Available online at www.sciencedirect.com
ScienceDirect
Remote Sensing of Environment 104 (2006) 96 – 102
Remote Sensing of Environment
www.elsevier.com/locate/rse

Determination of spring onset and growing season leaf development using satellite measurements

Qilong Min [a,*], Bing Lin [b]

[a] Atmospheric Sciences Research Center, State University of New York, Albany, United States
[b] Sciences Directorate, NASA Langley Research Center, Hampton, VA, United States

Received 14 November 2005; received in revised form 2 May 2006; accepted 7 May 2006

Abstract

An integrated approach to retrieve microwave emissivity difference vegetation index (EDVI) over land regions has been developed from combined multi-platform/multi-sensor satellite measurements, including SSM/I measurements. A possible relationship of the remotely sensed EDVI and the leaf physiology of canopy is explored at the Harvard Forest site for two growing seasons. This study finds that the EDVI is sensitive to leaf development through vegetation water content of the crown layer of the forest canopy, and has demonstrated that the spring onset and growing season duration can be determined accurately from the time series of satellite estimated EDVI within uncertainties of approximately 3 and 7 days for spring onset and growing season duration, respectively, compared to in situ observations. The leaf growing stage can also be monitored by a normalized EDVI. EDVI retrievals from satellite generally are possible during both daytime and nighttime when it is not raining. The EDVI technique studied here may provide higher temporal resolution observations for monitoring the onset of spring, the duration of growing season, and leaf development stage compared to current operational satellite methods.

Keywords: Spring onset detection; Growing season duration; Microwave remote sensing; Emissivity difference vegetation index (EDVI); Leaf development

1. Introduction

Accurate assessments of spring onset and growing season duration are crucial for the estimations of CO_2 uptake by the ecosystem in the global carbon cycle (Cayan et al., 2001; Nemani et al., 2002). Goulden et al. (1996) and Nemani et al. (2003) concluded that earlier springs and wetter autumns over the last two decades due to climate variations and changes resulted in a lengthening of the vegetation carbon uptake period that could account for two-thirds of the increase in observed forest growth rates. Most of the existing techniques to determine growing season duration and vegetation greenness from satellite data are based on the normalized difference vegetation index (NDVI) or its directly associated measurements at visible and near-infrared (VIS/NIR) wavelengths (Asrar et al., 1984; Goetz, 1997; Myneni et al., 1995; Sellers, 1985). Vegetation index derived from the optical technique is strongly influenced by clouds and aerosols and only available during daytime, which limits its temporal resolution and the accuracy of the detection of spring onset and determination of growing season duration (Gutman, 1999; Gutman & Ignatov, 1995). Furthermore, NDVI is saturated when the leaf area index (LAI) is greater than 3, thus losing its sensitivity to detect dense vegetation (e.g. forest) (Carlson & Riziley, 1997; Hatfield et al., 1985).

Vegetation significantly modulates the microwave emission from land surface. The microwave land surface emissivity (MLSE) derived from satellite measurements is strongly related to vegetation water content (VWC) and canopy structure (Jackson & Schmugge, 1991; Min & Lin, 2006; Njoku, 1999; Wigneron et al., 1993, 2003), and less influenced by atmospheric properties, such as clouds and aerosols, than the land surface reflections measured from VIS/NIR wavelengths. Moreover, MLSE can be retrieved during day and night, substantially increasing temporal sampling rates for ecosystem applications.

In a recent study, Min and Lin (2006) used a combined retrieval of microwave, infrared, and visible measurements to

* Corresponding author. Tel.: +1 518 437 8740; fax: +1 518 437 8758.
E-mail address: min@asrc.cestm.albany.edu (Q. Min).

0034-4257/$ - see front matter
doi:10.1016/j.rse.2006.05.006

estimate the MLSE at the Harvard Forest site and further defined the land surface microwave emissivity difference index (EDVI). They found that the EDVI values could be used to represent physical properties of crown vegetation such as vegetation water content of crown canopies. The collocated land surface turbulent and radiative fluxes were empirically linked together by the EDVI values. Combining retrieved EDVI with radiation measurements, they inferred land surface–atmosphere exchange of moisture and CO_2 at dense forest environments. In this paper, we further explore potentials of EDVI, along with VIS/NIR and broadband solar radiation measurements, for detecting the spring onset and determining the growing season duration and leaf development.

