assimilated atmospheric data over Asia. Journal of Meteorological Society of Japan 76, 663-671.

Suzuki, R., Nomaki, T., and Yasunari, T., 2001. Spatial distribution and its seasonality of satellite-derived vegetation index (NDVI) and climate in Siberia. International Journal of Climatology 21, 1321-1335.

Suzuki, R., Nomaki, T., and Yasunari, T., 2003. West-east contrast of phenology and climate in northern Asia revealed using a remotely sensed vegetation index. International Journal of Biometeorology 47, 126-138

Szilagyi, J., 2000. Can a vegetation index derived from remote sensing be indicative of areal transpiration? Ecological Modelling 127, 65-79.

Tape, K., Sturm, M., and Racine, C., 2006. The expansion for shrub expansion in Northern Alaska and the Pan-Arctic. Global Change Biology 12, 1-17.

Thenkabail, P.S., Smith, R.B. and Pauw, E.D. 1999. Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. Remote Sensing of Environment 71, 158-182.

Thoman, R., and Fathauer, T., 1998. An investigation into estimating green-up dates around Fairbanks Alaska using thermal indices. National Weather Service.

Thornthwaite, C.W., 1948. An approach towards a rational classification of climate. Geographic Review 38, 55-94.

Townshend, J.R. and Justice, C.O. 1986. Analysis of the dynamics of African vegetation using the normalized difference vegetation index. International Journal of Remote Sensing 7, 1435-1445.

Townshend, J.R.G., Justice, C.O., Gurney, C. and McManus, J., 1992. The impact of misregistration on change detection. IEEE Transaction on Geoscience and Remote Sensing 30, 1054-1577.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8, 127-150.

Tucker, C.J., Townshend, J.R.G., and Goff, T.E., 1985. African land-cover classification using satellite data. Science 227, 369-375.

Tucker, C.J. and Sellars, P.J., 1986. Satellite remote sensing of primary production. International Journal of Remote Sensing 7, 1395-1416.

Tucker, C.J., Slayback, D.A., Pinzon, J.E., Los, S.O., Myneni, R.B., Taylor, M.G., 2001. Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. Internal Journal of Biometeorology 45, 184-190.

Tucker, C., Pinzon, J., and Brown, M. 2004. Global Inventory Modeling and Mapping Studies (GIMMS) Satellite Drift Corrected and NOAA-16 incorporated Normalized Difference Vegetation Index (NDVI), Monthly 1981.

USGS/EROS, Sioux Falls, SD, Biweekly AVHRR NDVI composites, 2001-2004.

Vermote, E., El Saleous, N., Justice, C., Kaufman, Y., Privette, J., Remer, L., et al., 1997. Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: Background, operational algorithm and validation. Journal of Geophysical Research 102, 17131-17141.

Vermote, E.F., El Saleous, N., and Justice, C., 2002. Atmospheric correction of MODIS data in the visible to middle infrared: First results. Remote Sensing of Environment 83, 97-111.

Viereck, L. and Little, E., 1972. Alaska Trees and Shrubs. Agriculture Handbook No. 410. Forest Service, United States Department of Agriculture. Washington D.C.

Vogelmann, J.E., Howard, S.M., Yang L., Larson, C.R., Wylie, B.K., and Van Driel, N., 2001. Completion of the 1990s National Land Cover Data set for the coterminous United States from Landsat Thematic Mapper Data and Ancillary Data Sources. Photogrammetric Engineering and Remote Sensing 67, 650-652.

Walker, D., Epstein, H., Jia, G., Balser, A., Copass, C., Edwards, E., et al., 2003. Phytomass, LAI, and NDVI in Northern Alaska: relationships to summer warmth, soil pH, plant functional types, and extrapolation to the circumpolar Arctic. Journal of Geophysical Research 108, 8169, doi:10,1029/2001JD000986.

Weller, G., Anderson, P., Wang, B. (Eds.), 1999. The potential consequences of climate variability and change in Alaska: A report for the U.S. global change research program. Center for Global Change and Arctic Research, Fairbanks, AK, 40pp.

White, M.A., Thorton, P.E., and Running, S.W. 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Bioeochemical Cycles 11, 217-234.

White, M.A., Schwartz, M.D., and Running, S.W., 2000. Young students, satellites aid understanding of climate-biosphere link. EOS Transaction, American Geophysical Union, 81, 1-12.

White, M.A., Nemani, R.R., Thornton, P.E., and Running, S.W., 2002. Satellite evidence of phenological differences between urbanized and rural areas of the Eastern United States deciduous broadleaf forest. Ecosystems 5, 260-267.

Wilmont, C.J., 1982. Some comments on the evaluation of model performance. Bulletin American Meteorological Society 63, 1309-1313.

Zhang, X., Friedl, M., Schaaf, C., Strahler, A., Hodges, J., Gao, F., et al., 2003. Monitoring vegetation phenology using MODIS. Remote Sensing of Environment 84, 471-475.

Zhou, L., Tucker, C.J., Kaufman, R.K., Slaybeck, D., Shabanov, N.V., Myneni, R.B., and Taylor, M.G., 2001. Variation in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. Journal of Geophysical Research 106:20069-20083.