2. Methodology and measurements

When a vegetated land surface layer is very thick (e.g., a forest), microwave emissivity from the vegetated layer depends largely on properties of the canopy (Jackson et al., 1984; Jackson & Schmugge, 1991; Paloscia, 1995; Wigneron et al., 2003). The optical depth at microwave wavelengths has a semi-empirical linear relationship with vegetation water content (VWC) and varies systematically with both wavelength and canopy structure (Jackson & Schmugge, 1991). The satellite remotely sensed microwave surface emission above a canopy after the atmospheric correction is an integration of the microwave radiation from the whole canopy vertical profile weighted by its transmission. Microwave emissivity retrieved at the longer wavelength with a weaker attenuation by the vegetation in the canopy represents an effectively thicker layer than those observed at the shorter and stronger attenuation wavelength. The microwave emissivity difference between two wavelengths minimizes the influence of the soil emission underneath vegetation canopy and is sensitive to VWC and other vegetation properties between two emission layers in different effective thickness. Min and Lin (2006) proposed a new vegetation index: microwave emissivity difference vegetation index (EDVI), based on the microwave land surface emissivity difference between two wavelengths to indicate VWC and other vegetation properties of the canopy. The EDVI is defined as:

$$\mathrm{EDVI_P} = \frac{\mathrm{MLSE_P^{19}} - \mathrm{MLSE_P^{37}}}{0.5\left(\mathrm{MLSE_P^{19}} + \mathrm{MLSE_P^{37}}\right)}$$

where p represents a polarization at vertical or horizontal direction. 19 and 37 indicate 19.4 GHz and 37.0 GHz channels of microwave measurements, respectively. This normalized emissivity difference further minimizes its dependency on canopy skin temperature and thus substantially reduces its uncertainty when canopy skin temperature retrievals are problematic under cloudy conditions. Min and Lin (2006) used a simple conceptual two-layer model for microwave radiative transfer calculations to illustrate the fundamental physical linkage of EDVI to crown canopy VWC in heavy forest environments and its uncertainty to various factors. That study suggested that EDVI is insensitive to the soil moisture and has a near-linear relation to the VWC for the range of VWC in some canopies.

We retrieved MLSE values from the SSM/I data from Defense Meteorological Satellite Program (DMSP) F13 and F14 satellites from 1999 to 2001 at the Harvard Forest site for all SSM/I wavelengths and polarizations using a combined technique from multi-sensor/multi-platform measurements (Lin & Minnis, 2000; Min & Lin, 2006). These MLSE values are estimated based on an atmospheric microwave radiative transfer (MWRT) model (Lin et al., 1998), which accurately accounts for the atmospheric absorption and emission of gases and clouds, especially the temperature and pressure dependencies of these radiative properties (Lin et al., 2001). Only non-precipitating cases were analyzed to avoid the complexity of microwave scattering and the dependence of observed radiances on precipitating hydrometeors. The major inputs for the retrieval are effective land surface skin temperature, column water vapor (CWV), cloud water amount, surface air temperature and pressure. The European Center for Medium-range Weather Forecasts (ECMWF) assimilation data is used to estimate CWV values. Atmospheric optical depths inferred from total shortwave measurements assuming 8 μm cloud droplet effective radius were converted to cloud water amount. The vertical distributions of atmospheric temperature, pressure and gas abundance were constructed based on climatological profiles (McClathey et al., 1972) and interpolated to conform to the surface measurements of temperature and pressure and ECMWF CWV values. Since the coverage of forest at Harvard Forest within the footprint of 19 GHz channels (69×43 km^2, the largest of SSM/I) is very high, the possible heterogeneity contribution of forest to the emissivity is minimal. As indicated by the study of Min and Lin (2006), the vertical component of the EDVI has a higher correlation with the evapotranspiration than the horizontal component. We use the $\mathrm{EDVI_V}$ in this study.

To determine the spring onset quantitatively from satellite microwave measurements, the timing of an abrupt increase in the $\mathrm{EDVI_V}$, we apply a simple low-pass filter on retrieved $\mathrm{EDVI_V}$ values to smooth small daily fluctuations (Press et al., 1989), caused by uncertainties in retrievals, leaf development stage variations of various vegetation types, and possible water interception by the leaves. We, then, locate the maximum variation of $\mathrm{EDVI_V}$ change rates (curvature point) from the locally smoothed time series of $\mathrm{EDVI_V}$ in three steps: 1) take the first derivative in a range of days when the spring onset may occur (±14 days); 2) find the maximum of the second derivative; 3) in case of missing data around the day of the maximum, determine the day of the maximum using a quadratic function. Fig. 1 illustrates the procedure based on the data of year 2000. Fig. 1a shows the smoothed time series of $\mathrm{EDVI_V}$ with original retrievals between day 116 and day 130 of year 2000, a period in which the possible onset of spring may occur. Fig. 1b and c show the first and second derivatives of $\mathrm{EDVI_V}$ as a function of time. Day 124 with maximum of the second derivative is the time of the maximum curvature, i.e. the spring onset of year 2000. The same procedure is applied to the tail-end period of a growing season to detect the maximum of the second derivative, i.e., the end of the growing season. Once the

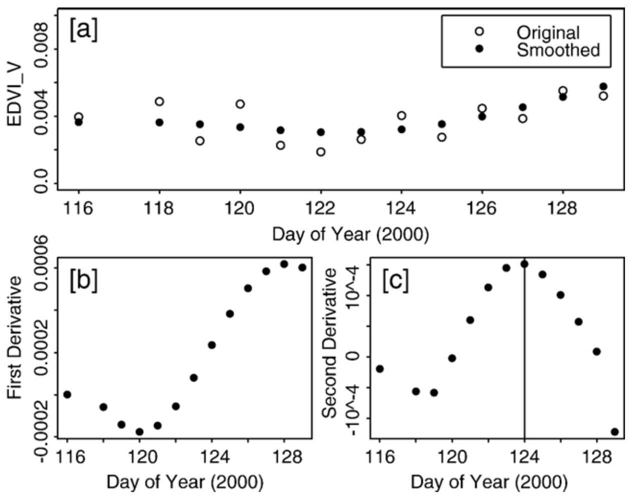

Fig. 1. Retrieved and smoothed EDVI_V between days 116 and 129 of year 2000 (up panel), and its first and second derivatives (bottom panels).

spring onset and the end of the growing season have been detected, the growing season duration is decided by the period between the two. We further define a normalized $EDVI_V$ to quantify the leaf development stage as:

$$^{N}EDVI_V = \frac{EDVI_V - EDVI_V^{onset}}{EDVI_V^{max} - EDVI_V^{onset}}$$

where $EDVI_V^{onset}$ and $EDVI_V^{max}$ are $EDVI_V$ at the spring onset and the maximum $EDVI_V$ during the growing season, respectively. The $^{N}EDVI_V$ is the relative change of $EDVI_V$ from its spring onset value during a growing season and represents the leaf growing stage during the growing season.

The Harvard Forest Environmental Monitoring Station (EMS) is located in north-central Massachusetts (42.54′N, 78.18′W). The forest is 50–70 years old and contains a mixture of red oak, red maple, and hemlock with an average tree height of 24 m. At the Harvard Forest site, the timing of woody vegetation development during the growing season has been observed at 3–7 day intervals for 109 trees from closed forest, through forest–swamp margins, to dry, open field (O'keef, 2004). The nature of the forest for spring onset and end of growing season may not be a single day but a short period due to multiple species. In this study, the normalized leaf amount, defined as the ratio of the leaf amount at the time of the in situ observation to the maximal leaf amount of the growing season averaged over all 109 trees, are used as an indication of leaf development stage in the area. The averaged time of observed initial bud break over six representative species of the 109 trees at Harvard Forest (red oak, white oak, red maple, yellow birch, witch hazel, and striped maple) is defined as the spring onset. The same procedure of averaging applies to observed 75% leaf development and 50% leaf fall to represent the time of those events at the site. The site has also been equipped with a suite of radiation and turbulent flux measurements since 1991 (Moore et al., 1996; Wofsy et al., 1993). Up-welling and down-welling radiation sensors mounted on an observation tower measure the surface shortwave (SW) and photosynthetically active radiation (PAR) albedos, which provide additional information on vegetation conditions and canopy growing stages (Moore et al., 1996; Sakai et al., 1997). Traditional NDVI values used here are the standard NASA Goddard products and derived from measurements of Advanced Very High Resolution Radiometer (AVHRR; http://daac.gsfc.nasa.gov/data/dataset/avhrr/). These NDVI estimates are the 10-day composite values. The coarse temporal resolution of the data is caused by various environmental conditions, such as clouds, aerosols and availabilities of solar spectrum measurements (i.e., daytimes).

3. Results

An ideal remote sensing experiment to determine land surface physical processes, particularly the cycle of leaf emergence and fall in a deciduous forest, is to monitor the annual cycle of vegetation development. Fig. 2 shows retrieved $^{N}EDVI_V$ from combined overpasses of F13 and F14 for the growing season of year 2000. The solid dots represent the normalized leaf amount observed at the Harvard Forest for both spring and fall seasons. The vertical lines indicate the averaged day of year (DOY) from in situ observations of bud break, 75% leaf development, and 50% leaf fall, respectively. The horizontal bars in each of the three corresponding leaf development stages represent the time ranges (or uncertainties) for all six major species of trees around the Harvard Forest site. These time ranges generally vary from 3 to 15 days (cf. Table 1) reflecting the differences in tree species. After the spring onset on DOY 128, $^{N}EDVI_V$ increased quasi-linearly in the first 20 days accompanied by leaf emergence until 75% leaves had developed. The $^{N}EDVI_V$ reached to value 0.75 on DOY 160, within the uncertainty of the averaged day of 75% leaf development of in situ observations at the surface site. It took an additional month for $^{N}EDVI_V$ to reach its maximum.

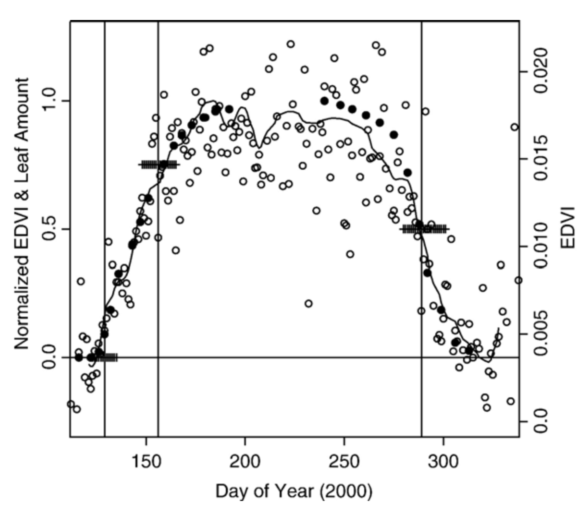

Fig. 2. Multi-sensor/multi-platform measurements at the Harvard Forest site for the growing season of 2000: $^{N}EDVI_V$ (solid curve), EDVI (open circles), and normalized leaf amount (solid dots). The vertical lines indicate the averaged DOY from in situ observations of bud break, 75% leaf development, and 50% leaf fall, respectively. The horizontal bars represent the time range in each of the three corresponding leaf development stages.

Table 1
Observed and inferred growing stages of leaf at the Harvard Forest site in years of 1999 and 2000

	1999				2000			
	The spring onset	75% leaf development	50% leaf fall	The end of season	The spring onset	75% leaf development	50% leaf fall	The end of season
Red oak	126	148	294	–	129	161	293	–
Red maple	126	146	286	–	129	156	283	–
Yellow birch	127	141	287	–	129	149	283	–
White oak	132	155	301	–	132	162	298	–
Witch hazel	122	142	–	–	126	151	–	–
Striped maple	125	146	–	–	127	155	–	–
Mean	126	146	292	–	129	156	289	–
F13_AM	124	149	274	313	–	–	–	–
F13_PM	128	152	274	308	–	–	–	–
F13	123	150	278	307	–	–	–	–
F14_AM	–	–	–	–	127	166	284	307
F14_PM	–	–	–	–	121	153	286	302
F14	–	–	–	–	127	157	286	323
F13 and F14	123	150	281	308	124	160	287	323
SW_albedo	132	–	–	312	127	–	–	316

Temporal variation of $^{N}EDVI_{V}$ agrees very well with observed normalized leaf amount (solid dots) at the surface site.

Leaf senescence is a slow process, occurring in the fall. The decrease trend of $^{N}EDVI_{V}$ from DOY 250 to the end of growing season indicates reduction of VWC and/or leaf areal coverage, representing the period of leaf senescence process. The decrease trend of $^{N}EDVI_{V}$ is consistent with the variation of observed leaf amount at the surface site. However, $^{N}EDVI_{V}$ values are lower than the normalized leaf amount of in situ observations at the surface site, due to the ripening process which reduces the VWC in the leaves. $^{N}EDVI_{V}$ quantitatively describes the VWC in the canopy, which is more important than the leaf amount for photosynthesis and vegetation–atmosphere interaction processes. As the ripening process proceeds, $^{N}EDVI_{V}$ further decreased substantially to small or negative values. At the end of the growing season on DOY 318, $^{N}EDVI_{V}$ was about zero. After that day, $^{N}EDVI_{V}$ went negative, indicating that the canopy as a whole at the time may be drier than at the beginning of the growing season. After DOY 323, $^{N}EDVI_{V}$ ended its decrease, indicating the end of leaf fall.

Surface albedos at optical wavelengths directly link to the characteristics of surface properties, as a result of absorption and reflection of canopy. The surface SW albedo derived from tower measurements, shown in Fig. 3, increased rapidly in the early spring, consistent with the variations of $^{N}EDVI_{V}$. However, the SW albedo reached its maximum before 75% leaf development and then gradually decreased throughout the rest of the growing season. The SW albedo started an abrupt drop 10 days after 50% leaf fall, which is inconsistent with observed leaf amount and differ from $^{N}EDVI_{V}$, and another indication of the saturation and sensitivity of SW observations to leaf amount (or vegetation development).

In the meantime, the PAR albedo, also shown in Fig. 3, illustrated a gradual decrease at the beginning of the growing season due to increases in the absorption of solar radiation at the PAR spectra caused by enhancing photosynthetic processes of the canopy. The gradual decrease of PAR albedo ended around DOY 170, approximately 10 days before $^{N}EDVI_{V}$ reached its maximum, and then PAR albedo stayed nearly constant for the rest of the growing season until the leaf senescence. The increase of PAR albedo, then, occurred on DOY 275 before 50% leaf fall indicating reduction of photosynthesis as a consequence of changing leaf color. Comparing to the variations of $^{N}EDVI_{V}$ in both early growing season (DOY 170–180) and leaf senescence (DOY 265–275), PAR albedo was apparently saturated to the development of leaf stage as LAI of canopy was high. The reason is that the penetration and reflection of photons at the optical wavelengths are limited to the top layer of the crown layer of a forest canopy, resulting surface albedos insensitive to leaf development in the sub-layers of crown canopy. Microwave emission, on the other hand, penetrates through a deeper crown layer of a forest than PAR and shortwave wavelengths, thus is a better way to detect the growing stage of entire crown canopy. NDVI retrievals from

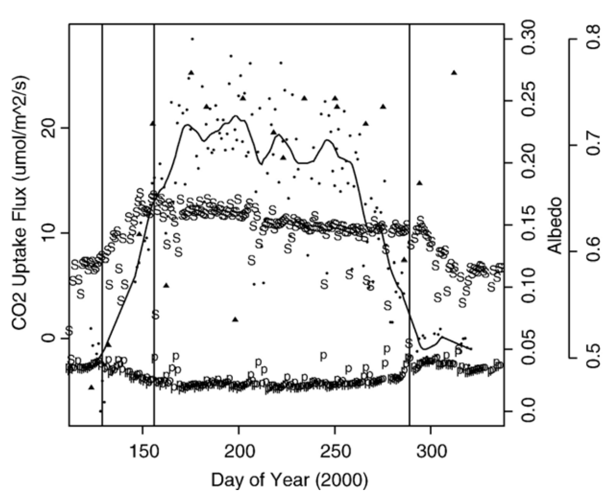

Fig. 3. Time series of measured CO_2 uptake flux (dots) and smoothed values (solid curve), shortwave albedo ("s"), PAR albedo ("p"), and NDVI (solid triangle). The vertical lines indicate the averaged DOY from in situ observations of bud break, 75% leaf development, and 50% leaf fall, respectively.

AVHRR show much coarser temporal resolution due to the limit of clear-sky conditions than that of ${}^{N}EDVI_V$. Small NDVI values, occasionally shown in the middle of the growing season, may result from cloud contaminations. Generally, the temporal variation of NDVI closely follows that of PAR and SW albedos, since they are all based on reflections in solar spectra. As indicated in previous studies, NDVI is saturated when the leaf area index (LAI) is greater than 3 and insensitive to the whole vegetation of dense canopy (Carlson & Riziley, 1997; Hatfield et al., 1985). This result indicates that the ${}^{N}EDVI_V$ may provide a better tool to estimate growing season duration than those from solar wavelengths.

Another quantitative measure of the onset and duration of growing season can be based on carbon uptake activities of vegetation. Because of the strong relationship between EDVI and physical properties of crown canopy, the temporal variation of EDVI should be consistent with that of observed carbon uptake flux. Min and Lin (2006) did find that there is a statistically significant, strong relationship between CO_2 uptake fluxes and the products of the EDVI and surface PAR measurements at Harvard Forest for all-weather conditions (both cloud and clear-sky). As pointed out by Min (2005), radiation-use-efficiency varies considerably from clear-sky, to partially cloudy, and to overcast conditions. The correlation (with the coefficient 0.97) of EDVI with CO_2 fluxes for clear-sky cases is stronger than not only that of all-sky cases but also those using NDVI (Min & Lin, 2006). The timing of decrease in ${}^{N}EDVI_V$ in the late summer reflects the first sign of leaf senescence. When ${}^{N}EDVI_V$ decreased significantly below zero, the carbon uptake fluxes were also near zero, indicating no noticeable photosynthetic activity in the periods and the end of growing seasons. However, SW reflections during these periods were significant higher than that during off-growing season, which is inconsistent with forest physiology. The physiological processes associated with leaves have an annual cycle shorter than that of their physical presence. These results, again, suggest that ${}^{N}EDVI_V$ values are more related to physiological activities of vegetation during growing seasons than solar wavelength indices. The variations of ${}^{N}EDVI_V$ during summer

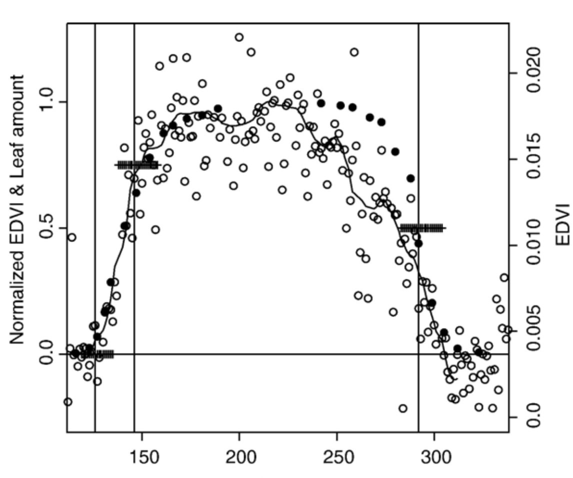

Fig. 4. The same as Fig. 2 but for the growing season of 1999.

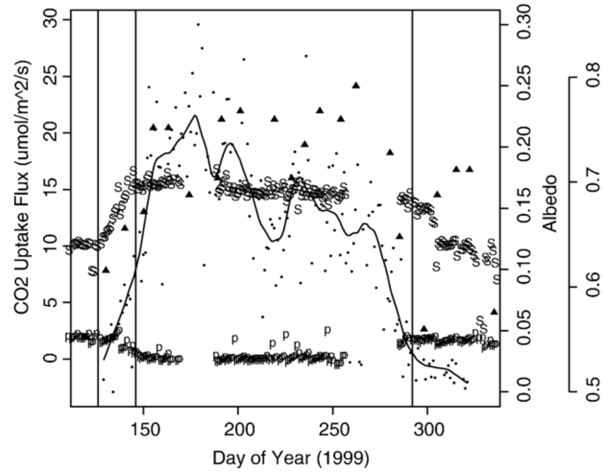

Fig. 5. The same as Fig. 3 but for the growing season of 1999.

time were also resulted from the physiological characteristic of forest dynamics. Other factors such as water stress may have significant impact on forest. It is worthwhile to notice that sky conditions (aerosols and clouds) have no impacts on surface derived albedos from tower measurements, and the temporal resolution of surface albedo used in this study is much better than that of most vegetation indexes derived from satellite optical observations because of strong atmospheric influence on these satellite optical retrievals. Thus, even with these merits of the surface optical measurements, the ${}^{N}EDVI_V$ still shows advantages in monitoring forests.

The characteristics of detecting leaf development in the year 1999 are similar to that of the year 2000, shown in Figs. 4 and 5, although some surface measurements were missed in that year. Table 1 summarizes the days of leaf growth stages, observed at surface for six major species and inferred from ${}^{N}EDVI_V$ for various satellite passes. We also include the leaf growth stages estimated from the time series of measured SW albedo using the same procedure as that of ${}^{N}EDVI_V$ for comparison. For each overpass of each DMSP satellite, ${}^{N}EDVI_V$ demonstrates its capability to monitor various stages of leaf development within the uncertainty of ground observation. The ${}^{N}EDVI_V$ derived stage times of leaf development from the average of all overpasses (morning and afternoon, F13 and F14) provide the most accurate assessment of the spring onset and the growing season duration, among all the products and methods tested in this paper.

4. Summary and discussion

Making a connection between remotely sensed data and canopy physiology is useful for studies of regional and continental scale land surface properties. Through its influence on the radiation fields of forest canopies and the restriction of momentum exchange of atmosphere and surface, the seasonally changing leaf physiology of canopy has a dramatic impact not only on the land–atmosphere exchange of moisture and CO_2 uptake fluxes, but also on sub-canopy exchange processes. In this study, we explored a possible linkage of measurements of surface albedo at optical wavelengths and land surface microwave emissivity difference index to the leaf physiology of canopy at the Harvard Forest site. The maximum curvature technique developed in this study detects the spring onset and growing season duration from time series of $EDVI_V$. Clearly, these measurements can be retrieved from satellites, and provide us a great potential for large scale vegetation monitoring.

We also used the normalized EDVI to quantify canopy leaf development. Surface albedos at SW and PAR wavelengths have high spatial resolutions for vegetation measurements, but are sensitive only to the leaf development of the uppermost part of the crown layer of forest canopies, and lack information for sub-layers of crown canopies of forests when canopy LAI is high. Thus, surface albedos (and associated indexes) at optical wavelengths alone cannot accurately represent the leaf development stage of a canopy. In contrast, microwave radiation has much better penetration for vegetated areas than that at optical wavelengths, ensuring that $^{N}EDVI_V$ is more sensitive to large parts of the column of a canopy. Retrievals of $EDVI_V$ from satellite microwave measurements are generally possible during day and night under most atmospheric conditions (except for precipitation). The microwave technique provides higher temporal resolution on monitoring the onset of spring and determining the duration of growing season than reflection measurements at optical wavelengths. This study also supports the fundamental conclusion of our previous study (Min & Lin, 2006) that a combined retrieval of microwave, infrared, and visible measurements from satellite can accurately estimate land surface–atmosphere exchange at dense forest environments. The shortcoming of satellite microwave measurements is their lower spatial resolution than that of optical observations. Combining visible, near-infrared, infrared, and microwave measurements would substantially reduce the ambiguities inherent in individual spectral regime, and increase effective temporal and spatial sampling rates of required data sets for remotely sensing forest–atmosphere exchange.

Acknowledgements

This research was supported by the Office of Science (BER), U.S. Department of Energy, through the Atmospheric Radiation Measurements (ARM) and Northeast Regional Center (NRC) of the National Institute for Global Environmental Change (NIGEC) under Cooperative Agreement No. DE-FC03-90ER61010. The support is also from the Earth System Science Research Program under NASA Earth Observing System (EOS) Mission and the NASA Energy and Water cycle Study (NEWS) and EOS science and data analysis programs. SSM/I data were downloaded from NASA MSFC Data Center, NDVI data were downloaded from NASA GSFC DAAC, and surface data were obtained from the NIGEC-NRC at Harvard University.

References

Asrar, G. E., Fuchs, M., Kanemasu, E. T., & Hatfield, J. L. (1984). Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agronomy Journal*, *76*, 300−306.

Carlson, Tobu N., & Riziley, David A. (1997). On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment*, *62*, 241−252.

Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M., & Peterson, D. H. (2001). Changes in the onset of spring in the Western United States. *Bulletin of the American Meteorological Society*, *82*, 399−415.

Goetz, S. J. (1997). Multi-sensor analysis of NDVI, surface temperature, and biophysical variables at a mixed grassland site. *International Journal of Remote Sensing*, *18*(1), 71−94.

Goulden, M. L., Munger, J. W., Fan, S. M., Daube, B. C., & Wofsy, S. C. (1996). Exchange of carbon dioxide by a decidulous forest: Response to interannual climate variability. *Science*, *271*, 1576−1578.

Gutman, G. (1999). On the use of long-term global data of land reflectances and vegetation indices derived from the advanced very high resolution radiometer. *Journal of Geophysical Research*, *104*, 6241−6255.

Gutman, G., & Ignatov, A. (1995). Global land monitoring from AVHRR: Potential and limitations. *International Journal of Remote Sensing*, *16*, 2301−2309.

Hatfield, J. L., Kanemasu, E. T., Asrar, G., Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., et al. (1985). Leaf area estimates from spectral measurements over various planting dates of wheat. *International Journal of Remote Sensing*, *6*, 167−175.

Jackson, T. J., & Schmugge, T. J. (1991). Vegetation effects on the microwave emission of soils. *Remote Sensing of Environment*, *36*, 203−212.

Jackson, T. J., Schmugge, T. J., & O'Neill, P. (1984). Passive microwave remote sensing of soil moisture from an Aircraft platform. *Remote Sensing of Environment*, *14*, 135−151.

Lin, B., & Minnis, P. (2000). Temporal variations of land surface microwave emissivities over the atmospheric radiation measurement program southern great plains site. *Journal of Applied Meteorology*, *39*, 1103−1116.

Lin, B., Minnis, P., Fan, A., Curry, J., & Gerber, H. (2001). Comparison of cloud liquid water paths derived from in situ and microwave radiometer data taken during the SHEBA/FIREACE. *Geophysical Research Letters*, *28*, 975−978.

Lin, B., Wielicki, B., Minnis, P., & Rossow, W. B. (1998). Estimation of water cloud properties from satellite microwave, infrared, and visible measurements in oceanic environments. I: Microwave brightness temperature simulations. *Geophysical Research Letters*, *103*, 3873−3886.

McClathey, R. A., Fenn, R. W., Selby, J. E. A., Voltz, F. E., & Garing, J. S. (1972). Optical properties of the atmosphere. Air Force Cambridge Research Laboratories, AFCRL-72-0497. *Environmental Research Papers*, *411*.

Min, Q. -L. (2005). Impacts of aerosols and clouds on CO_2 uptake over Harvard Forest. *Journal of Geophysical Research*, *110*(D6), D06203 (doi:10.1029/2004JD004858).

Min, Q., & Lin, B. (2006). Remote sensing of evapotranspiration and carbon uptake at Harvard Forest. *Remote Sensing of Environment*, *100*, 379−387.

Moore, K. E., Fitzjarald, D. R., Sakai, R. K., Goulden, M. L., Munger, J. W., & Wofsy, S. C. (1996). Seasonal variation in radiative and turbulent exchange at a deciduous forest in Central Massachusetts. *Journal of Applied Meteorology*, *35*, 122−134.

Myneni, R. B., Hall, F. B., Sellers, P. J., & Marshak, A. L. (1995). The interpretation of spectral vegetation indices. *IEEE Transactions on Geoscience and Remote Sensing*, *33*, 481−486.

Nemani, R. R., White, M., Thornton, P., Nishida, K., Reddy, S., Jenkins, J., et al. (2002). Recent trends in hydrologic balance have enhanced the terrestrial carbon sink in the United States. *Geophysical Research Letters*, *29*, 1468 (doi:10.1029/2002GL014867).

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., et al. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science*, *300*, 1560−1563.

Njoku, E. G. (1999). *AMSR land surface parameters: Surface soil moisture, land surface temperature, vegetation water content, ATBD of AMSR-E Science Team, NASA EOS Project.*

O'keef, J. (2004). Woody species phenology, Prospect Hill Tract, Harvard Forest—2003. *Proceedings of Harvard University LTER and NIGEC programs.* Harvard Forest.

Paloscia, S. (1995). Microwave emission from vegetation. In B. J. Choudhury, Y. H. Kerr, E. G. Njoku, & P. Pampaloni (Eds.), *Passive microwave remote sensing of land-atmosphere interactions.* Netherlands VSP BV.

Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. (1989). *Numerical recipes.* Cambridge University Press.

Sakai, R., Fitzjarrald, D. R., & Moore, K. E. (1997). Detecting leaf area and surface resistance during transition seasons. *Agricultural and Forest Meteorology*, *84*, 273−284.

Sellers, P. J. (1985). Canopy reflectance, photosynthesis, and transpiration. *International Journal of Remote Sensing*, *6*, 1335−1372.

Wigneron, J. -P., Calvet, J. -C., Kerr, Y. H., Chanzy, A., & Lopes, A. (1993). Microwave emission of vegetation: Sensitivity to leaf characteristics. *IEEE Transactions on Geoscience and Remote Sensing*, *31*, 716−726.

Wigneron, J. -P., Calvet, J. -C., Pellarin, T., Van de Griend, A. A., Berger, M., & Ferrazzoli, P. (2003). Retrieving near-surface soil moisture from microwave radiometric observations: Current status and future plans. *Remote Sensing of Environment*, *85*, 489−506.

Wofsy, S. C., Goulden, M. L., Munger, J. W., Fan, S. -M., Bakwin, P. S., Daube, B. C., et al. (1993). Net exchange of CO_2 in midlatitude forests. *Science*, *260*, 2224−2238.